Multiplatform Observations for Measuring Wetland Landscape Topography
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Measuring Wetland Landscape Topography

Krishna K. Talukdar

Foreword by

Dr. Dorothy K. Hall
NASA Goddard Space Flight Center
Cover page image: The Earth photograph (only half is shown here) as seen by the Apollo 17 crew traveling toward the Moon. The photo was taken from Apollo 17 spacecraft on December 7, 1972, at a distance of about 45,000 km. Almost the entire coastline of Africa, Arabian Peninsula and Madagascar is clearly visible (Source: http://en.wikipedia.org/wiki/The_Blue_Marble). Platform (aircraft and spacecraft) images are taken from various sources.
Let noble thoughts come to us from everywhere.

(RigVeda 1.89.1)
Man is not traveling from error to truth, but from truth to truth, from lower to higher truth.

(Swami Vivekananda, 1893)
Dedicated

To

The Loving Memory of
My Parents
Multiplatform Observations for Measuring Wetland Landscape Topography

Proefschrift

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*Keywords:* Multiplatform; remote observation; landscape topography; digital elevation model; land cover; bias calibration; data integration; accuracy assessment; Okavango Delta.

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Foreword

Optimum management of the world’s largest inland wetland ecosystem, the Okavango Delta, is of critical importance to keep up with the region’s growing demand for water. The Okavango Delta is vitally important because of its strategic location with respect to the African countries of Angola, Namibia and Botswana, and its resources may offer some potential relief as the demand for water in the region accelerates.

The author employs a multitude of satellites and instruments launched by many different countries. As examples, he makes use of data from Landsat, IKONOS, ASTER, SPOT, SRTM, ICESat, CryoSat-2 and GPS satellites. Many detailed figures, satellite images and pictures illustrate the work and reinforce and illuminate the sophisticated instrumentation, techniques and model results described in the dissertation. The author’s multisensor, multiplatform approach allows him to construct wetland topographic models through mapping the water surface, channels, and land cover. Accurate DEMs are lacking in the Okavango Delta, and as described in Chapter 4, can provide vital information needed to model landscape processes, and can be used to improve mapping and characterization of landscapes, e.g. channel networks and catchment areas. Use of ICESat GLAS LiDAR data allow measurement of water surface topography and thus water level fluctuations, as well as change in water level over time (2003 – 2009). The author calculates water surface elevation changes with startling accuracy.

The 1972 launch of the Landsat-1 satellite (then known as Earth Resources Technology Satellite-1, or ERTS-1) revolutionized remote sensing of the Earth’s surface. Satellite data, represented by ‘digital numbers’ printed on computer printouts at the time, were translated mathematically along with ancillary data into physical quantities to enable quantitative analyses. Also in the early 1970s, Side-Looking Airborne Radar, or SLAR data, were becoming very important for studying features on the Earth such as lakes, rivers and flooded areas, though initially the data were not calibrated. The Landsat series has continued to today, now going strong with Landsat-8 in orbit, while SLAR has largely evolved into radar remote sensing from satellite, using SARs from different satellites since the 1978 launch of the first spaceborne SAR, known as Seasat. Though it only operated for 100 days, Seasat had a tremendous impact on remote sensing of the Earth, paving the way for many advanced SAR sensors that have since provided calibrated SAR data in multiple wavelengths and polarizations. At the turn of the new Millennium, advanced and well-calibrated instrumentation began to flow from Earth Observation System (EOS) instruments such as the MODIS and ASTER in 2000. The ICESat satellite was launched in 2003 to measure elevation change of the Earth’s surface. Because of the many sensors available today, remote and data-poor areas such as the Okavango Delta can be studied in detail from space, using instruments operating in different parts of the electromagnetic spectrum, to improve quantification of surface features.

Chapter 6 is devoted to describing the accuracy of the derived topographic data and models, and the importance of understanding the errors inherent in the measurements. Many references are made to important earlier works allowing the reader to envisage how we have been able to arrive at the advanced state of remote sensing that we enjoy today. The underpinning of today’s cutting-edge technology for mapping surface topography is revealed in the historical context provided in this dissertation. Information from the ground, air and space was used to improve the accuracy of topographic models as described in Chapter 7. This required development of novel approaches for integrating disparate but complementary...
elevation datasets. Additionally, in Chapter 8 the author provides his vision for future research aimed at improving topographic modeling over wetland environments, especially over the Okavango Delta.

The techniques presented in this dissertation will guide future work on mapping topography, surface water and land cover, and represent the basis for measuring change in the area. In consideration of the critical need for water-resource management of the Okavango Delta, the publication of this work is a timely and important achievement.

Dorothy K. Hall
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This exciting research was an untiring journey to explore, to adventure, to investigate, to contribute, and above to achieve scientific rewards. Many scientists, scholars, technical professionals and support personals contributed, directly or indirectly, to make this dissertation possible.

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Significant part of this dissertation was done at the Institute of Geodesy and Photogrammetry (IGP), Swiss Federal Institute of Technology (ETH) Zurich, Switzerland. The work was originated in a research project of ETH Zurich and Government of Botswana's Department of Water Affairs. I thank Professor Armin Grün for initiating me into this research at the ETH Zurich. I also thank Dr. Emmanuel Baltsavias and other colleagues at the IGP for their support and cooperation. Particular thanks to Zhang Li (IGP) for support on digital photogrammetric DSM generation, and Peter Bauer (Institute of Environmental Engineering, IEE/ETH Zurich) and Stefan Meile (IGP) for their contributions during GPS field campaign. I thank the Department of Water Affairs, Government of Botswana, for providing assistance for the field campaign. I appreciate the support of Lesego Kgotlhang, Carmen Alberich and Professor Wolfgang Kinzelbach (IEE, ETH Zurich). I thank Professor Gábor Székely (Computer Vision Laboratory, ETH Zurich) for his comments on filtering elevation data. I also thank C. Brandenberger (Institute of Cartography, ETH Zurich) for his support on map projection and coordinate transformation.

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Delft, The Netherlands
Abstract

This dissertation contributes to advance a multiplatform observation approach to landscape topographic modeling, with a reference to African wetland landscape topography.

Observations from remote platforms have considerably improved mapping and understanding of landscape topography of the Earth and other planetary bodies. However, despite technological advancements, in many parts of the Earth measurements of landscape topography and processes are limited by inconsistent data, coverage, resolution, and accuracy. To overcome these limitations, this study used observations from a suite of instruments on multiple platforms (terrestrial, aerial, and space) to construct variable resolution topographic models of the Okavango Delta region in the Kalahari basin (Africa) and evaluate their quality. The science objectives were 1) to measure and construct wetland digital elevation models (DEMs) including the water surface from multiplatform observations and evaluate the quality of data products, 2) to map wetland land cover from spaceborne dual-resolution optical observations (used as a determinant of elevation data accuracy), and 3) to integrate multiplatform elevation observations to produce improved quality DEMs, considering land cover as a determinant of elevation accuracy and bias calibration.

This dissertation describes measurements and modeling 1) microtopography from airborne and spaceborne (IKONOS) optical stereo-observations using photogrammetry, 2) regional mesotopography from global positioning system (GPS), airborne profiling (AGS) and spaceborne interferometric (SRTM) radar, and spaceborne optical stereo (ASTER) observations, and 3) water surface topography from spaceborne interferometric radar and profiling laser (SRTM and ICESat) observations. Wetland land cover has been mapped from spaceborne dual-resolution optical (IKONOS and Landsat 7) images by automatic clustering and classification, and demonstrated the potential of single-band over multi-band images for the delineation of water in wetlands. Finally, multiplatform (AGS, SRTM, ASTER, ICESat, GPS, and CryoSat [profiling radar]) elevation data were integrated through a frequency fusion (Fourier domain) and a merging approach devised by the author (test site to regional scale).

Photogrammetry-based microtopographic modeling (test sites) resulted in high vertical accuracy (root mean square error, RMSE) of ~1 m to 1.5 m, when evaluated against GPS elevations (~0.16 m vertical accuracy). Regional mesotopographic modeling from GPS, AGS, SRTM, and ASTER data resulted in ~1.5 m to ~4.5 m vertical accuracy (evaluated against independent GPS measurements with ~0.16 m vertical accuracy). The GPS model provided the highest accuracy, AGS and SRTM medium, and ASTER the lowest. ICESat laser altimeter observations gave ~1.2 m vertical accuracy on the delta landscapes compared to GPS elevations. Water surface elevation measurement from SRTM and ICESat observations has resulted in ~2 m and ~0.75 m vertical accuracy, respectively (evaluated against GPS elevations). ICESat measurements revealed the water level dynamics in the delta with ~1.5 m fluctuations between 2003 and 2009, and has recorded the historical flooding (biggest since 1960s) of April 2009 with an estimated water level rise of 0.8 m over 2007. Fusion of SRTM with AGS and GPS-based elevation datasets improved the quality of fused models, compared to individual datasets. Bias calibration of SRTM and ASTER data using ICESat measurements marginally improved their quality. The real improvement of merging multiplatform observations to produce mesotopographic models came from integrated ICESat
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and CryoSat data (IceCryo model), and integrated ICESat, CryoSat and GPS data (ICG model). Integrated IceCryo and ICG models provided for the first time most accurate topographic data on the Okavango Delta region with $-1.7$ m and $-1.5$ m vertical accuracy, respectively (evaluated against independent GPS measurements).

This dissertation has made significant original contributions to the advancement of a multiplatform approach to landscape topographic modeling in general, and to wetland topographic modeling in particular. Note, this is the first in-depth landscape topographic modeling work on the Okavango Delta region, Africa. The results have many implications, e.g. for improved understanding of the micro- and mesotopographic (including water surface) and biophysical characteristics of the landscape, providing key inputs to modeling hydrological and environmental processes, and for monitoring wetland processes and impacts of regional climate change. These aspects need to be considered in future studies using data from more advanced instruments on satellite platforms (e.g. ICESat-2 and SWOT). Approaches and methods developed in this dissertation can be applied to other situations, regionally and globally. Further, the revealed similarity in topographic patterns (at varied scales) of this desert mega-alluvial fan may well serve (as a terrestrial analogue) to improve understanding of the planetary fan-shaped features (e.g. Mars landscape features).

Keywords: Multiplatform; optical imaging; profiling radar; imaging radar; profiling laser; GPS; stereophotogrammetry; elevation modeling; microtopography; mesotopography; water surface topography; land cover; bias calibration; accuracy assessment; data integration; integrated model; error budget; Okavango Delta; Kalahari.
Samenvatting

Dit proefschrift draagt bij aan het verbeteren van een aanpak met multiplatform-observaties van landschapstopografiemodellering met een voorbeeld voor de Afrikaanse moeraslandschapstopografi.

Waarnemingen vanaf platformen op afstand hebben de kartering en de kennis van de landschapstopografi van de Aarde en andere planeten aanzienlijk verbeterd. Ondanks de technologische vooruitgang worden in veel gebieden op Aarde metingen van landschapstopografi en -processen echter beperkt door inconsistentie data, de dekking, de resolutie en de nauwkeurigheid. Om deze beperkingen het hoofd te bieden heeft dit onderzoek waarnemingen van een verzameling van instrumenten aan boord van verscheidene platformen (terrestrisch, in de lucht en in de ruimte) gebruikt voor het vervaardigen van topografische modellen met variabele resolutie van de regio van de Okavangodelta in het Kalaharibekken (Afrika) en voor het evalueren van hun kwaliteit. De wetenschappelijke doelen waren 1) het meten en vervaardigen van digitale hoogtemodellen (DEM) van moeras inclusief het wateroppervlak op basis van multiplatform-observaties en het evalueren van de kwaliteit van de dataproducten, 2) het karteren van landoppervlakklassen van moeras op basis van optische waarnemingen vanuit de ruimte met twee resoluties (gebruikt als indicator voor de nauwkeurigheid van de hoogtedata) en 3) het integreren van multiplatform-hoogtemetingen om verbeterde DEMs te produceren, rekening houdend met de landoppervlakklassen als indicator van de hoogtenauwkeurigheid en voor de kalibratie van de systematische afwijkingen.

Dit proefschrift beschrijft metingen en modellering van 1) microtopografi vanuit de lucht en vanuit de ruimte op basis van optische stereowaarnemingen met fotogrammetrie (IKONOS); 2) regionale mesotopografi op basis van metingen met het global positioning system (GPS), hoogteprofielmetingen vanuit de lucht (AGS) en interferometrische radarwaarnemingen vanuit de ruimte (SRTM) en optische stereowaarnemingen vanuit de ruimte (ASTER); 3) topografi van het wateroppervlak op basis van interferometrische radarwaarnemingen vanuit de ruimte en hoogteprofielmetingen vanuit de lucht (SRTM en ICESat). Moeraslandoppervlakklassen zijn gekarteerd op basis van optische beelden met twee resoluties vanuit de ruimte (IKONOS en Landsat 7) met automatische segmentatie en classificatie en het toonde de potentie van beelden met een enkele band ten opzichte van beelden met meerdere banden voor de begrenzing van water in moeras. Tenslotte zijn multiplatform-hoogtedata (AGS, SRTM, ASTER, ICESat, GPS en CryoSat [radarhoogteprofielen]) geïntegreerd met een aanpak met datafusie in het frequentiedomein (Fourierdomein) en met een aanpak met een door de auteur bedachte samenvoeging (van testlocatie naar regionale schaal).

Modellering van microtopografi gebaseerd op stereofotogrammetrie (testlocaties) resulteerde in hoge nauwkeurigheid (kwadratisch gemiddelde fout, RMSE) van ca. 1 tot 1,5 m, als deze vergeleken worden met GPS-hoogtes (0,16 m verticale nauwkeurigheid). Regionale mesotopografiemodellering op basis van GPS-, AGS-, SRTM- en ASTER-data resulteerde in ca. 1,5 m tot ca. 4,5 m verticale nauwkeurigheid (vergeleken met onafhankelijke GPS-metingen met 0,16 m verticale nauwkeurigheid). Het GPS-model gaf de hoogste nauwkeurigheid, AGS en SRTM medium en ASTER de laagste. ICESat-laseraltimetriemetingen gaven ca. 1,2 m verticale nauwkeurigheid in de deltalandschappen.
vergeleken met GPS-hoogtes. Hoogtemeting van het wateroppervlak op basis van SRTM- en ICESat-waarnemingen heeft geresulteerd in respectievelijk ca. 2 m en ca. 0,75 m verticale nauwkeurigheid (vergeleken met GPS-hoogtes). ICESat-metingen toonden de dynamiek van het waterpeil in de delta met fluctuaties van ca. 1,5 m tussen 2003 en 2009 en registreerde de historische (grootste sinds de 60-er jaren van de 20de eeuw) overstroming van april 2009 met een geschatte stijging van het waterpeil van 0,8 m ten opzichte van 2007. Datafusie van SRTM- met AGS- en GPS-hoogtedatat verzamelingen verbeterde de kwaliteit van de gefuseerde modellen vergeleken met de individuele dataverzamelingen. Kalibratie van de systematische afwijkingen van SRTM- en ASTER-data op basis van ICESat-metingen verbeterde hun kwaliteit marginaal. De echte verbetering door het samenvoegen van multiplatform-observaties om mesotopografische modellen te produceren kwam van geïntegreerde ICESat- en CryoSat-data (IceCryo-model) en geïntegreerde ICESat-, CryoSat- en GPS-data (ICG-model). Geïntegreerde IceCryo- en ICG-modellen gaven voor de eerste keer zeer nauwkeurige topografische data van de regio van de Okavangodelta met respectievelijk ca. 1,7 m en ca. 1,5 m nauwkeurigheid (vergeleken met onafhankelijke GPS-metingen).

Dit proefschrift heeft belangrijke nieuwe bijdragen geleverd aan de ontwikkeling van een multiplatform-aanpak van landschapstopografische modellering in het algemeen en van topografische modellering van moeras in het bijzonder. Merk op, dit is het eerste diepgaande werk over landschapstopografische modellering van de regio van de Okavangodelta, Afrika. De resultaten hebben verschillende implicaties, bijv. voor verbetering van het begrip van de micro- en mesotopografische (inclusief het wateroppervlak) en biofysische eigenschappen van het landschap, voor het geven van essentiele data voor het modelleren van hydrologische en ecologische processen en voor het monitoren van processen in moeras en de effecten van regionale klimaatverandering. Deze aspecten moeten meegenomen worden in toekomstige studies die gebruikmaken van data van meerdere geavanceerde instrumenten aan boord van satellieten (bijv. ICESat-2 en SWOT). De aanpak en methoden ontwikkeld in dit proefschrift kunnen toegepast worden in andere situaties, regionaal en wereldwijd. Verder zou de ontdekte gelijkvormigheid in topografische patronen (op diverse schalen) van deze mega-puinwaaier in een woestijn kunnen dienen (als aardse analogie) voor verbetering van het begrip van planetaire waaiervormige structuren (bijv. landschapsstructuren op Mars).

Trefwoorden: Multiplatform; optische beelden; radarhoogteprofielen; beeldvormende radar; lasserhoogteprofielen; GPS; stereofotogrammetrie; hoogtemodellering; microtopografie; mesotopografie; wateroppervlaktopografie; landoppervlakklassen; kalibratie van systematische afwijking; nauwkeurigheidsbeoordeling; datafusie; gecombineerd model; foutmarge; Okavangodelta; Kalahari.
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8.1 Multitechnology-based mesotopographic models and their error characteristics on the delta

8.2 Multiplatform technology-based mesotopographic models and their error characteristics as assessed by GPS measurements
# Acronyms

<table>
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<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>amsl</td>
<td>Above mean sea level</td>
</tr>
<tr>
<td>AGS</td>
<td>Airborne Geophysical Survey</td>
</tr>
<tr>
<td>ALI</td>
<td>Advanced Land Imager</td>
</tr>
<tr>
<td>ALOS</td>
<td>Advanced Land Observing Satellite</td>
</tr>
<tr>
<td>AltiKa</td>
<td>Ka-band Altimeter system</td>
</tr>
<tr>
<td>ARGOS</td>
<td>Advanced Research and Global Observation Satellite</td>
</tr>
<tr>
<td>ASTER</td>
<td>Advanced Spaceborne Thermal Emission and Reflection Radiometer</td>
</tr>
<tr>
<td>ATSR</td>
<td>Along Track Scanning Radiometer</td>
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<tr>
<td>ATSR 2</td>
<td>Along Track Scanning Radiometer</td>
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<tr>
<td>AVHRR</td>
<td>Advanced Very High Resolution Radiometer</td>
</tr>
<tr>
<td>CERES</td>
<td>Clouds and the Earth's Radiant Energy System</td>
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<tr>
<td>CP</td>
<td>Check Point</td>
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<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
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<tr>
<td>DFT</td>
<td>Discrete Fourier Transform</td>
</tr>
<tr>
<td>DGPS</td>
<td>Differential Global Positioning System</td>
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<tr>
<td>DN</td>
<td>Digital Number</td>
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<tr>
<td>DSM</td>
<td>Digital Surface model</td>
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<td>DTM</td>
<td>Digital Terrain model</td>
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<td>EGM96</td>
<td>Earth Gravity Model 1996</td>
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<tr>
<td>Envisat</td>
<td>European Environmental Satellite</td>
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<td>EO-1</td>
<td>Earth Observing-1 Satellite</td>
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<tr>
<td>EOS</td>
<td>Earth Observing System</td>
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<td>ERS</td>
<td>European Remote Sensing Satellite</td>
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<td>ERTS</td>
<td>Earth Resources Technology Satellite</td>
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<td>ETHZ</td>
<td>Eidgenössische Technische Hochschule Zürich</td>
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<tr>
<td>ETM+</td>
<td>Enhanced Thematic Mapper Plus</td>
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<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
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<td>GCP</td>
<td>Ground Control Point</td>
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<td>GDEM</td>
<td>Global Digital Elevation Model</td>
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<td>GEO</td>
<td>Geostationary Earth Orbit</td>
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<td>GIS</td>
<td>Geographic Information System/Science</td>
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<td>GLAS</td>
<td>Geoscience Laser Altimeter System</td>
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<td>GLA14</td>
<td>Global GLAS Laser Altimetry product 14</td>
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<tr>
<td>GLONASS</td>
<td>Global'naya Navigatsionnaya Sputnikovaya Sistema</td>
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<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
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<td>GPS</td>
<td>Global Positioning System</td>
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<td>HRG</td>
<td>High Resolution Geometric</td>
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<td>HRS</td>
<td>High Resolution Stereoscopic</td>
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<td>IceCryo</td>
<td>Integrated ICESat and CryoSat model</td>
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<td>ICG</td>
<td>Integrated ICESat, CryoSat and GPS model</td>
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<td>ICESat</td>
<td>Ice, Cloud, and Land Elevation Satellite</td>
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<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>IFFT</td>
<td>Inverse Fast Fourier Transform</td>
</tr>
<tr>
<td>IGP</td>
<td>Institute of Geodesy and Photogrammetry</td>
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<tr>
<td>IHPF</td>
<td>Ideal Highpass Filter</td>
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<tr>
<td>IKONOS</td>
<td>IKONOS Satellite</td>
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<tr>
<td>ILPF</td>
<td>Ideal Lowpass Filter</td>
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<tr>
<td>Acronym</td>
<td>Full Form</td>
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<td>---------------------------------------------------------------------------</td>
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<tr>
<td>InSAR</td>
<td>Interferometric Synthetic Aperture Radar</td>
</tr>
<tr>
<td>INSAT</td>
<td>Indian National Satellite System</td>
</tr>
<tr>
<td>INTELSAT</td>
<td>International Telecommunications Satellite Organization</td>
</tr>
<tr>
<td>IR&amp;PL</td>
<td>Imaging Radar and Profiling Laser</td>
</tr>
<tr>
<td>IRS</td>
<td>Indian Remote Sensing Satellite</td>
</tr>
<tr>
<td>ISRO</td>
<td>Indian Space Research Organization</td>
</tr>
<tr>
<td>ITRF</td>
<td>International Terrestrial Reference Frame</td>
</tr>
<tr>
<td>IUCN</td>
<td>International Union for Conservation of Nature and Natural Resources</td>
</tr>
<tr>
<td>JPL</td>
<td>Jet Propulsion Laboratory</td>
</tr>
<tr>
<td>JERS</td>
<td>Japanese Earth Remote Sensing Satellite</td>
</tr>
<tr>
<td>JSC</td>
<td>Johnson Space Center</td>
</tr>
<tr>
<td>LASER</td>
<td>Light Amplification by Stimulated Emission of Radiation</td>
</tr>
<tr>
<td>LEO</td>
<td>Low Earth Orbit</td>
</tr>
<tr>
<td>LiDAR</td>
<td>Light Detection And Ranging</td>
</tr>
<tr>
<td>LISS</td>
<td>Linear Imaging Self Scanner</td>
</tr>
<tr>
<td>MEO</td>
<td>Medium Earth Orbit</td>
</tr>
<tr>
<td>MDEM</td>
<td>GPS-based Digital Elevation Model</td>
</tr>
<tr>
<td>MIR</td>
<td>Mid Infrared</td>
</tr>
<tr>
<td>MISR</td>
<td>Multi-angle Imaging Spectro-Radiometer</td>
</tr>
<tr>
<td>MODIS</td>
<td>Moderate Resolution Imaging Spectroradiometer</td>
</tr>
<tr>
<td>MOPITT</td>
<td>Measurements Of Pollution In The Troposphere</td>
</tr>
<tr>
<td>MS</td>
<td>Multispectral</td>
</tr>
<tr>
<td>MSS</td>
<td>Multispectral Scanner</td>
</tr>
<tr>
<td>msl</td>
<td>Mean sea level</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
<tr>
<td>NDMI</td>
<td>Normalised Difference Moisture Index</td>
</tr>
<tr>
<td>NDVI</td>
<td>Normalised Difference Vegetation Index</td>
</tr>
<tr>
<td>NDWI</td>
<td>Normalised Difference Water Index</td>
</tr>
<tr>
<td>NGA</td>
<td>National Geospatial-Intelligence Agency</td>
</tr>
<tr>
<td>NIMA</td>
<td>National Imagery and Mapping Agency</td>
</tr>
<tr>
<td>NIR</td>
<td>Near Infrared</td>
</tr>
<tr>
<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
</tr>
<tr>
<td>NSIDC</td>
<td>National Snow and Ice Data Center</td>
</tr>
<tr>
<td>ORB</td>
<td>Okavango River Basin</td>
</tr>
<tr>
<td>OSI&amp;PL</td>
<td>Optical Stereo Imaging and Profiling Laser</td>
</tr>
<tr>
<td>Pan</td>
<td>Panchromatic</td>
</tr>
<tr>
<td>PATB</td>
<td>Photogrammetric Aero-Triangulation with Bundle blocks</td>
</tr>
<tr>
<td>PL&amp;R</td>
<td>Profiling Laser and Radar</td>
</tr>
<tr>
<td>PL&amp;R &amp; PS</td>
<td>Profiling Laser and Radar, and Positioning System</td>
</tr>
<tr>
<td>RADAR</td>
<td>RADioWave Detection And Ranging</td>
</tr>
<tr>
<td>Ramsar</td>
<td>The Convention on Wetlands (Ramsar, Iran, 1971)</td>
</tr>
<tr>
<td>RISAT</td>
<td>Radar Imaging Satellite</td>
</tr>
<tr>
<td>SAR</td>
<td>Synthetic Aperture Radar</td>
</tr>
<tr>
<td>SARAL</td>
<td>Satellite with Argos and AltiKa</td>
</tr>
<tr>
<td>SAT-PP</td>
<td>High-Resolution Satellite Imagery Precision Processing Software</td>
</tr>
<tr>
<td>SPOT</td>
<td>Satellite Pour l’Observation de la Terre</td>
</tr>
<tr>
<td>SWOT</td>
<td>Surface Water and Ocean Topography satellite</td>
</tr>
<tr>
<td>SRTM</td>
<td>Shuttle Radar Topography Mission</td>
</tr>
<tr>
<td>SWIR</td>
<td>Short Wave Infrared</td>
</tr>
<tr>
<td>Terra</td>
<td>EOS AM-1 Satellite</td>
</tr>
<tr>
<td>TIR</td>
<td>Thermal Infrared</td>
</tr>
<tr>
<td>TM</td>
<td>Thematic Mapper</td>
</tr>
<tr>
<td>Acronyms</td>
<td>Full Form</td>
</tr>
<tr>
<td>----------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>TOPEX/Poseidon</td>
<td>Topography Experiment/Poseidon</td>
</tr>
<tr>
<td>TOPSAR</td>
<td>Topographic Synthetic Aperture Radar</td>
</tr>
<tr>
<td>UCT</td>
<td>University of Cape Town</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>UTM</td>
<td>Universal Transverse Mercator</td>
</tr>
<tr>
<td>VIS</td>
<td>Visible</td>
</tr>
<tr>
<td>WGS84</td>
<td>World Geodetic System 1984</td>
</tr>
<tr>
<td>WRS</td>
<td>Worldwide Reference System</td>
</tr>
<tr>
<td>XS</td>
<td>Multispectral</td>
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</tbody>
</table>
PART I.
Problem, Objectives and Perspective
Chapter 1

Introduction

The nation behaves well if it treats the natural resources as assets which it must turn over to the next generation increased, and not impaired, in value.

— Theodore Roosevelt (1858–1919)

This chapter presents research background and the problem, an overview of the landscape topography, followed by science questions. The objectives of the research are then devised and finally, the structure of the thesis is presented.

Keywords: Multiplatform; remote observation; remote measurement; landscape topography; wetland; digital elevation model; land cover; accuracy assessment; bias calibration; data integration; science question; science objective; thesis structure.

1.1 Background and Motivation

The imagination of the human mind how to map the Earth’s surface and its environment, to monitor and model surface processes the Earth undergoes led to the development of remote observation and measurement technology. They evolved from terrestrial observing systems to sensors on board low Earth flying objects (e.g. balloons, kites) and aircrafts to Earth-orbiting spacecrafts (Simonett et al., 1983; Seeber, 2003; Aronoff, 2005; Misra and Enge, 2006; Jensen, 2007; Lillesand et al., 2008). With the rapid advancement of space technology, the various platform-based measurement devices are delivering data at increasing rates and higher resolutions for diverse applications. Space exploration led to provide vital inputs for the optimal management of our natural resources – both renewable and non-renewable (Rao, 1989). However, despite these technological advancements, in many developing countries, the measurement of landscape topography and processes that are fundamental to diverse science and engineering applications are limited by data coverage, resolution and accuracy. As no single platform can provide all the desired data needed, the combination of complementary observations from multiple platforms (terrestrial, aerial and space) is the key to address such shortcomings.

The ever-increasing variety of sensors/instruments on multiple platforms and developments in data processing techniques has enabled remote measurement of essential earth surface parameters (Massonnet, 1997; Wolf and Dewitt, 2000; van Sickle, 2001; Zwally et al., 2002; Elachi and van Zyl, 2006; Misra and Enge, 2006; Alsdorf et al., 2007; Farr et al., 2007). Remote observations, for example, provide diverse ways to map the earth’s landscape topography using stereo-photogrammetry, global positioning system (GPS), interferometric synthetic aperture radar (InSAR), light detection and ranging (LIDAR), and light
amplification by stimulated emission of radiation (laser) altimeter techniques, and thus deriving parameters such as terrain elevation, slope and aspect. Observations from multiple platforms enable construction of variable scale (test site to global level) and resolution (horizontal and vertical) topographic datasets (Ritchie, 1995; Farr and Kobrick, 2000; Talukdar, 2003a; Schutz et al., 2005; Toutin, 2008) depending on the requirements and data availability. Remotely sensed data facilitate accurate and fast delineation of surface water extent (McFeeters, 1996; Smith, 1997; Rango and Shalaby, 1999; Alsdorf et al., 2007; Papa et al., 2010) and the extent of wetlands (Butera, 1983; Munyati, 2000; Prigent et al., 2001; Ozesmi and Bauer, 2002; Papa et al., 2006; Prigent et al., 2007), monitoring water level change (Alsdorf et al., 2000; Birkett et al., 2002; LeFavour and Alsdorf, 2005; Kiel et al., 2006) and mapping land cover (Townshend, 1980; Tucker et al., 1985; Talukdar, 2001, 2004; Wright and Gallant, 2007; Bwangoy et al., 2010). Space-based remote sensing is an effective means to frequently observe hydrological state variables (e.g. land cover, soil moisture and precipitation) over large areas (Schultz, 1988; Bates et al., 1997; Smith, 1997; Cihlar, 2000; Schmugge et al., 2002), without the need for expensive ground surveys, thus satisfying the hydrological and environmental modeling requirements. For example, Landsat 7 and 8 (Landsat 8 is the Landsat Data Continuity Mission, LDCM) observes an area every 16 days with a scene covering 185 km x 170 km (31,450 km²). Although extensive studies were done on various aspects of the earth and the environment using remote observations, not enough research has been done on measuring and modeling wetland landscape topography.

The fundamental assumption that propelled the present research is that observation from diverse platforms coupled with appropriate measurement techniques allows for a detailed and accurate representation of landscape topography, especially digital elevation models (DEMs) and land cover. In a wetland landscape and processes, the topographic structure is extremely complex and dynamic; its understanding is crucial to effective conservation and management. The limitation of appropriate datasets have made the present research a challenging task, driving scientific investigations to develop approaches and methods for constructing topographic models from diverse observations. A multiplatform experimental approach is designed and demonstrated for a large wetland in southern Africa, i.e. the Okavango Delta. The main purpose is to construct (vertically accurate) improved quality wetland topographic models. The study addresses the questions (Section 1.4) on four major aspects: 1) multiplatform approach to measure and construct topographic models, 2) mapping land cover (as determinants to elevation data), 3) assess elevation data accuracy, and 4) improve topographic model quality through integration of multisource elevation data.

1.2 Problem Statement

The Okavango Delta is the world’s largest inland wetland ecosystem and it is unique in its topographic and biophysical characteristics. Water is critical to the preservation of semi-arid wetlands like the Okavango, whose very survival depends on effective management of water resources. This extremely complex and dynamic wetland ecosystem faces increasing water demand from the Okavango River basin sharing countries: Angola, Namibia and Botswana. The growing demand has put the scarce water resource under rising pressure and poses complex management problems. The scientific approach to construct management scenarios of this situation lies in a thorough understanding of the problem, which requires accurate and reliable terrain elevation and land cover information. These information serves as inputs to modeling hydrological and environmental processes and climate change. The creation of such datasets for a large data poor region such as the Okavango Delta, which currently lacks high resolution and accurate elevation and land cover information is a challenging task.
Measuring wetland topography at a high resolution (horizontal and vertical) and vertical accuracy from remote platform observations is challenging due to the gently undulating structure, which is characterised by short-wavelengths on a local scale. The measurement of water surface elevation in a wetland environment from remote observations is equally challenging. To construct topographic models of such landscapes involves careful examination of the various quantitative components, i.e. elevation, slope and aspect. Likewise, the accurate mapping of land cover features from multispectral satellite observations of a wetland environment is problematic. The boundaries of spatial objects such as the wetland extent, scattered varying-sized islands, vegetated margins of channel networks, and shallow open water surfaces are complex and spectrally mixed. Remote sensing and other geospatial technologies such as photogrammetry, digital image and signal processing, global positioning system (GPS), and data integration may provide complementary approaches to measure effectively landscape topography in such complex environments.

The broad problem statement addressed in this study is: How can we measure and construct variable resolution topographic models of wetland landscapes from observations acquired by devices on board diverse remote sensing and measurement platforms, and integrate multisource elevation data to produce vertically improved models? To address this problem, specific science questions are articulated in Section 1.4.

1.3 Measuring Landscape Topography: An Overview

Topographic data are fundamental to many scientific, engineering, and planning and management applications (Miller, 1958; Moore et al., 1991; Wilson and Gallant, 2000). The observations from remote platforms have considerably improved the mapping and understanding of topography of the Earth (Zwally et al., 2002; Farr et al., 2007; Hayakawa et al., 2008) and other planetary bodies (Smith et al., 1997, 1999, 2001; Araki et al. 2009). In this study, the term landscape topography means the representation of surface topography by elevation models with land cover as determinant of elevation data accuracy. Table 1.1 characterises the topographic data/model terminologies used in this thesis. The literature on remote sensing of terrain elevation and land cover of the Earth's surface is vast. The chapters in the thesis addressing specific research problems include reviews of relevant work. Here, we present a concise review of work on measuring elevation and mapping land cover in wetland environments with a focus on the Okavango Delta. The review highlights the issues and methods used, their merits and demerits, and identifies the research gaps.

Elevation Models

Measuring topography of a landscape, particularly the elevation is a mathematical process to model and analyse the relationships between the topography and its various features. A DEM provides the basis for various applications such as topographic analysis, hydrological-geomorphological modeling and landscape visualization (Ackermann, 1994).

Because of its location in a developing country, little research has been done on topographic aspects of the Okavango wetland (Table 1.2 gives a summary). Early attempts to create generalised topographic contour maps were made by UNDP (1976) and Cooke (1980), based on sparsely distributed Government trigonometric beacons in and around the delta. After a gap of nearly two decades, a GPS survey was carried out to generate orthometric heights for the water gauges/water surfaces in the delta (Merry et al., 1998). The Geological Survey of Botswana carried out a regional gravity survey, which involved precise elevation determination on ~7.5 km spacing postings, using the differential global positioning system (DGPS). This survey resulted in the generation of first generalised topographic map of the Okavango Delta region (Modisi et al., 2000). The results of the regional gravity survey were
Table 1.1 Characterisation of topographic data/model terminologies used in this thesis.

<table>
<thead>
<tr>
<th>Terms</th>
<th>Characterisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>General</td>
<td></td>
</tr>
<tr>
<td>Elevation data</td>
<td>Includes all elevation data – postings, footprints and grid-based models. The term <em>topographic data</em> is also used interchangeably, depending on the context.</td>
</tr>
<tr>
<td>Elevation model</td>
<td>Includes all grid-based elevation models, continuous elevation surface (e.g. digital surface model [DSM], DEM). The term <em>topographic model</em> is also used interchangeably.</td>
</tr>
<tr>
<td>Landscape topographic model</td>
<td>All elevation models (e.g. DSM, DEM) in association with characterisation of topographic structure, and land cover map as a determinant to elevation data.</td>
</tr>
<tr>
<td>Specific</td>
<td></td>
</tr>
<tr>
<td>Elevation posting</td>
<td>Elevation measured at a specific point location (e.g. GPS (x,y,z) point coordinates).</td>
</tr>
<tr>
<td>Elevation footprint</td>
<td>Elevation measured at a specific footprint location (e.g. ICESat laser (x,y,z) footprint coordinates, (x,y) represent a (\sim 70) m footprint).</td>
</tr>
<tr>
<td>DSM</td>
<td>A grid-based surface elevation model, presents top of object elevation (e.g. SRTM C-radar and ASTER elevation models).</td>
</tr>
<tr>
<td>DEM</td>
<td>A grid-based terrain elevation model, presents bare earth elevation (e.g. analytical stereo-photogrammetric model).</td>
</tr>
</tbody>
</table>

integrated with other available topographic data as well as satellite-derived information on water distribution to produce a topographic contour map of the Okavango Delta region (Gumbricht *et al.*, 2001). The present author used analytical photogrammetric method to derive a micro-topographic model from aerial stereo-images over a test site in the Maunachira area of the delta (Bauer *et al.*, 2002). The test site result was compared with traditional levelling measurements and was found to be promising. The present author along with co-researchers from the Swiss Federal Institute of Technology (ETH) Zurich carried out a GPS survey in the delta to measure ground control points (GCPs), which resulted in highly accurate 47 elevation postings \((x,y,z)\) over three physiographic settings (Talukdar, 2003). To improve their earlier work, Gumbricht *et al.* (2005) produced an elevation model of the delta by assigning empirical elevations to remotely sensed vegetation community classes. Although the result was labelled as micro-topography (with 28.5 m spatial resolution) it does not present detailed topographic structure. The Okavango wetland, in general, lacks high spatial resolution (10 m and better) and vertically accurate DEMs. The reviewed work presents the current state of the elevation data availability over the delta, and it is a good reference for the development of new approaches and methods to produce improved quality DEMs.
Table 1.2 Overview of Okavango Delta wetland landscape topography research.

<table>
<thead>
<tr>
<th>Topographic information</th>
<th>Method of generation</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contour maps</td>
<td>Based on trigonometric beacons</td>
<td>UNDP (1976); Cooke (1980)</td>
</tr>
<tr>
<td>Orthometric heights for the water gauges/water surface</td>
<td>Position data ((x,y,z)) by GPS survey</td>
<td>Merry et al. (1998)</td>
</tr>
<tr>
<td>Generalised topographic map of the delta</td>
<td>Position data ((x,y,z)) by GPS survey</td>
<td>Modisi et al. (2000)</td>
</tr>
<tr>
<td>Generalised topographic contour map of the delta</td>
<td>Position data ((x,y,z)) by GPS integrated with other topographic information</td>
<td>Gumbrecht et al. (2001)</td>
</tr>
<tr>
<td>Micro-topographic model of a test site</td>
<td>Aerial (analytical) stereophotogrammetry</td>
<td>Bauer et al. (2002)</td>
</tr>
<tr>
<td>Ground controls points over three test sites</td>
<td>Position data ((x,y,z)) by GPS survey</td>
<td>Talukdar (2003)</td>
</tr>
<tr>
<td>Digital elevation model of the delta</td>
<td>Position data ((x,y,z)) by GPS, and assigning empirical elevations to remotely sensed vegetation classes</td>
<td>Gumbrecht et al. (2005)</td>
</tr>
</tbody>
</table>

Single platform and instrument observations are not sufficient to accurately and reliably model the topography of complex landscapes such as wetlands having complex structures and low gradients (e.g. Okavango). Therefore, a multiplatform observation approach is proposed in this thesis, which is an effective way to model wetland topography using a combination of measurements, calibration and integration of data, particularly in data poor regions. The main purpose of this study is to produce higher quality elevation models and provide alternate possibilities.

**Land Cover**

Remotely sensed observations of the earth surface have revolutionized our perception and our approach to understand landscapes and regions (Forman, 1995). In the Okavango Delta, the land cover features comprise a mosaic of landscape elements such as channels, wetlands, islands, lagoons, salt marsh, grasslands/woodlands, and bare earth or soil. The literature review on the Okavango land cover research focuses on two aspects, delineation of wetland boundaries and mapping of land cover features. Table 1.3 summaries land cover research done on the Okavango Delta.

**Extent of the Delta and Wetland**

UNDP (1977) provided an early estimate of the spatial extent of the Okavango alluvial fan (i.e. the delta), which is 18,000 km², while Merry et al. (1998) mentioned the fan size to be about 22,000 km². However, no information were given on the methods of estimation. Visually interpreting satellite remote sensing images, Watson (1991) estimated the Okavango alluvial fan and the wetland to be about 16,000 km² and 10,000 km², respectively. Based on ecological zoning maps of 1989 at 1:250,000 and 1:100,000 scales, Scudder et al. (1993) estimated the Okavango wetland to be ~15,850 km². McCarthy et al. (1998) stated that the wetland area is about 12,000 km²; however, no information was given about the method of estimation. Gumbrecht et al. (2004b) estimated the wetland as 13,500 km² using remotely sensed data.
Land Cover Features

The earliest remote sensing-based land cover study of the Okavango ecosystem was done by Ringrose et al. (1988) for ecological zoning using Landsat MSS data. Watson (1991) used Landsat images (no mention about sensor) to create a mosaic of the Okavango Delta and visually interpreted the image to provide general information on the ecosystem. McCarthy et al. (1993) studied the environmental processes in the Okavango Delta from SPOT multispectral imagery, while land degradation was investigated by Ringrose et al. (1997) using Landsat TM data. Neuenschwander et al. (2002) used Earth Observing-1 (EO-1) satellite data to monitor seasonal flooding in the Okavango Delta. They also carried out experiments to examine the performance achievable with EO-1 Advanced Land Imager (ALI) data compared to Landsat 7 ETM+ for land cover mapping (Neuenschwander et al., 2005). McCarthy et al. (2003) carried out a multi-temporal study on flooding patterns and changes using NOAA AVHRR and Landsat MSS/ETM sensor data (degraded to 500 m spatial resolution) for over 20 years period. These authors used ERS-2 ATSR, Landsat TM/ETM+ image classification as 'true' to evaluate the AVHRR (1 km spatial resolution) classification result. Talukdar (2004) investigated an image fusion approach to extract land cover information from SPOT 5 HRG (5 m panchromatic and 10 m multispectral) and Landsat 7 ETM+ (15 m panchromatic and 30 m multispectral) images over the delta. The author found by visual inspection that increasing spatial resolution allows the extraction of detail land cover features, but it increases heterogeneity of ground objects resulting in lower classification accuracy. Gumbricht et al. (2004a) delineated the major islands in the wetland from Landsat TM data, while the spatial extent of annual flooding in the delta was studied using NOAA AVHRR (1 km spatial resolution) time series data (Gumbricht et al., 2004b). McCarthy et al. (2005) carried out an ecoregional classification of the delta with medium and low spatial resolution multi-temporal remote sensing data. Hamandawana et al. (2007) examined the influence of natural and human factors on environmental change in the Okavango Delta over fifteen decades (1849-2001) using historical and multi-date remote sensing images. The author concluded that although natural factors account for most of the changes in the delta, human activities are also playing a significant role by accelerating naturally induced deterioration. Most of these reviewed studies are limited by geo-positional and land cover classification accuracy, which are important aspects for data to be useful to science applications (e.g. determinants to elevation data accuracy assessment and bias calibration). The key aspects of accurate land cover classification by image processing of remotely sensed data such as image rectification, methods of classification and accuracy assessments were rarely considered. These studies, however, provided the state of the land cover data availability on the delta, and offered important bases for the development of new approaches and methods to produce improved quality land cover data. In general, the Okavango Delta lacks high spatial resolution and accurate land cover information. This study focuses on the development of a simple yet effective approach to classify accurately wetland land cover from optical satellite observations, which we will use later.
Table 1.3 Overview of Okavango Delta wetland land cover research.

<table>
<thead>
<tr>
<th>Land cover information</th>
<th>Data and generation method</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extent of delta/wetland:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alluvial fan (i.e. Delta)</td>
<td>Not mentioned</td>
<td>UNDP (1977); Merry et al. (1998)</td>
</tr>
<tr>
<td>Alluvial fan and wetland</td>
<td>Visual analysis of Landsat data</td>
<td>Watson (1991)</td>
</tr>
<tr>
<td>Wetland</td>
<td>Ecological zoning maps of 1989</td>
<td>Scudder et al. (1993)</td>
</tr>
<tr>
<td></td>
<td>Not mentioned</td>
<td>McCarthy et al. (1998)</td>
</tr>
<tr>
<td></td>
<td>Remote sensing data</td>
<td>Gumbricht et al. (2004a)</td>
</tr>
<tr>
<td>Land cover:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ecological zoning of the delta</td>
<td>Visual and digital analysis of Landsat MSS data</td>
<td>Ringrose et al. (1988)</td>
</tr>
<tr>
<td>Environmental processes</td>
<td>SPOT multispectral data</td>
<td>McCarthy et al. (1993)</td>
</tr>
<tr>
<td>Land degradation problems</td>
<td>Landsat TM data</td>
<td>Ringrose et al. (1997)</td>
</tr>
<tr>
<td>Monitoring seasonal flooding</td>
<td>Earth Observing (EO)-1 satellite data</td>
<td>Neuschwander et al. (2002; 2005)</td>
</tr>
<tr>
<td>Land cover mapping</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flooding patterns and changes</td>
<td>NOAA AVHRR and Landsat MSS/TM data</td>
<td>McCarthy et al. (2003)</td>
</tr>
<tr>
<td>Land cover features</td>
<td>SPOT 5 HRG and Landsat 7 ETM + image fusion</td>
<td>Talukdar (2004)</td>
</tr>
<tr>
<td>Spatial extent of annual flood</td>
<td>NOAA AVHRR data</td>
<td>Gumbricht et al. (2004a)</td>
</tr>
<tr>
<td>Distribution of islands</td>
<td>Landsat TM data</td>
<td>Gumbricht et al. (2004b)</td>
</tr>
<tr>
<td>Ecoregion classification of the delta</td>
<td>Multi-temporal remote sensing data (medium and low resolution)</td>
<td>McCarthy et al. (2005)</td>
</tr>
<tr>
<td>Environmental change</td>
<td>Historical and multi-date remote sensing data</td>
<td>Hamandawana et al. (2007)</td>
</tr>
</tbody>
</table>

1.4 Science Questions

The questions formulated for this investigation were based on the complex topographic-biophysical conditions of the study site, inadequate research on landscape topography and its significance, and scarce and disparate elevation datasets. This study investigates the following science questions:

1. What is the advantage of a multiplatform observation approach to measure and construct landscape topographic models of a wetland environment? (Chapter 4)
2. How significant is single-channel spectral information (e.g. Landsat 7 mid-infrared) content compared to multispectral observations for mapping wetland land cover? (Chapter 5)
3. To what extent does physiography and land cover acts as a determinant of vertical errors in elevation data (e.g. SRTM DSM)? (Chapter 6)
4. How far does integration (fusion and merging) of multiplatform elevation data increases accuracy and reliability of elevation models? (Chapter 7) and
5. To what extent does bias calibration in elevation data (e.g. SRTM and ASTER DSMs) improve vertical accuracy? (Chapter 7)

1.5 Science Goal and Objectives

The main goal of this study is to devise a multiplatform approach to measure and model landscape topography in a wetland environment. This goal addresses the science questions formulated in the preceding section. The primary objectives are:

1. To measure and model topography (including water surface) from multiple platform observations on wetland landscapes; (Chapter 4)
2. To investigate single-channel information content over multi-channels in mapping wetland land cover from spaceborne optical observations (as a determinant of elevation data accuracy); (Chapter 5)
3. To assess the accuracy of topographic data and models, including water surface elevation; (Chapter 6)
4. To develop approaches for fusion and merging of multiplatform elevation data to produce improved quality elevation models; (Chapter 7) and
5. To calibrate bias in elevation data (Chapter 7), and finally map the error budgets of elevation datasets (Chapter 8).

1.6 Scope and Limitations

This research is confined to produce (vertically accurate) improved quality wetland elevation models through a multiplatform observation approach. It addresses two issues: measuring landscape topography as DEMs and mapping land cover as a determinant of elevation data accuracy and model bias calibration. The study focuses on constructing, assessing and improving elevation models from a combination of measurements as well as calibrating and integrating elevation data from diverse platforms over a large wetland region. The research emphasises on: 1) microtopographic modeling from optical stereo-observations (test sites), 2) mesotopographic modeling from positioning, profiling and imaging radar, and optical stereo-imaging (regional level), and 3) water surface elevation measurement from imaging radar and profiling laser (delta level). This study also focuses on classifying wetland land cover from dual-spatial resolution optical observations and demonstrating the potentiality of a single-band observation approach over multi-band observations. A few limitations of the study are: a) lack of adequate reference elevation data for evaluation of microtopographic models, b) lack of bathymetric (underwater depths) data of channels, lakes, and other water bodies, c) inadequate cross track and cross over profiling laser observations for in-depth measurement of delta water level changes, and d) assessment of land cover classification accuracy by visual inspection (and no ground verification).

1.7 Structure of the Thesis

This thesis is broadly divided into three parts, which are structured into eight chapters (Figure 1.1). Introduction to the thesis forms the Chapter 1.

Chapter 2 presents the background and research perspective from which this study has arisen. This chapter describes the Okavango wetland environment and its complex topographic and biophysical characteristics. The multiplatform data acquisition techniques, availability of data and requirements of landscape topographic information, and techniques for measurement are presented. The research issues for the investigation are identified.
Chapter 3 devises a multiplatform observation approach to measure and model wetland landscape topography, assess elevation data accuracy, and to improve elevation models through integration of multiplatform elevation observations.

Chapter 4 is devoted to approaches and methods to construct elevation models at various scales and resolution from diverse platform observations. The chapter measures microtopographic models from air- and spaceborne stereo imaging, and constructs mesotopographic models from GPS postings, airborne profiling radar, spaceborne imaging radar, and spaceborne optical stereo-imaging. Then, it constructs water surface topography from spaceborne imaging radar and measures water level changes from spaceborne profiling laser. Finally, it characterises the multi-technology elevation data and models.

Chapter 5 provides an approach for classifying wetland land cover from dual-spatial resolution optical observations acquired from satellite platforms. It compares single-band spectral information content with multispectral observations to classify wetland land cover.

Chapter 6 is devoted to establishing reference datasets, assessing the comparability of spaceborne profiling laser and GPS measurements, and describing geolocation accuracy of datasets. Then, it assesses the accuracy of elevation data/models constructed from diverse platform observations at microtopographic, mesotopographic and water level. Finally, it characterises the errors in multi-technology elevation data.

Chapter 7 presents approaches and methods to integrate multiplatform elevation observations for producing improved quality topographic models. The chapter explores frequency domain fusion, bias calibration, and merging elevation data. Then, it evaluates the quality of integrated elevation data and models.

Chapter 8 summarises the major science contributions of the study, maps the error budgets of elevation datasets, highlights research implications, suggests directions for future research, and finally concludes the thesis.
PART I.
RESEARCH PROBLEM
OBJECTIVES
AND
PERSPECTIVE

Chapter 1.
Introduction

Chapter 2.
The Okavango Wetland
and Multiplatform
Observations

PART II.
APPROACH
EXPERIMENTS
AND
RESULTS

Chapter 3. Multiplatform Approach:
Measuring and Modeling Landscape Topography

Chapter 4.
Measuring and
Modeling Landscape
Topography

Chapter 5.
Mapping Land Cover
from Optical
Observations

Chapter 6.
Assessing the Accuracy
of Topographic Data
and Models

Chapter 7.
Integrating Multi-
platform Elevation
Observations

PART III.
CONCLUSIONS

Chapter 8.
Summary and
Conclusions

Direct link
Indirect link

Figure 1.1 The schematic outline of the thesis. Three parts of the thesis are structured into eight chapters.
Chapter 2

The Okavango Wetland and Multiplatform Observations

As we go higher and higher we get a larger perspective coverage of the Earth, even though the details that we can discern will be less.

- Krishnaswamy Kasturirangan (1940-)

This chapter provides the research perspective of this study. 1) The Okavango wetland environment and its landscape topography is described, 2) multiplatform observations as effective and complementary data sources, and the need for terrain elevation and land cover information are presented, and 3) techniques for measuring and mapping elevation and land cover are elucidated.

Keywords: Multiplatform; remote observations; landscape topography; terrain elevation; land cover; measurement techniques; mapping techniques; Okavango wetland.

2.1 Introduction

Observations acquired from remote sensing and measurement platforms led to an accurate quantitative characterisation of the earth surface and provided the basis for the scientific understanding of the earth system (NASA, 1988). The understanding of wetland landscapes from such observations helps us to predict the future state of their environment and response to natural events and anthropogenic activities. Wetlands form a fundamental component of the earth system and their sustainable management assists in balancing regional and global climate change. As a complex system, the scientific understanding of wetland processes requires accurate information on landscape topography. In the context of wetland remote sensing observations, important measurable aspects are terrain elevation and land cover. While the terrain information in the form of DEMs characterise the landscape topographic structure, land cover data characterise the landscape structure and cover in relation to natural and human activities. In a wetland setting, however, it is a challenging task to obtain high resolution terrain elevation and land cover data in a consistent and accurate manner. It also involves a scale issue as the landscape is measured in three dimensions for DEMs (x,y,z assuming elevation (z) does not change within a short time) and four dimensions for land cover (x,y,t,A, where x,y = position, A = land cover attribute, t = time) over diverse landscape situations. The resolution and accuracy of DEMs (or topographic elevation matrix) and land cover is a vital issue since modeling physical processes such as hydrologic processes is sensitive to data resolution (Wolock and Price, 1994; Zhang and Montgomery, 1994); even to
smaller changes in elevation (Kenward et al., 2000; Bauer, 2004). The advancement of technology has greatly enhanced the capability to measure terrain elevation and land cover information reliably at high (10 m and better) and medium (10 m to 100 m) spatial resolution from multiple platform observations, coupled with appropriate photogrammetric and image processing techniques.

However, in many parts of the world the lack of appropriate data, inaccessibility to the study sites and costs has made it a difficult task to produce reliable elevation and land cover information. To overcome this situation, the Okavango Delta provides a challenging case for demonstrating the potential of a multiplatform observation approach to produce such information. A comprehensive understanding of the study site, data requirements and availability, and techniques are essential to this experiment. The main purpose of this chapter is to 1) describe the Okavango wetland environment and its landscape topography, 2) present multiplatform observations as efficient and complementary data sources and the need for elevation and land cover data and 3) elucidate the techniques for measuring elevation and land cover.

2.2 The Okavango Wetland Environment

*Geographic Setting*

The Okavango Delta, variably termed as the jewel of the Kalahari (Ross, 1987), an African paradise (Balfour, 1992), Africa’s last Eden (Lanting et al., 1993), Africa’s Wetland Wilderness (Bailey, 1998), is one of the remaining pristine natural ecosystems of the world. It is situated between 21°45’ E to 24°00’ E longitudes and 18°15’ S to 20°15’ S latitudes (upper-left X,Y: 579288 Easting, 7982168 Northing; lower-right X,Y: 812418 Easting, 7702816 Northing in UTM Zone 34 S), which covers a rectangular area of approximately 66,875 km². The delta is located in the central-eastern part of the Okavango River basin, and within the larger Makgadikgadi basin (Figure 2.1). It is called a delta (the Greek letter Δ), since it presents a ‘birds-foot’ like feature with a roughly triangular shape. The two main rivers, the Cubango and the Cuito, originate in the east of Huambo on the Bie plateau in central Angola and flow to the south, where they form part of the Angola-Namibia border. In Namibia, the river is known as the Kuvango and finally through the Caprivi Strip (Namibia) it enters Botswana at Mohembo as the Okavango River, and after meandering about a hundred kilometres it branches out to form the Okavango Delta. The delta forms one of the largest inland wetland ecosystems in the world, which comprises an area between 15,000 to 16,000 km² (Table 2.1). The catchment of rivers and the delta together known as the Okavango River basin comprises ~429,400 km² area (Ashton and Neal, 2003). FAO (2003) estimated the Okavango River basin to be 323,192 km². The estimation differs due to differences in basin definition and the method of measurement. The Okavango River sub-basin is part of the larger Makgadikgadi basin (Figure 2.1), which covers an area approximately 725,293 km² (Ashton and Neal, 2003) or 721,277 km² (World Resources Institute, 2003). The Okavango is the fourth longest river in southern Africa (1,610 km). The remarkable feature of this river is that it does not find an ocean or a large lake, instead terminates in the desert that lodges the Okavango graben and form the largest inland delta in the world.

*Geologic Setting*

The Okavango Delta is the last remnant of the ancient great Makgadikgadi Lake (Figure 2.1); the lake was formed by the Kalahari sands about three million years ago (Ross, 1987). The delta is a graben (the German word for a ditch), formed on a downthrown block between two
The Okavango Wetland and Multiplatform Observations

normal faults (Figure 2.2a), which is the southerly extension of the East African rift system. A half-graben structure is, however, bounded by a major fault only on one side (Figure 2.2b).

Figure 2.1 Location of the Okavango River Basin and Delta (•) in Southern Africa, and within the larger Makgadikgadi basin. (Adapted from: United Nations Cartographic Section, 2000, 2009). The delta is located in the north-western part of Botswana, which is the approximate northern limit (—) of Kalahari Desert.

The East African rift system is a series of tectonic basins formed by descending troughs or grabens ~100 km long and tens of kilometers wide (Chorowicz, 2005). The Okavango graben is bounded by the Gomare fault in the north-west, and Kunyere and Thamalakane faults in the

Figure 2.2 Down-faulted structures. a) Graben, b) half-graben (after Summerfield, 1991; cited in Hugget, 2007). A graben (e.g. Okavango) is a down-faulted block between two normal faults.
south-east (see Figure 2.5). For detail about the Kalahari environment, see Thomas and Shaw (1991).

Geomorphologically, this inland delta is an alluvial fan formed by the deposition of alluvium carried by the Okavango River and wind-blown sands of the Kalahari Desert. The alluvial fan is a better physiographic description than the term delta (Watson, 1991) as the landscape is shaped by deposition of sands. These depositional landforms are generally created where steep high-power channels enter a zone of reduced stream power (Blair and McPherson, 1994). Figure 2.3 shows the spatial extent of the Okavango alluvium, a vast tract of broadly elongated southwest-northeast landmass. The longitudinal sand dunes occupy the region west of this alluvium; dune crests carry woodland and the troughs grassland (Watson, 1991). The sand dunes of the Okavango Delta region as observed by the ETM+ sensor on Landsat 7 is shown in Figures 2.4a&b. The panchromatic image (a) and fused panchromatic-multispectral image (b) with 15 m spatial resolution shows the parallel dunes, where trough-to-trough and crest-to-crest distance is about two kilometres. Figure 2.5 shows the cross-profile of these dune geomorphic components, which can be divided into: a) the backslope or windward surface, b) the crest, and c) the slip face or lee slope (Ritter et al., 2011). Crests are generally convex-up, separating zones of erosion and deposition on the dune. Although dune height varies from few meters to about a hundred meters, crest-to-crest spacing of dunes in the Okavango region (linear dark features in the panchromatic and pink in the fused image, Figures 2.4a&b) correlates well.

**Figure 2.3** The Okavango alluvium as part of the Kalahari beds (adapted from Mallick et al., 1981; cited in Key and Ayres, 2000). The alluvium comprises a vast elongated southwest-northeast landmass.
**Figure 2.4** Sand dunes in the Okavango Delta region of Kalahari Desert (west of Panhandle) observed from Landsat 7, April 2000. a) Panchromatic image (15 m spatial resolution), b) panchromatic and 30 m multispectral fused image (15 m). The parallel linear features (dark in the panchromatic image and pink in the fused image) are dune crests between troughs (or valleys). The image covers an area of ~680 km² (29.8 km x 22.8 km).

**Figure 2.5** Cross-profile of normal dune showing common geomorphic components (adapted from Ritter et al., 2011).

**Physiographic Characteristics**

The general physiographic environment of the central southern Africa is characterized by Kalahari Desert and its sediments group, the Okavango oasis in the heart of Kalahari, and semi-arid sandy desert topography (Figure 2.6). The Okavango River and the Delta comprises the major water body in land-locked Botswana, whose largest part is covered by Kalahari sediments (Figure 2.6a). The Kalahari Desert forms the northern limit of Botswana, the region which lodge the Okavango wetland. Terrain elevation in the Okavango River basin ranges between 800 to 1300 m above mean sea level (msl) (Figure 2.6b).

The Okavango alluvial fan is broadly divided into four physiographic regions: the panhandle, permanent swamp (~6,000 km²), seasonal swamp (between 4,000 to 12,000 km²) and the occasional swamp (varies inter-annually) (McCarthy et al., 1997). Figure 2.7 presents a synoptic view of the Okavango Delta and region ecosystem, as observed from Landsat 7. The mid-infrared (MIR), near-infrared (NIR) and green band combination of images, acquired in April 2000, show the spatial extent of the ‘birds-foot’ shaped delta, distributary channels, and physiographic regions and landscape features. This band combination provides best contrast to highlight water and wetland surface from surrounding grasslands, woodlands and sand dune features, as in the NIR and MIR regions water and wetlands increasingly absorb radiation. The delta is located in a semi-arid region, which experiences large variations in
flooding on the swamps and other occasionally flooded areas. Water depth in the permanent swamp averages 1.5 m (UNDP, 1977), while in the seasonal swamp it is generally less than 1 m (McCarthy et al., 1998) (Figure 2.7). The spatial extent of open water and wetlands varies inter-annually and intra-annually, depending on the water level in the delta in response to the river inflow and local precipitation.

The Okavango Delta environment comprises swamps and island mosaics within the wetland, and surrounding dry wood/grassland areas and sand dunes. In this study, the wetland is defined as a contiguous area of permanent, seasonal and occasional swamps and islands within the wetland. The Okavango wetland comprises about 15,000 km² area (early flooding season, measured by this author based on Landsat 7 multispectral image of April 2000), which is close to the flooding season estimation of 15,850 km² by the International Union for Conservation of Nature, IUCN (Scudder, 1993) (see also OKACOM [Okavango River Basin Water Commission], which presumably used the IUCN estimation [www.okacom.org]). The delta (only alluvial fan area) comprises 28,000 km² (6.52%) (Ramberg et al., 2006), out of 429,400 km² of the Okavango River basin. Figure 2.8 presents a schematic view of the areal extent of the Okavango River basin (B), the delta (D), and the wetland (W). There is, however, no agreement on the size of the Okavango wetland and the alluvial fan (Table 2.1). The estimates for the wetland range from about 10,000 km² to nearly 15,900 km², while the
Figure 2.7 The Okavango Delta ecosystem at flooding (wet season) observed by Landsat 7 ETM+ sensor (30 m spatial resolution; 5, 4, 2 [MIR, NIR, Green] band combination), acquired on 3 and 10 April 2000. The mosaic covers an area of 66203 km² (239 km x 277 km). The Gumare (north-west) and Thamalakane Faults (south-east) form the boundaries of the Okavango Rift (an extension of the East African Rift System (Modisi, 2000)).
alluvial fan size ranges from about 16,000 km$^2$ to 40,000 km$^2$. Differences in estimation is because of dynamic nature of the Okavango wetland and the alluvial fan, definitional variation as well as the data and methods of estimation.

### Table 2.1 Estimated size of the Okavango wetland and alluvial fan.

<table>
<thead>
<tr>
<th>Area (km$^2$)</th>
<th>Wetland</th>
<th>Alluvial fan</th>
<th>Data used for estimation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;15,000</td>
<td>-</td>
<td>-</td>
<td>Landsat 7 ETM+, 2000</td>
<td>Present author</td>
</tr>
<tr>
<td>15,850</td>
<td>-</td>
<td>-</td>
<td>Not known</td>
<td>OKACOM (undated)</td>
</tr>
<tr>
<td>-</td>
<td>28,000</td>
<td>40,000</td>
<td>Based on earlier studies</td>
<td>Ramberg et al. (2006)</td>
</tr>
<tr>
<td>~14,000</td>
<td>40,000</td>
<td>-</td>
<td>Satellite remote sensing</td>
<td>Gumbricht et al. (2005)</td>
</tr>
<tr>
<td>~13,500</td>
<td>~40,000</td>
<td>-</td>
<td>Satellite remote sensing</td>
<td>Gumbricht et al. (2004a)</td>
</tr>
<tr>
<td>&gt;12,000</td>
<td>~25,000</td>
<td>&gt;22,000</td>
<td>Not known</td>
<td>McCarthy et al. (1998)</td>
</tr>
<tr>
<td>~15,850</td>
<td>-</td>
<td>Not known</td>
<td>Ecological zoning maps 1989 at 1:250,000, 1:100,000 scale</td>
<td>Merry et al. (1998)</td>
</tr>
<tr>
<td>&gt;10,000</td>
<td>&gt;16,000</td>
<td>18,000</td>
<td>Landsat images</td>
<td>Watson (1991)</td>
</tr>
<tr>
<td>-</td>
<td>18,000</td>
<td>Not known</td>
<td>UNDP (1977)</td>
<td></td>
</tr>
</tbody>
</table>

### 2.3 Landscape Characteristics

#### 2.3.1 Topography

Topographic information, particularly terrain morphology is increasingly used in analyses in diverse fields as a means both of explaining processes and of predicting them through modeling (Moore et al., 1991; Rodriguez-Iturbe and Rinaldo 1997; Huggett and Cheesman, 2002; Alsdorf et al., 2007). The quality of the topographic data available determines the depth of the understanding, and consequently of modeling these processes. The fundamental data for depicting topography consists of terrain elevation values above (or below) the geoid (i.e. mean sea level) at individual point locations. Terrain elevation is the primary topographic attribute of the Okavango wetland, as it is characterised by a very low-relief surface and by
other topographic features such as variable size islands, oxbow lakes and channel networks. The high grounds in the permanent and seasonal swamp form islands; their size ranges from a termite mound to several square kilometres. Some islands are a result of tectonic movements, but most are the results of termite nest building activity (McCarthy, 1993). Termite mounds (or ant hills, as called in Africa) are generally conical shapes with an average height of 2-3 m.

**Terrain Elevations**

The regional relief (i.e. terrain elevation difference) in the Okavango Delta from Mohembo to Maun (from the apex of the panhandle to the bottom of the delta, a distance of about 250 km) is approximately 58 m (estimated based on SRTM 30 m spectral filtered elevation model [downscaled from 90 m], Figure 2.9a). The terrain is gently undulating with a mean local relief (i.e. the average elevation difference between points along transect $A$), of 1 m over 4.3 km distance (Figure 2.9a & b). The transect $b$ (Figure 2.9c) shows the gentle topography of the Panhandle or the entry corridor; this can also be seen in the aerial picture (Figure 2.10). The relief is less than 25 m, over a distance of about 100 km. There is a slight steeper gradient

![Terrain characteristics of the Okavango Delta. a) SRTM filtered elevation model with transect location, b) transect $A$ from Mohembo to Maun, c) transect $b$ from Mohembo to the end of Panhandle, d) transect $c$ from Panhandle end to Maun.](image)

**Figure 2.9** Terrain characteristics of the Okavango Delta. a) SRTM filtered elevation model with transect location, b) transect $A$ from Mohembo to Maun, c) transect $b$ from Mohembo to the end of Panhandle, d) transect $c$ from Panhandle end to Maun.
from the Panhandle end towards Maun with a relief of around 40 m, over a distance of ~150 km (transect c, Figure 2.9d). Transect A divides the delta into two halves diagonally, with no distinct differences in elevations on either side.

Figure 2.10 Okavango Panhandle, the entry channel of the delta. This meandering channel flows from northern reaches at Mohembo and extends downward for nearly 100 km. (Photo: Thomas Gumbricht)

Figure 2.11 shows the 231 km long north-south elevation profile in the delta (transect d, Figure 2.9a) derived from SRTM (30 m) spectral filtered elevation model. The transect runs from sand dune and land-vegetation areas in the north, through the permanent swamp to the northern edge of Lake Ngami. It shows that elevation decreases from 986 m to 935 m (from north to south), with an average elevation of 961 m and a regional relief of 51 m. The regional topography is gently-sloping (standard deviation, σ = 12.91 m), with a local gradient of 4.5 m per 1 km distance.

Figure 2.11 North-south elevation profile in the Okavango Delta, derived from SRTM filtered elevation model (transect d, Figure 2.9a). Topography is gently-sloping with a relief of 51 m over 231 km distance.
Islands and Channels

The Okavango wetland contains thousands of islands of varying size, ranging from few square meters to large, e.g. the Chief’s island (Figure 2.7). They are distributed mostly in the permanent and seasonal swamps (Figure 2.12) and comprises woody and grass covered surface surrounded by open water and swamps. In the permanent swamp, island centres are generally composed of salt crusts.

Figure 2.12 Spatial distribution of islands in the seasonal swamp of the Okavango Delta. Salt crusts (white) occupy centre-portions of many islands (Photo: Thomas Gumbrich)

Channels provide the network of routes along which water and sediment is carried out of a drainage basin. They receive water and sediment from the hillsides, and transmit these downstream, both delaying and storing the water and sediment on the way (Kirkby, 1993). In the Okavango Delta, the water depth in the permanent swamp is up to 4 m (Watson, 1991), and characterized by permanently flowing channels and lagoons with beds/margins vegetated by papyrus and reeds (Figure 2.13). The shallow channel networks, open or blocked by the

Figure 2.13 Papyrus vegetated channel margins of the permanent swamp of the Okavango Delta.
papyrus, are found in the seasonal swamp. The different types of channels in the delta are formed in response to the loss of confinement of flow as the river enter the graben (McCarthy, 2004).

Figure 2.14 shows the general channel topographic characteristics in the delta; the variations in water level occurs perpendicular to the channel at each study sites (A-J). The water surface generally slopes away from the main channel into the flanking swamps, the steepest being a fall of 47 cm over 50 m (site F, left bank). In some channel sites such as H, I and J, which are characterized by low gradient slopes on both banks, lateral slopes increase downstream (McCarthy, 1991).

![Figure 2.14 Channel topographic characteristics in the Okavango Delta. Channel widths are not to scale (after McCarthy, 1991). Generally, the water surface slopes away from the main channel into the flanking swamps (e.g. site F, steepest fall on left bank).](image-url)
2.3.2 Biophysical Features

Wetland landscapes are dynamic, shaped by physical and biological processes and human impacts on the environment. The Okavango Delta displays a complex mosaic of biophysical features – their variable size and shapes, semi-arid location, geomorphic setting, climate, soil structure, water regime, water chemistry, flora and fauna. The measurement and characterization of these features are important for management of the wetland. The present study focuses on two important aspects, from a remote sensing perspective – the extent of the wetland, and land and vegetation cover. The delta experiences annual flooding, the extent of flooding and magnitude vary. The extent of the wetland also varies inter-annually and intra-annually, depending on the flow of water from the Okavango River and the amount of local precipitation. The delta ecosystem comprises diverse vegetation (Figure 2.15) and land cover types. The key features are dry-wood and forests, grasslands, water bodies, wetlands, and sparse settlements.

![Vegetation cover in the seasonal swamp of the Okavango Delta. Grasslands occupy much of seasonal swamps.](image)

2.4 Multiplatform Observations

This section first briefly describes the acquisition techniques of observations from varied platforms and by sensors/instruments, and then describes in detail the availability of data from varied platforms for this study. Then, it highlights the requirements of terrain elevation and land cover data.

2.4.1 Acquisition Techniques

Platforms

Today, we have several hundred spacecrafts orbiting the Earth at varying altitudes (Figure 2.16), performing varied functions that range from remote sensing of the earth surface and the environment to remote positioning/navigation and communication. The platforms can be divided into (as per altitudinal location above the earth): ground and low Earth, Low Earth
Figure 2.16 Earth observation and global positioning system platforms, as per altitude. (a) Platforms and orbits in general. (b) Platforms used in the present study (values in parenthesis give the altitude in km).
Orbit (LEO), Medium Earth Orbit (MEO) and Geostationary Earth Orbit (GEO). Examples of such platforms are ground-based, aircrafts and helicopters, Space Shuttles, space stations (e.g. International Space Station), polar-orbiting Earth observation satellites, geostationary satellites, and positioning system and navigation satellites (Figure 2.16a).

Satellite orbits are commonly characterized by their orbital height (Seeber, 2003), which can generally be distinguished into:

- **LEO** = Low Earth Orbit (up to 2000 km),
- **MEO** = Medium Earth Orbit (5000–20,000 km), and
- **GEO** = Geostationary Earth Orbit (36,000 km).

The orbital heights of remote sensing satellites such as Landsat, SPOT, Terra, IKONOS, ICESat are between 600 – 1000 km, while orbital heights of shuttles and space stations are between 150 – 500 km. The remote positioning instruments use a MEO constellation of satellites (minimum of 24 satellites) to measure positions (xyz) almost anywhere on earth. The most well-known such systems are GPS and GLONASS (about 20,000 km). GEOS are used for meteorological and communication satellites (e.g. INTELSAT, INSAT). For detail about satellite orbits and platforms see Montenbruck and Gill (2001), Seeber (2003) and Lillesand et al. (2008). The details about various platform observations used in this study is given in Figure 2.16b and Table 2.2.

**Sensors/Instruments**

Remote observation instruments can be grouped into sensing and positioning systems. There are diverse arrays of sensors used to acquire information about the earth’s surface and the environment from ground, aerial and space platforms. They can broadly be grouped into passive and active, depending on the source of energy. Passive sensors use natural energy (e.g. Sun) to measure (e.g. ETM+ on Landsat 7, HRG on SPOT 5, LISS on IRS, and ASTER on Terra), while active sensors use their own energy (e.g. SAR on SRTM, Envisat and Risat; GLAS on ICESat). The remote positioning systems carry atomic clocks on GPS and GLONASS constellation of satellites.

**2.4.2 Availability of Data**

The detailed sources and characteristics about data used in this study are given in Table 2.3 and Table 2.4.

**Data for Measuring Microtopography**

**Airborne Data:** Aerial stereo images, diapositives as well as contact prints of standard black and white (B&W, 23 cm x 23 cm) imagery, acquired on 29 August 1991 with a Wild Universal Aviogon II camera lens (f = 153 mm) at a scale of 1:50,000. The parameters and descriptions of aerial images are given in Appendix I. The diapositives were scanned at 15 μm with an Ultrascan 5000.

**Spaceborne Data:** IKONOS1 panchromatic stereo image pairs with 1 m spatial resolution, acquired on 11 and 14 October 2003. The IKONOS satellite acquires stereo images almost simultaneously for a given area by agile pointing of the sensor through rotation of the satellite. This approach yields only small radiometric differences between images. The sensor characteristics of IKONOS satellite are given in Chapter 5.

1 As per Space Imaging, IKONOS rather than Ikonos is the correct form (Cited in Goward et al., 2003).
Table 2.2 Main features of the aerial and spacecraft platforms used in this study.

<table>
<thead>
<tr>
<th>Main features</th>
<th>Platforms</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nature of mission</strong></td>
<td><strong>Platforms</strong></td>
</tr>
<tr>
<td>Low Earth</td>
<td>IKONOS</td>
</tr>
<tr>
<td><strong>Altitude (km)</strong></td>
<td>Polar, circular, Sun-syn, LEO</td>
</tr>
<tr>
<td>&lt;10</td>
<td>681</td>
</tr>
<tr>
<td><strong>Orbital inclination (deg)</strong></td>
<td>98.10</td>
</tr>
<tr>
<td><strong>Orbital period (minutes)</strong></td>
<td>98.33</td>
</tr>
<tr>
<td><strong>Mass (kg)</strong></td>
<td>726</td>
</tr>
<tr>
<td><strong>Repeat cycles (days)</strong></td>
<td>3 at 40° latitude</td>
</tr>
<tr>
<td><strong>Equatorial crossing time</strong></td>
<td>Nominally 10:30 AM</td>
</tr>
<tr>
<td><strong>Sensors onboard</strong></td>
<td>Visible</td>
</tr>
<tr>
<td><strong>Launch vehicle</strong></td>
<td>Aircraft/ Helicopter</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technology</th>
<th>Sources of elevation data</th>
<th>Method of generation</th>
<th>Merits</th>
<th>Demerits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical remote sensing</td>
<td>Aerial stereo-image</td>
<td>Analytical</td>
<td>High resolution</td>
<td>Test site, poor image texture</td>
</tr>
<tr>
<td></td>
<td></td>
<td>stereophotogrammetry</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>IKONOS stereo-image</td>
<td>Digital</td>
<td>High resolution</td>
<td>Test site, moderate image texture</td>
</tr>
<tr>
<td></td>
<td></td>
<td>stereophotogrammetry</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ASTER DSM V2</td>
<td>Digital</td>
<td>Medium resolution, regional</td>
<td>Low accuracy, moderate structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td>stereophotogrammetry</td>
<td>coverage</td>
<td></td>
</tr>
<tr>
<td>Radar remote sensing</td>
<td>AGS DSM</td>
<td>Radar altimetry</td>
<td>Medium resolution, regional</td>
<td>Low accuracy, moderate structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>coverage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SRTM C-radar DSM</td>
<td>Interferometry SAR</td>
<td>Medium resolution, regional</td>
<td>Low accuracy, moderate structure</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>coverage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>CryoSat-2 SIRAL footprints</td>
<td>SAR/Interferometric radar altimeter</td>
<td>Regional coverage</td>
<td>Medium accuracy, coarse resolution footprints</td>
</tr>
<tr>
<td>Laser remote sensing</td>
<td>ICESat GLAS footprints</td>
<td>Laser altimetry</td>
<td>High resolution along profiles, high accuracy, good validation data, regional coverage</td>
<td>No consistent distribution of points, structure along profiles only</td>
</tr>
<tr>
<td>Positioning system</td>
<td>GPS postings (GCPs)</td>
<td>Ground-based survey</td>
<td>High accuracy, good validation data</td>
<td>Three test sites only</td>
</tr>
<tr>
<td></td>
<td>GPS postings</td>
<td>Airborne survey</td>
<td>As above, regional coverage</td>
<td>Sparse sampling density</td>
</tr>
<tr>
<td></td>
<td>MDEM (GPS-based)</td>
<td>Interpolation of postings using land cover info.</td>
<td>Generalised contour map, high accuracy around GPS postings, regional coverage</td>
<td>Coarse resolution, poor model structure</td>
</tr>
</tbody>
</table>

Table 2.3 Summary of the elevation data over the Okavango Delta: General merits and demerits.

The relative merits and demerits of elevation data over the Okavango Delta were assessed based on the following parameters - spatial resolution, vertical accuracy, spatial structure, and coverage.

1. Spatial resolution (based on grid size): High (10 m and less), medium (~ 10 m to 100 m), and coarse (~ 100 m).
2. Vertical accuracy (based on RMSE): Very high (< 1 m), high (1 m to 2 m), moderate (2 m to 5 m), low (5 m to 10 m), and very low (< 10 m).
4. Coverage (based on spatial extent): Test site (small area) and regional coverage (the delta).
### Table 2.4 Summary of data for measuring terrain elevation over the Okavango Delta: Location, spatial coverage, resolution and accuracy.

<table>
<thead>
<tr>
<th>Data</th>
<th>Location (UTM Zone 34 South, in m)</th>
<th>Ellipsoid: Clarke1880, Datum: Cape</th>
<th>Original coordinate system</th>
<th>Spatial coverage</th>
<th>Resolution/accuracy (m)</th>
<th>Reference data for calculating RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Upper-left XY (Eastings/Northings)</td>
<td>Lower-right XY (Eastings/Northings)</td>
<td>Coordinates</td>
<td>Ellipsoids</td>
<td>Horizontal resolution</td>
<td>Vertical accuracy (RMSE)</td>
</tr>
<tr>
<td>Aerial stereo-image (diapositive)</td>
<td>732583.664/788830.938</td>
<td>738863.674/7878230.647</td>
<td>Test site</td>
<td>-</td>
<td>-</td>
<td>0.76</td>
</tr>
<tr>
<td>IKONOS stereo-image</td>
<td>654141.74 / 7898518.23</td>
<td>659641.74 / 7889278.23</td>
<td>Test site</td>
<td>Geographic</td>
<td>WGS84</td>
<td>1</td>
</tr>
<tr>
<td>Terra ASTER DSM</td>
<td>579287.983 / 7982167.818</td>
<td>812417.942 / 7702816.262</td>
<td>Delta</td>
<td>Geographic</td>
<td>WGS84</td>
<td>30</td>
</tr>
<tr>
<td>AGS DSM</td>
<td>579287.983 / 7982167.818</td>
<td>812417.942 / 7702816.262</td>
<td>Most part of delta</td>
<td>UTM</td>
<td>WGS84</td>
<td>50</td>
</tr>
<tr>
<td>SRTM DSM</td>
<td>As above</td>
<td>Delta</td>
<td>Geographic</td>
<td>WGS84</td>
<td>90</td>
<td>2.21</td>
</tr>
<tr>
<td>CryoSat SIRAL points</td>
<td>As above</td>
<td>Delta</td>
<td>Geographic</td>
<td>WGS84</td>
<td>30 m spots</td>
<td>250 m along-track (AT)</td>
</tr>
<tr>
<td>ICESat GLAS elevation points</td>
<td>579287.983 / 7982167.818</td>
<td>812417.942 / 7702816.262</td>
<td>Delta</td>
<td>Geographic</td>
<td>TOPEX/ Poseidon</td>
<td>70 m spots</td>
</tr>
<tr>
<td>GPS-based DEM (MDEM)</td>
<td>72583.664/788830.998</td>
<td>738863.664/7878230.938</td>
<td>Test site</td>
<td>UTM</td>
<td>WGS84</td>
<td>28.5</td>
</tr>
<tr>
<td>GPS postings</td>
<td>579287.983 / 7982167.818</td>
<td>812417.942 / 7702816.262</td>
<td>Delta</td>
<td>Geographic</td>
<td>WGS84</td>
<td>~7500 distance</td>
</tr>
<tr>
<td>GPS ground control points</td>
<td>Various point location</td>
<td>Three test sites</td>
<td>Geographic</td>
<td>WGS84</td>
<td>47 postings</td>
<td>~0.16</td>
</tr>
</tbody>
</table>

*Test sites: Aerial image = 73 km²; IKONOS = 53 km²; MDEM = 67 km²; Delta = 66875 km².* **See Figure 2.14.

Note: Data are arranged by technologies: 1) Optical remote sensing, 2) radar remote sensing, 3) laser remote sensing, and 4) positioning system.
Data for Measuring Mesotopography

**Airborne Data:** An airborne geophysical survey (AGS), which included a radar altimetry instrument, was carried out by the Geological Survey of Botswana at different times in the 1990s. The radar altimetry elevation data \((x, y, z)\) were interpolated to 50 m grid format.

**Spaceborne Data:** The postings and GCPs measurements using differential GPS, and elevation data measured by SRTM C-radar and Terra ASTER.

**Positioning Data:** There are 1099 GPS elevation postings data available over the delta (the present study area). They were measured by the Geological Survey of Botswana (GSB), The University of Cape Town (UCT), South Africa, and Swiss Federal Institute of Technology Zurich (ETHZ) at various times. The Geological Survey of Botswana carried out a GPS elevation measurement survey over the delta region at ~7.5 km distance postings, which resulted in 4003 elevation points (Poseidon Geophysics, 1998). Out of 4003 postings, 1002 elevation postings are located in the present study area. The University of Cape Town carried out GPS elevation measurement surveys along the main channels of the delta during 1994-98 that resulted in 50 GPS elevation postings.

**GPS Survey**

The ETH Zurich carried out a GPS survey in 2002, which measured 47 ground control points (GCPs) (Appendix II) in three physiographic locations in the delta (Figure 2.17), i.e. permanent, seasonal, and occasional swamps (Talukdar, 2003a). The purpose of this survey was to establish GCPs for orientation of air- and spaceborne stereo models to generate DEMs. The measurement of GCPs was challenging because of difficulties in locating identical features (control points) on aerial images (acquired in 1991) and on the ground (survey date 2002).

![Figure 2.17 Location of aerial stereo-photographic blocks and GCPs in the Okavango Delta. a) Block location – Maunachira, Jao and Xudum, b) GCPs in the Maunachira block on two stereo-models (024/023 and 220/221).](image-url)
Post-processing

The positioning with GPS measurements resulted in \( x, y, z \) coordinates; applying transformation the ellipsoidal coordinates were obtained (\( \Phi, \lambda, h \); latitude, longitude, ellipsoidal height). The formula:

\[
h = H + N
\]

where \( h \) = ellipsoidal height
\( H \) = orthometric height
\( N \) = geoidal height (undulation)

is the relationship between the ellipsoid and the geoid (Figure 2.18). The transformation to orthometric heights is achieved by the equation:

\[
H = h - N
\]

where \( H \) = orthometric height, i.e., height above mean sea level (msl)
\( h \) = ellipsoidal height
\( N \) = geoidal height.

The orthometric height calculation of a point from GPS measurements is a two-step process: (i) determining the ellipsoidal coordinates \( [\Phi, \lambda, h] \) from GPS measurements, and (ii) determining the geoidal height from a database, and subtract it from the ellipsoidal height \( h \) (Misra and Enge, 2006).

![Figure 2.18 Relationship between geoid and ellipsoid.](image)

The GPS survey data were post-processed using Leica Geosystem’s SKI-Pro Version 2.5 software. First, geographic coordinates with ellipsoid heights (WGS84 ellipsoid) were derived. Then, WGS84 ellipsoidal heights were transformed into orthometric heights in Cape datum using the Earth Gravity Model 1996 (EGM96). Geographical coordinates were transformed into Clarke 1880 ellipsoid and converted to Cartesian coordinates using UTM projection, Zone 34 South. The following datum transformation parameters are applied (between WGS84 and Clarke 1880):

\[
\begin{align*}
dx & : 135.4 \text{ m} \\
dy & : 106.7 \text{ m} \\
dz & : 291.7 \text{ m} \\
Rx & = Ry = Rz = 0.0'' \\
\text{Scale} & : 0.0 \text{ ppm}
\end{align*}
\]

Geoid: EGM96
Precision and Accuracy of Control Point Measurements

To assess the accuracy of GCP measurements by GPS, seven newly (2002) measured points were compared with the existing fixed points (measured by earlier [1990s] GPS surveys). The comparison of the difference between newly computed and existing fixed point coordinates is given in Table 2.5. The survey gave -0.36 m horizontal \((x, y)\) and -0.15 m vertical \((z)\) precisions. The horizontal precision was calculated by comparing seven existing and seven new measurements and then computing the square root: \(\sqrt{(0.119)^2 + (0.335)^2} = \sqrt{0.12639} = 0.356\) m (standard deviation, \(\sigma\)). The vertical accuracy (root mean squared error, RMSE) of new GPS measurements resulted in 0.157 m, computed based on the difference of six new and six existing measurements (using existing measurements as a reference). The result of this comparison (15% sample) provides the representative precision and accuracy of 47 GCPs.

Table 2.5 Comparison of planimetric and orthometric height measurements of 2002 (ETHZ) and 1990s (existing) GPS surveys.

<table>
<thead>
<tr>
<th>Station ID</th>
<th>Planimetric difference (m)</th>
<th>Orthom. height difference (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(\text{Northing (2002 - 1990s)})</td>
<td>(\text{Easting (2002 - 1990s)})</td>
</tr>
<tr>
<td>BPS253</td>
<td>0.059</td>
<td>0.006</td>
</tr>
<tr>
<td>BPS260</td>
<td>-0.186</td>
<td>0.711</td>
</tr>
<tr>
<td>BPS267</td>
<td>-0.284</td>
<td>0.669</td>
</tr>
<tr>
<td>UCT26</td>
<td>-0.074</td>
<td>-0.021</td>
</tr>
<tr>
<td>UCT32</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>UCT33</td>
<td>-0.066</td>
<td>0.044</td>
</tr>
<tr>
<td>UCT6</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Mean difference</td>
<td>-0.079</td>
<td>0.201</td>
</tr>
<tr>
<td>Standard deviation diff.</td>
<td>0.119</td>
<td>0.335</td>
</tr>
<tr>
<td>RMSE</td>
<td>0.146</td>
<td>0.399</td>
</tr>
</tbody>
</table>

Shuttle Radar Topography Mission Data: The Shuttle Radar Topography Mission (SRTM), a low earth-orbiting spacecraft (233 km altitude), employed two synthetic aperture radars (SAR) instruments – a C-band system (5.6 cm, C radar) and an X-band system (3.1 cm, X radar). The mission consisted of a specially modified radar system (Hensley et al., 2000), which acquired interferometric radar data over a major part of the Earth’s land surface, from 60\(^\circ\) N and 56\(^\circ\) S latitudes, during its 11-day mission in February 2000. The present study focuses on the SRTM C-band radar (hereafter SRTM) elevation measurements, acquired at 90 m grid spacing. The SRTM radar imagery is essentially a 10 day snapshot view of the Earth, as observed with 5.6 cm wavelength radar signals that were transmitted from the Shuttle, reflected by the Earth, and then recorded on the Shuttle (Farr et al., 2007). Table 2.6 presents the specification of SRTM topographic product.

The SRTM ‘finished’ data (Version 2) is used in the present study. The data tiles were downloaded from the NASA Jet Propulsion Laboratory (JPL) site (http://www2.jpl.nasa.gov/srtm/). Another version of SRTM data (based on SRTM Version 2) were downloaded from Global Land Cover Facility (GLCF) of the University of Maryland at College Park (http://www.landcover.org/data/srtm/), which were referenced to Landsat Worldwide Reference System (WRS) Path/Row mosaic. The difference between datasets is that in the JPL version of the SRTM ‘finished’ data the only major data voids are filled, while most data voids are filled in the GLCF version of the SRTM data. In the JPL version, data voids in SRTM surface model over the Okavango Delta were detected and identified through
visualization, while the GLCF version helped to fill the void pixels through spatial interpolation.

### Table 2.6 SRTM C-radar topography product specifications.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>C radar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projection</td>
<td>none (&quot;geographic&quot;)</td>
</tr>
<tr>
<td>Horizontal spacing</td>
<td>1 x 1 arc sec (~30 x 30 m) or 3 x 3 arc sec (~90 x 90 m) latitude/longitude</td>
</tr>
<tr>
<td>Vertical quantization</td>
<td>1 m</td>
</tr>
<tr>
<td>Horizontal reference</td>
<td>WGS84</td>
</tr>
<tr>
<td>Vertical reference</td>
<td>EGM96 geoid</td>
</tr>
<tr>
<td>Data format</td>
<td>16-bit signed integer, IEEE byte order</td>
</tr>
<tr>
<td>Void value</td>
<td>-32768</td>
</tr>
<tr>
<td>Wavelength</td>
<td>5.66 cm</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Look angle</td>
<td>~30°~58°</td>
</tr>
</tbody>
</table>

*Source: Farr et al., 2007.*

**ASTER Elevation Data:** The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), an imaging instrument on Terra satellite, put into a low earth-orbit (705 km altitude) in 1999. The instrument carries 14 spectral bands that includes three visible and near-infrared (VNIR) bands (15 m spatial resolution), six shortwave-infrared (SWIR) bands (30 m spatial resolution) and five thermal infrared (TIR) bands (90 m spatial resolution). The specification of ASTER instrument and bands used for creating global DEM (GDEM) is given in Appendix III. The VNIR band-3 (0.76-0.86 um) provides along-track stereo coverage that resulted in the GDEM, derived by digital photogrammetric stereo-correlation method (Abrams et al. 2010). The present study acquired ASTER DEM product (Version 2) from NASA JPL site (http://asterweb.jpl.nasa.gov/gdem.asp) and mosaicked into a regional model of the delta (same area as SRTM). The details about this DEM product is described in Chapter 4 (Section 4.3.4).

**ICESat Geoscience Laser Altimeter System Data:** The Ice, Cloud, and land Elevation Satellite (ICESat), a low earth-orbiting spacecraft (600 km altitude), carried the Geoscience Laser Altimetry System (GLAS) sensor with three 1064 nm Nd-YAG lasers. The mission (launched in January 2003), as part of NASA’s Earth Observing System, goal was to measure the global ice-sheet elevations, changes in elevation through time, height profiles of clouds and aerosols and land elevations and vegetation cover (Zwally et al. 2002). The specification of ICESat GLAS is given in Appendix IV. The present study focuses on the ICESat land topography data products (GLA-14) acquired at ~70 m diameter footprints at every ~170 m along-track spacing. The across-track spacing on the Okavango Delta region is ~50 km. The multi-temporal (2003-2009) GLA-14 data products are acquired (on personal request) from the National Snow and Ice Data Center (NSIDC), University of Colorado, Boulder. These datasets per processing level and acquisition date over the Okavango Delta are given in Appendix V. The details about GLAS data products and their characteristics can be found at: https://nsidc.org/data/icesat/data.html.
CryoSat-2 SAR Interferometric Radar Altimeter Data: CryoSat-2, a low earth-orbiting spacecraft (717 km altitude), carried the SAR interferometric Radar Altimeter (SIRAL). This European Space Agency mission (launched in April 2010) is exclusively designed for cryospheric studies (Drinkwater et al., 2004 and Wingham et al., 2006). CryoSat-2 SIRAL data (Level 2 product, 2010-2013) is acquired from the European Space Agency (http://www.esa.int/esaLP/ESAFAQJ1VMOC_LPcryosat_0.html). It’s advanced radar altimeter provides ~300 m footprints at every 250 m along-track, with variable across-track distances depends on latitude.

Data for Measuring Water Surface Elevation

The datasets used for measuring water surface elevation are airborne profiling radar (AGS), spaceborne imaging radar (SRTM), spaceborne profiling laser (ICESat) and GPS measurements. They are described in the above sections.

Data for Mapping Land Cover

Airborne Data: Diapositives as well as contact prints of standard vertical black and white (B&W) aerial images (23 cm x 23 cm), acquired in 29 August 1991 at ~1:50,000 scale. The aerial platform flying height for image acquisition was about 7650 m amsl, and carried a Wild Universal Aviogon II camera lens with a focal length of 152.822 mm (Camera type unknown). The detail information about image acquisition parameters is given in Appendix I.

Spaceborne Data: The main characteristics and specifications of the Landsat 7, SPOT 5 and IKONOS satellite sensors and images used in this study are summarised in Table 2.7. These three satellites orbit the earth in sun-synchronous mode (at inclinations of 98.2°, 98.7°, and 98.1° degree, respectively).

Table 2.7 Specifications of Landsat 7, SPOT 5 and IKONOS satellites and sensors.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Sensors</th>
<th>Spatial (m)</th>
<th>Radio metric</th>
<th>Spectral (no.)</th>
<th>Temporal (days)</th>
<th>Image size (km)</th>
<th>Date of data acquisition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat 7</td>
<td>ETM+</td>
<td>15 (Pan) 30 (MS) 60 (TIR)</td>
<td>8 bits</td>
<td>Band 8 Band 1-5, 7 Band 6</td>
<td>16</td>
<td>183x170</td>
<td>10/04/2000 03/04/2000</td>
</tr>
<tr>
<td>SPOT 5</td>
<td>HRG</td>
<td>5 (Pan) 10 (XS) 20 (SWIR)</td>
<td>8 bits</td>
<td>Pan band Band 1-3 Band 4</td>
<td>26</td>
<td>60 x 60</td>
<td>12/11/2002</td>
</tr>
<tr>
<td>IKONOS</td>
<td>Pan MS</td>
<td>1 (Pan) 4 (MS)</td>
<td>11 bits</td>
<td>Pan band Band 1-4</td>
<td>3 - 4</td>
<td>13 x 13</td>
<td>14/10/2003 11/10/2003</td>
</tr>
</tbody>
</table>

Landsat 7 Satellite Data: Landsat 7 satellite carries Enhanced Thematic Mapper Plus (ETM+) instrument, which is an eight-band multispectral (MS) scanning radiometer providing imaging information in the panchromatic (Pan) band (15 m spatial resolution), and in 6 visible, near and short-wave infrared bands (30 m spatial resolution) and in the thermal infrared band (60 m spatial resolution). The following datasets are used in this study: Path/Row (P/R): 175/073 and 175/074 (acquired in 10 April 2000); and P/R: 174/073 and 174/074 (acquired on 3 April 2000). The P/R 175/073 image covers the main delta, while other scenes cover remaining
parts of the delta. Each ETM+ scene covers a ground area of 183 km x 170 km. Because of its large swath, four ETM+ images cover the entire Okavango Delta region.

**SPOT 5 Satellite Data:** SPOT 5 satellite carries three instruments – High Resolution Geometric (HRG), High Resolution Stereo (HRS) and the low-resolution VEGETATION 2 (Gleyzes et al., 2003). Here we used the HRG instrument observations, which is a five-band multispectral scanner providing information in the Pan band (5 m spatial resolution), and in the multispectral (XS) band (10 m spatial resolution, visible band 1-3; and 20 m spatial resolution resampled to 10 m, short-wave infrared band 4). A Pan and a XS scene (Path/Row: 188/388, 60 km x 60 km ground area), acquired on 12 November 2002, are used in this study.

**IKONOS Satellite Data:** IKONOS satellite instrument carries a five-band multispectral scanning radiometer providing imaging information in the Pan band (1 m spatial resolution), and in the multispectral band (4 m spatial resolution). The multispectral image data includes three visible and one near-infrared channels. IKONOS was the first commercially owned satellite providing such high resolution image data (Dial et al., 2003). In this study, multispectral images acquired on 11 October 2003 are used. A nominal single scene of IKONOS covers a ground area of 13 km x 13 km. However, the tile size for the scene used in this study was around 6 km x 10 km.

The location of Landsat 7, SPOT 5 and IKONOS scenes over the Okavango Delta are shown in Figure 2.19. The detail sensor characteristics of Landsat 7 and IKONOS (main datasets used in this study) are given in Table 5.2 (Chapter 5).

![Figure 2.19 Landsat 7 ETM+, SPOT 5 HRG and IKONOS (Path/Row) scene locations on the Okavango Delta. Four Landsat 7 scenes (red) cover the delta region; a SPOT 5 scene (pink) covers 60 km x 60 km area; IKONOS scene (black) covers 11 km x 8 km area.](image-url)
Other Geospatial Data

Other data used are topographic maps at scales 1:50,000, 1:250,000 and 1:350,000 of the Department of Surveys and Lands, Government of Botswana, published between 1970 and 1990. Several GPS GCPs, surveyed in 2002 were also used as ancillary data.

2.4.3 Requirements of Elevation and Land Cover Data

This section describes two important aspects of landscape topography, i.e. terrain elevation and land cover (as defined in Chapter 1).

Terrain Elevation

The terrain elevation surface or DEM consists of a regular array of elevations referenced horizontally to a geographic coordinate system. DEMs can be used to derive a wealth of information about the morphology of the land surface (USGS, 1993). It is increasingly becoming an important input parameter for modeling hydrological processes, and it provides the key missing factors of many geomorphological analyses of the past (Rodriguez-Iturbe and Rinaldo, 1997). The most critical spatial data required for modeling wetland surface processes and hydrology is the terrain elevation, which is often represented in the form of a grid-based digital elevation matrix. An accurate topography is probably the most important boundary condition in hydrological modeling (Bamber, 2004) and influencing driver of groundwater flow systems (Forster and Smith, 1988). It is one of the water erosion controlling factors, other being soils, vegetation and soil conservation practices (Vrieling, 2006; Jarvis, 2007). Several topographic attributes can be derived from a DEM for diverse applications such as elevation, slope and aspect. A comprehensive review of hydrological, geomorphological, and biological applications of DEMs is given in Moore et al. (1991). For managing wetland ecosystems, topographic data are vital as it is the primary controlling factor for various processes. In the Okavango Delta, terrain elevation is an important input for modeling hydrological, geomorphological, environmental and climate change processes. It is also fundamental information for better management of land, soil and biodiversity. This study focuses on measuring and constructing variable resolution micro- and mesotopographic models to produce this input parameter.

Land Cover

Land cover data are essential environmental information (Cihlar, 2000) and they are needed for research, resource management, and for planning and management at different levels of governance and policy-making. Today, land cover data has become vital information for regional and global climate change research. For sustainable wetland management, accurate land cover information is a fundamental input to surface process modeling and water resources management. It is needed to manage biodiversity and ecology and fundamental for many GIS-based decision support systems. Land cover as a data product is the result of the development of remote sensing because of its large coverage and repeatability (Colwell, 1997). Remote sensing offers a powerful tool for mapping, characterization and monitoring land cover at different spatial and temporal resolutions. Satellite remote sensing provides the basis for geo-referenced land cover characterization that is internally consistent, repeatable, and potentially more reliable than ground-based sources, when dealing with data poor environments like the Okavango. Accurate land cover information will aid in monitoring and management of this wetland, and this information can be acquired from space platform
observations. This study focuses on the following variables: wetland boundary, open water surface, wetland surface, physiographic units, and land cover types. Examples of important parameters are given below.

**Wetland Extent**

The wetland boundary defines the spatial extent of wetlands, which is one of the important parameters for modeling hydrological and environmental processes. Satellite remote sensing is suitable for monitoring and mapping the extent of wetlands and their morphology. Figure 2.20 shows the synoptic view of changing wetlands of the Okavango Delta. The left-image (Figure 2.20a), acquired by ARGON satellite in September 1963, shows the full spatial spread of the delta with water-filled distributaries. However, the middle-image (Figure 2.20b), acquired from the Space Shuttle NM22 platform with a Hasselblad camera (100 mm focal length) in mid-October 1996, shows the drying distributaries of the delta because of drought in the Kalahari. The distal ends of many distributaries are dry, especially on the western and southern side of the delta. This dry scenario changed in 2000, as seen on the image acquired from Landsat 7 platform in early-April 2000 (Figure 2.20c), with distributaries again filled with water. The Landsat 7 NIR channel edge-enhanced image shows the full Okavango wetland compared to dry delta in October 1996. Figure 2.20d, acquired in June 2011 from the International Space Station, shows the similar distributary-filled water as in 2000 and 1996. Barring occasional dry years (e.g. 1996), the delta remains secure in water resources.

**Channel Network and Open Water Surface**

Spatial information on channel networks and open water features are important inputs for modeling hydrological and wetland processes. Channel network maps are essential for studying watershed processes, river basin geomorphology and drainage network development (Rodriguez-Iturbe and Rinaldo, 1997). Figure 2.21 shows the channel patterns and open water features in the permanent-seasonal swamp of the delta on the multispectral image, as observed from SPOT 5. This subset image was taken from the SPOT 5 XS scene (see Appendix VI). Channel banks are vegetated by papyrus (red reflectance).

**Islands**

Islands are unique features in the Okavango wetland because of their formation, structure and the patterns of distribution. Their size and shapes vary depending on the dynamics of flooding and sedimentation. Figure 2.22 shows the distribution of various size and shapes of islands in the permanent swamp of the delta on the multispectral image, as observed from SPOT 5 (see the full scene at Appendix VI). Channel margins are lined by papyrus (see terrestrial photograph, Figure 2.13), while island peripheries are vegetated by trees.
Figure 2.20 Changing wetlands of the Okavango Delta. a) ARGON satellite photographic image (Mission number 9058A, Camera resolution: Vertical low, 2 September 1963; Source: U.S. Geological Survey, Declassified Satellite Imagery-1 [1996]); b) Space Shuttle Mission NM22 image (NM22-723-083, 16 October 1996; Source: Image Science and Analysis Laboratory, NASA-JSC, 1996); c) Landsat 7 ETM+ NIR channel Sobel filtered mosaicked image (3 & 10 April 2000); d) International Space Station astronaut photograph (ISS028-E-6830, Camera: Nikon D2Xs with 28 mm lens, 2 June 2011; Source: Image Science and Analysis Laboratory, NASA-JSC, 2011).
Figure 2.21 Channel networks and open water surface as seen in SPOT 5 HRG sensor images, acquired on 23 November 2002 (10 m spatial resolution, band 1,2,3 [green, red, NIR] combination). The channel margins are vegetated by papyrus (red); open water looks blue, as seen in the south-centre margin of the image.

Figure 2.22 Islands in the Okavango Delta as seen in SPOT 5 HRG sensor multispectral image, acquired on 23 November 2002 (10 m spatial resolution, band 1,2,3 [green, red, NIR] combination). White areas/spots (salt marsh) with edges vegetated by trees (red) are islands. Round-shaped red features are smaller islands.
2.5 Techniques for Measuring Elevation and Land Cover

Several methods and techniques exist to measure terrain elevation and land cover features. This study, however, is limited to techniques of measuring elevation, extraction of land cover features, and creation of (vertically accurate) improve quality DEMs through integration of remotely-measured multisource elevation data.

2.5.1 Elevation

Several methods and techniques exist to derive DEMs, depending on the technology, data and characteristics. The three main interrelated tasks in the derivation of a DEM are data capture (i.e. the reduction of real world to a finite number of discrete data values), specification of the digital representation of the topographic surface (by interpolation), and derivation of topographic attributes such as slope, aspect and drainage information from the DEM. The techniques that are used to measure elevation are stereophotography-based topographic maps, optical stereo imaging, radar interferometry, profiling altimetry, surveying and levelling, positioning systems, and integrated multiplatform elevation data. The present study uses all above techniques except topographic maps and surveying and levelling. However, for completeness a brief description of all is given below.

Topographic Maps

Topographic maps provide the traditional technique (Slocum et al., 2009) and commonly available data source for generating DEMs. These maps are derived from aerial stereophotographs using photogrammetric techniques (earlier: analogue and analytical, and now: mostly digital). The distinct characteristic of a topographic map is that the shape of the Earth’s surface is depicted by contour lines, i.e. the lines of equal elevation on the surface of the land above or below a reference surface, such as the mean sea level. The contours that provide elevation information can either be extracted through manual digitization in a GIS environment or automatically by feature extraction technique. Digital contour lines are then interpolated to create a continuous elevation surface. It is a low-cost solution; however, there are limitations in contour-derived DEMs, since they do not fully represent the topographic structure. Moreover, it requires up-to-date and accurate large-scale topographic maps, which are not available in many developing countries such as Botswana. Surveying and levelling are other methods to measure terrain elevation.

Optical Stereo Imaging

Airborne optical stereo imaging is the oldest remote sensing technology for topographic mapping (as mentioned above). With the advent of the space-era, satellite-borne stereo imaging technology has taken the lead over airborne technology in providing data for DEM generation. SPOT-1 satellite, launched in 1986, has provided the first opportunity to produce topographic maps from space on an operational basis (Gugan, 1987). Today, we have several high spatial resolution (2.5 m and better) stereo-imaging satellites such as GeoEye-1 (0.41 m), IKONOS (1 m), OrbView-3 (1 m), QuickBird-2 (0.61 m), Cartosat-1/2/2A (1 m to 2.5 m), SPOT-5 (2.5 m), and ALOS (2.5 m). The stereophotogrammetry is the means of deriving reliable topographic information from optical stereo-images. The principal task is to meticulously establish the geometric relationship between the image and the object as it existed at the time of the imaging event. Once this relationship is correctly established, we can then derive information about objects from imagery. This relationship can be established by three broadly classified techniques – analogue, analytical, and digital (Wolf and Dewitt,
Multiplatform Observations for Measuring Wetland Landscape Topography

2000; Mikhail et al., 2001). The present study focuses on analytical and digital techniques. Note, although photogrammetric technique can offer dense grid spacing and high vertical accuracy topographic information, it is expensive both in costs and labour. For a large and remote wetland in a developing country such as the Okavango Delta, it is an enormous task.

Radar Interferometry

A few radar satellites were launched during last three decades that provides data for topographic mapping using interferometric technique. Satellites such as ERS-1/2 (launched in 1991/1995), JERS (1992), Radarsat (1995), Envisat (2002) and Risat-2/1 (2009/2012) carries synthetic aperture radar (SAR) instruments, which provides interferometric (or paired) images to derive DEMs of the earth’s surface. Interferometric SAR (InSAR) technology makes use of phase-difference measurements derived from two radar images acquired with a very small base to height ratio (typically 0.0002) to measure topography (Farr et al., 2007). The biggest endeavour of creating a global medium resolution DSM (~90 m spatial resolution) using InSAR technology is the SRTM dataset (for detail see Farr and Kobrick, 2000; Farr et al., 2007). The spaceborne InSAR measurement overcomes the problem of cloud cover and is a cost-effective method for producing up-to-date and accurate topographic maps of large areas.

Profiling Altimetry

Air- and spaceborne altimetry provides an important technology for measuring and studying the Earth’s landscape topography. The altimeter can be categorised into radar and laser-based, and they provide a complementary approach to characterise the Earth’s surface.

Radar Altimetry

Radar altimetry is a profiling technique, designed to measure the vertical distance between the radar and the surface below (Raney, 2008). It provides an innovative technology in measuring along-track topographic elevations; the altimeter is mounted either on aircraft or spacecraft. The resulting ‘altitude’ is a measure of the clearance beneath the air- and spacecrafts; however, space-based radar altimetry determines the local sea level relative to the earth’s geoid (Raney, 2008). The spacecraft radar altimetry begins with the Skylab (launched in 1973) and Seasat (1978), followed by a series of spacecrafts providing centimetre level vertical measurements such as ERS-1/2 (1991/1995), Topex/Poseidon (1992), TRMM (1997), Jason-1/2 (2001/2008), Envisat (2002), Cryosat-2 (2010) and SARAL (2013). The Geological Survey of Botswana carried out an airborne geophysical survey that included a radar altimetry instrument on the Okavango Delta region (Sefofane Geophysics, 2003). From these radar measurements, a coarse resolution DSM was created.

Laser Altimetry

Laser altimetry is a recent development in remote sensing to measure accurate topographic elevations of the earth (Measures, 1992; Ritchie, 1995; Ackermann, 1999; Baltasvias, 1999b; Petzold et al., 1999; Zwally et al., 2002; Abdalati et al., 2010) and planetary bodies (Smith et al., 1998, 2001; Araki et al., 2009). The altimeter is mounted either on an aircraft or spacecraft. While airborne laser altimetry can provide high vertical and horizontal resolution data over a study site (Ritchie, 1995), spaceborne instrument provides near-global coverage of high vertical resolution data and sparse across-track and along-track samplings. The Lidar In-
space Technology Experiment (LITE, an atmospheric lidar), the first earth-orbiting spaceborne laser altimeter, was flown on the Space Shuttle Discovery (STS-64) by the NASA Langley Research Center in September 1994 (Winker et al., 1996). This was followed by the Shuttle Laser Altimeter (SLA) on the Space Shuttle Endeavour (January 1996) for range measurements of ocean, land and cloud features (Garvin et al., 1998). The Geoscience Laser Altimeter System (GLAS) was mounted on board the Ice, Cloud, and land Elevation Satellite (ICESat) for measuring global ice sheet mass balance, cloud and aerosol heights, as well as land topography and vegetation characteristics (NASA <http://icesat.gsfc.nasa.gov/> [15/04/2011]). The laser altimeter measurements of terrain surface provides accurate information on topographic properties; however, the measurements are limited by low sampling density. It is expected that the ICESat-2 mission (likely to be launched in 2016) will provide much denser samplings (Abdalati et al., 2010).

Positioning Systems

To determine the position of any point on the earth precisely led to the development of earth-orbiting satellite-based navigation system, commonly known as the GPS, developed by the United States Department of Defence in the early 1970s. A similar system was developed by Russia, known as the GLONASS (Global’naya Navigatsionnaya Sputnikovaya Sistema), and the Galileo Global Navigation Satellite System (GNSS) is underway in Europe (Misra and Enge, 2006). Here we focus on GPS (a world-wide available service), which is a constellation of at least 24 operational satellites and provides continuous positioning and timing information in all-weather situation. GPS has revolutionised the spatial positioning \((x,y,z)\) technique in terms of planimetric \((x,y)\) and vertical \((z)\) precisions, and producing centimetre-level \((x,y,z)\) accuracy. For remote a region such as the Okavango Delta, GPS measurement produces precise ground control points (GCPs), which are used for orientation of air- and spaceborne stereo-images using photogrammetric techniques to generate DEMs. In the late 1990s, the Geological Survey of Botswana carried out GPS surveys on the Okavango Delta region and measured 4003 elevation postings \((x,y,z)\) at a ~7.5 km ground distance and these postings are used to create a topographic map (Poseidon Geophysics, 1999).

Multiplatform Elevation Data

The integration (fusion and merging) of elevation data from multiple platforms acquired by diverse technologies (e.g. optical, radar, laser and GPS) can produce improved quality DEMs in regions that lack high spatial resolution and vertically accurate elevation data (e.g. Okavango Delta). However, there is no straight forward approach for DEM fusion, as elevation datasets come from disparate sources generated by different technologies with different spatial resolution and accuracy. Assessment of characteristics of the elevation datasets is needed before attempting elevation data fusion. Depending on the quality, the fusion of elevation data can be performed in the spatial or frequency domain. The quality of elevation data can be judged from their geo-positional accuracy, elevation accuracy and representation of topographic structure. The removal of erroneous elevation values from the datasets (e.g. SRTM DSM) are needed in creating topographically realistic elevation model. This study investigates multisource data integration based on 1) the Fourier transforms for noise filtering and fusion of elevation models at the frequency level and 2) merging elevation data after physiographic and land cover unit-wise calibration with higher accuracy data.
2.5.2 Land Cover

Several methods and approaches exist to map land cover from remotely sensed observations depending on the technology and characteristics of the images. Early efforts of remote sensing of land cover were based on aerial photography (civil and military) and military spy satellite photography (e.g., ARGON satellite). And land cover information were extracted by visual interpretation of photographs. This study uses optical observations; however, for completeness all techniques used for land cover extraction are briefly described. These techniques can broadly be divided into 1) optical imaging, 2) radar imaging, and 3) laser scanning and profiling. The civil satellite remote sensing of land cover began with the launch of Earth Resources Technology Satellite (ERTS) in 1972 (USA), later renamed as Landsat. This was followed by a series of Landsat, SPOT (France) and IRS (India) optical satellites. As optical sensors penetration to the earth surface is limited by clouds and night darkness, radar (active) satellites with capabilities of cloud penetration and day-and-night observation were launched (e.g., ERS and Envisat (Europe), Radarsat (Canada), JERS (Japan), and Risat (India). In recent years, airborne laser scanning and spaceborne laser profiling (e.g., ICESat) have emerged to accurately measure land cover attributes. Land cover information from aerial/space data can be extracted either by visual interpretation (traditional technique) or digital classification of images. While visual interpretation dominated the early remote sensing, semi-automatic and automatic classification has become a standard approach in current remote sensing-based land cover information extraction. Data fusion added a new dimension to optimise land cover information through combination of data from different sensors (e.g., fusion of panchromatic and multispectral images, fusion of optical and radar images). The present study uses spaceborne optical observations to investigate the performance of single-band spectral information content over multispectral information in mapping wetland land cover.

2.6 Conclusion

Observations from diverse platforms provide better understanding of the wetland topographic-biophysical characteristics and to devise approaches for measuring and modeling landscape topography. The Okavango Delta provides a challenging case to apply such observations, as understanding its landscape topographic characteristic enables us to predict the future state of its environment. The delta is characterised by its semi-arid desert location, complexity of landscapes, remoteness, and scarce and disparate datasets for landscape topographic modeling. This chapter describes landscape characteristic of the delta, highlights data acquisition techniques from multiple platforms, explores data availability for the present investigation and outlines the requirement of terrain elevation and land cover data (related to science questions formulated in Chapter 1, Section 1.4). Datasets and requirements are for three levels of investigation (at various resolution and scale): microtopography (test sites), mesotopography (regional) and water level elevation (regional). Then, it presents the techniques for measuring and modeling terrain elevation and land cover. This chapter provides an in-depth understanding of the topographic and biophysical characteristics of the Okavango Delta. It advances the understanding of the availability of data, and demonstrates the role of multiplatform observation approach, as complementary data source, for wetland landscape topographic modeling.
PART II.

Approach, Experiments and Results
Chapter 3

Multiplatform Approach:
Measuring and Modeling Landscape Topography

"Experiment is the sole source of truth. It alone can teach us something new; it alone can give us certainty."

– Henri Poincaré (1854–1912)

This chapter devises a multiplatform experimental approach to measure wetland landscape topography: 1) measure and model topography, 2) map land cover, 3) assess elevation data accuracy, and 4) improve elevation modeling. In Chapters 4-7, these aspects are implemented to achieve the objectives of the research.

Keywords: Multiplatform; remote observation; remote measurement; landscape topography; elevation modeling; DEM; water surface elevation; land cover; elevation error; reference data; accuracy assessment; model improvement; integrated elevation model; error budgets; wetland.

3.1 Overview

Purpose: This study used observations from a suite of instruments on multiple platforms (terrestrial, aerial and space) to measure elevation and construct variable resolution topographic models of wetland landscapes and assesses their vertical accuracy. Then, the study integrates elevation data through fusion and merging to produce vertically improved models considering land cover as a determinant of elevation data accuracy and model bias. The main goal was to create topographic model scenarios and then produce improved quality models on the Okavango Delta. As no single dataset provides an optimal solution to achieve the goal, we devised a multiplatform approach whereby diverse sets of observations are used. Observations used are: 1) global datasets (i.e. all elevation datasets used) for measuring topography, 2) reference datasets (i.e. independent higher accuracy elevation datasets) for elevation data accuracy assessment and validation, and 3) determinant dataset (i.e. land cover dataset as a control) for elevation data accuracy assessment and bias calibration.

Global Datasets: They are elevation datasets (local and regional levels) at various resolutions and levels of accuracy (for details see Chapter 2, Section 2.4.2). For convenience, datasets for various products are briefly mentioned:

1) Microtopography (test site) – airborne and spaceborne (IKONOS) optical stereo-images (Maunachira and Jao test sites, respectively); GPS ground controls for geo-referencing and rectification of stereo-models.
2) Mesotopography (regional) – GPS measurements (GCPs and postings), and observations from airborne profiling radar, spaceborne imaging radar (SRTM), spaceborne optical stereo-imaging (ASTER). GPS GCPs and GPS-based rectified aerial and satellite images (IKONOS, SPOT 5 and Landsat 7 panchromatic images) for geo-referencing air- and spaceborne radar, and spaceborne optical stereo-imaging data (Appendix IX).

3) Water surface topography (regional) – airborne profiling and spaceborne imaging radar, and spaceborne profiling laser (ICESat).

4) Integrated topography – a) fused models (test site): (i) air- and spaceborne radar, and (ii) spaceborne imaging radar and GPS-based model, i.e. MDEM (a micro-DEM created by Gumbricht et al., 2005). Airborne stereo-photogrammetric DEM to assess the vertical accuracy of fused models; b) merged elevation data (regional) – spaceborne imaging radar, spaceborne optical stereo imaging, spaceborne profiling laser, spaceborne profiling radar (CryoSat), and GPS measurements. Spaceborne laser for calibration of elevation bias, and GPS GCPs/postings for validation of integrated models.

Reference/Validation Datasets: For assessing vertical accuracy of elevation models constructed from global datasets, the following higher quality elevation datasets are used: 1) GPS measurements (test site GCPs and regional postings) 2) airborne stereo-photogrammetric DEM (test site), and 3) spaceborne profiling laser measurements (regional).

Determinant Dataset: Land cover (e.g. vegetation) produces measurement bias in elevation data by spaceborne sensors. The land cover-dependent bias needed to be corrected before use. Thus, land cover forms an important determinant of elevation data accuracy, and calibration of spaceborne radar and optical stereo elevation models. Spaceborne optical multispectral images are used for mapping land cover at the regional level and at test sites. For geo-referencing of satellite images, GPS GCPs and GPS-based rectified high spatial resolution satellite images were used. A delta water surface extent (mask) was also derived from spaceborne optical mid-infrared (MIR) observations.

3.2 Multiplatform Approach

The multiplatform approach comprises six steps and they were implemented during the research (Table 3.1, Figure 3.1). These steps are briefly stated in this chapter and described in

<table>
<thead>
<tr>
<th>Steps</th>
<th>Experiments</th>
<th>Chapters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><em>Measuring</em> and <em>modeling</em> micro- and mesotopography</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td><em>Mapping</em> land cover (as a determinant of elevation data accuracy and bias calibration)</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td><em>Establishing</em> reference/validation elevation datasets</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td><em>Assessing</em> elevation data accuracy</td>
<td>6 &amp; 7</td>
</tr>
<tr>
<td>5</td>
<td><em>Integrating</em> elevation data to improve quality of topographic modeling</td>
<td>7</td>
</tr>
<tr>
<td>6</td>
<td><em>Mapping</em> error budgets of elevation datasets</td>
<td>8</td>
</tr>
</tbody>
</table>
Figure 3.1 The multiplatform approach to wetland landscape topographic modeling (with steps, in numbers). The details about data from various platforms are given in Section 3.1 (this chapter) and Chapter 2 (Section 2.4.2 and Table 2.2). Table 3.2 presented the production methods and technology for topographic modeling, while Table 3.3 characterised the terminologies used in this multiplatform approach.
Chapters 4-8. Table 3.2 illustrates the methods and technology for measuring and modeling wetland topography from various platform observations at local and regional levels. The products are micro- and mesotopographic models, water surface mask and land cover map. A schematic design of the multiplatform experimental protocol is presented in Figure 3.1. The approach involves a series of steps to derive required information from data, i.e. elevation models from multiple platform observations. Table 3.3 characterizes the terminologies used in the multiplatform approach to landscape topographic modeling (Table 3.1 and Figure 3.1).

Table 3.2 Production methods and technology for landscape topographic modeling.

<table>
<thead>
<tr>
<th>Spatial level</th>
<th>Products</th>
<th>Production method and technology</th>
<th>Product description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local</td>
<td>Elevation models</td>
<td>Stereo-photogrammetry</td>
<td>Microtopography (Test sites: Maunachira &amp; Jao)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fusion of remotely-measured elevation data</td>
<td>Microtopography (Test site 1: Maunachira)</td>
</tr>
<tr>
<td></td>
<td>Land cover map</td>
<td>Image classification</td>
<td>Major land cover types (Test site 2: Jao)</td>
</tr>
<tr>
<td>Regional</td>
<td>Elevation models</td>
<td>GPS GCP/posting survey</td>
<td>Mesotopography at an increasing spatial resolution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Airborne profiling radar</td>
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<td></td>
<td></td>
<td>Spaceborne imaging radar</td>
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<td></td>
<td>Spaceborne optical stereo</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Land cover map</td>
<td>Image classification</td>
<td>Wetlands-nonwetlands</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Major land cover types</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Water surface mask</td>
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<tr>
<td></td>
<td>Water surface elevation models</td>
<td>Spaceborne imaging radar</td>
<td>Water surface mesotopography</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Spaceborne profiling laser</td>
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<tr>
<td></td>
<td>Improved elevation models</td>
<td>Merging multiplatform elevation data</td>
<td>Improved mesotopography</td>
</tr>
</tbody>
</table>
### Table 3.3 Characterisation of terminologies used in the multiplatform approach to landscape topographic modeling.

<table>
<thead>
<tr>
<th>Terms</th>
<th>Characterisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Topography</td>
<td>Elevation data/models representing the landscape in three dimensions (x,y,z coordinates), e.g. GPS GCPs, laser footprints and DEMs.</td>
</tr>
<tr>
<td>Microtopography</td>
<td>Elevation model with horizontal resolution 10 m and higher, e.g. stereo-photogrammetric elevation model (test sites).</td>
</tr>
<tr>
<td>Mesotopography</td>
<td>Elevation model with horizontal resolution &gt;10 m to 100 m, e.g. C-radar and ASTER DSMs (delta region).</td>
</tr>
<tr>
<td>Water surface</td>
<td>Water level elevation model with horizontal resolution 30 m, e.g. C-radar and laser water surface elevation (WSE) (delta).</td>
</tr>
<tr>
<td>DSM</td>
<td>Elevation model with measurements on bare earth and top of surface objects (trees and man-made structures).</td>
</tr>
<tr>
<td>DEM</td>
<td>Elevation model representing measurements on bare earth.</td>
</tr>
<tr>
<td>2) Land cover</td>
<td>Biophysical features that describe the dominant observable objects or structures present on the surface such as vegetation and man-made structures.</td>
</tr>
<tr>
<td>Determinant</td>
<td>A (land cover) biophysical parameter to determine the outcome in elevation data accuracy assessment and calibration.</td>
</tr>
<tr>
<td>3) Reference data</td>
<td>Elevation data with higher accuracy (horizontal and vertical) for evaluation of elevation data/models, e.g. GPS measurements.</td>
</tr>
<tr>
<td>4) Elevation error</td>
<td>Discrepancies in vertical accuracy of elevation data/models from the reference data.</td>
</tr>
<tr>
<td>Assessment</td>
<td>Evaluation of vertical accuracy of elevation data/models with reference data.</td>
</tr>
<tr>
<td>5) Integration of elevation data</td>
<td>Combining disparate elevation data/models to produce vertically improved elevation models, e.g. fusing air-and spaceborne radar elevation.</td>
</tr>
<tr>
<td>Fusion</td>
<td>Combining elevation models in the frequency domain.</td>
</tr>
<tr>
<td>Merging</td>
<td>Combining elevation data with calibration information (offset or measurement bias) and from multiple sources, and land cover as determinants.</td>
</tr>
<tr>
<td>6) Error budget</td>
<td>Final statistical outcome of measured and constructed models, as evaluated with reference data.</td>
</tr>
</tbody>
</table>

### 3.3 Landscape Topography

#### 3.3.1 Constructing Elevation Models

The study measures topography at two levels (Chapter 4): 1) local microtopographic models from optical stereo-observations (high spatial resolution), 2) regional mesotopographic
models from positioning, profiling and imaging radar, and optical stereo observations (medium spatial resolution); and water surface elevation from imaging radar and laser altimetry observations.

**Microtopography**

*Airborne Optical Stereo Imaging*: A test site (Site 1, Maunachira), a mixed permanent and seasonal swamp, was selected in the Okavango Delta and aerial stereo-images were acquired. A GPS field campaign was carried out for measuring ground control points (GCPs) (Talukdar, 2003), which are used to set-up and orient the stereo-model in the analytical photogrammetric plotter. A profiling method was used to measure terrain elevations on the stereo-model; additional elevations are measured as breakline on channels and islands. These profile and breakline postings are interpolated to construct a micro-topographic model (Section 4.2.1).

*Spaceborne Optical Stereo Imaging*: A test site (Site 2, Jao) was selected in the permanent swamp of the delta to construct a micro-topographic model from spaceborne stereo-observations. GPS GCPs are acquired by field campaign (Talukdar, 2003) and they were used to set-up and orient the stereo-model in the digital photogrammetric system. After pre-processing of stereo-images, an image matching algorithm (Zhang and Gruen, 2004) was used to generate elevation data from the stereo-model and a high spatial resolution microtopographic surface model was constructed. The resulted surface model was filtered to remove erroneous elevation points (Section 4.2.2).

**Mesotopography**

The Okavango wetland and surrounding areas form the regional study site to construct topographic models at a medium spatial resolution from GPS, airborne profiling and spaceborne imaging radar, and spaceborne optical stereo observations.

*Global Positioning System*: Two sets of GPS data were used: 1) existing surveys (Section 2.4.2) and 2) ETZ field campaign (Talukdar, 2003). These terrain elevation postings were evaluated through visualization and statistical analysis, and erroneous points were removed. Then, these points were interpolated to construct a medium spatial resolution (100 m) topographic model of the delta (Section 4.3.1).

*Airborne Profiling Radar*: This dataset was acquired from existing geophysical surveys that carried a profiling radar instrument, and converted into a grid-based model at 50 m resolution. The model was evaluated through visualization and then filtered in the frequency domain to remove erroneous elevation values (Section 4.3.2).

*Spaceborne Imaging Radar*: This dataset (SRTM C-radar) was acquired from NASA Jet Propulsion Laboratory (JPL) site and mosaicked into a regional DSM. The voids in the dataset were filled by elevations from airborne radar model, and on smaller voids through interpolation using surrounding pixels (see Figure 4.17, Section 4.3.3). The DSM was resampled to a 30 m grid from the original 90 m to make the dataset compatible with other elevation (e.g. ASTER DSM with 30 m resolution) and image datasets (Landsat 7 multispectral, 30 m resolution). Finally, the model was filtered in the frequency domain to remove and reduce erroneous values (Section 4.3.3).

*Spaceborne Optical Stereo Imaging*: This dataset (ASTER DSM V2) was acquired from NASA JPL site and mosaicked into a regional DSM. The data anomalies were corrected by
visualization of the model, and finally filtered in the frequency domain to remove erroneous values (Section 4.3.4).

**Water Surface Topography**

To construct water surface topography (WST) on the delta airborne profiling radar, spaceborne imaging radar, and spaceborne profiling laser observations are used.

*Spaceborne Imaging Radar:* The SRTM C-radar dataset over the delta water-wetland surface was extracted using a Landsat 7 multispectral image-derived water-wetland mask (Section 5.5.1). Voids in the dataset were removed (Section 4.3.3) and the water surface topographic model was created with a radar-optical approach (Section 4.4.1) (see preceding section about SRTM data).

*Spaceborne Profiling Laser:* The multi-temporal profiling laser data were acquired from the National Snow and Ice Data Center, University of Colorado, Boulder (personal request). These datasets were thoroughly checked and outliers removed (Section 4.4.2). Landsat 7 multispectral image-derived water surface mask (Section 6.5.1) was used to extract water area laser elevations. Then, the water surface elevation and elevation changes were estimated with a laser-optical approach (Section 4.4.2).

The qualities of measured and constructed models were assessed with higher accuracy reference data (Chapter 6). This experimental step addresses the science question 1 (Chapter 1): What is the advantage of a multiplatform observation approach to measure and construct landscape topographic models in a wetland environment?

### 3.3.2 Mapping Land Cover

This part was designed to map wetland land cover at the regional level and at a test site (Chapter 5). Landsat 7 multispectral image of wetland area was masked (as main focus of the study) from the mosaicicked image on the delta. Then, an attempt was made to demonstrate the role of single-band optical observations (e.g., Landsat 7 MIR) over multi-bands in deriving required wetland land cover type data. These data products serve as determinants of elevation data accuracy (Chapters 6 & 7) and model bias calibration (Chapter 7). Elevation data products were assessed using higher accuracy reference data relative to land cover, while elevation data/model calibration was done to correct land cover-dependent bias in elevation measurements. A water surface mask of the delta was derived from Landsat 7 multispectral image, and the product was used as 1) a mask for extracting water surface elevation from spaceborne radar and laser observations (Chapter 4), and 2) assessing the vertical accuracy of water elevation data (Chapter 6).

*Regional Level:* To map land cover at the regional level (Section 5.5.1), spaceborne optical images (Landsat 7) were acquired, and georeferenced using test site GPS ground controls (Section 2.4.2) and GPS-based rectified higher spatial resolution satellite images (Appendix IX). Three categories of land cover data were extracted from Landsat 7 multispectral observations (Section 5.5.1): 1) wetland mask that separates wetlands from non-wetlands, 2) major land cover types, and 3) delta water-wetland and open water surfaces.

*Test Site:* To map land cover of a test site (Section 5.5.2) a spaceborne optical image was acquired and georeferenced using GPS ground controls (Appendix IX). The rectified multispectral image of IKONOS (by GPS ground controls and GPS-based rectified IKONOS
panchromatic image) was classified into major land cover types using an unsupervised classification approach (Section 5.5.2).

This step addresses the science question 2: How significant is single-channel spectral information content (e.g. Landsat 7 mid-infrared) compared to multispectral observations for mapping wetland land cover?

3.3.3 Establishing Reference Elevation Datasets

The reference (or true) elevation datasets were selected based on the vertical accuracy and data availability, and they are used to evaluate the constructed elevation models (Chapters 4 & 7). The main reference data are GPS measurements: 1) GCPs of three test sites in the Okavango Delta and 2) sparse regional postings on the whole delta. The vertical accuracy of GPS GCPs is ~0.16 m, while vertical accuracy of postings is ~0.15 m (Section 2.4.2). Since GPS postings are sparse, although well-distributed, two additional reference datasets are established using GPS as reference. They are: 1) airborne optical stereo-photogrammetric DEM (Test site 1) measured by analytical stereo-photogrammetry, and 2) spaceborne laser altimetry measurements. These datasets were compared against GPS to establish their vertical accuracy, which resulted in ~1 m (RMSE) for airborne stereo-photogrammetric DEM and 1.2 m (RMSE) for spaceborne laser altimetry (Section 6.2.3). The stereo-photogrammetric DEM provided detailed topographic information, while laser footprints provided sparse but large samples (about 100 times than the GPS samples) over the delta region.

3.3.4 Assessing Elevation Data Accuracy

The topographic models (Chapters 4 and 7) were evaluated using reference elevation data (Table 3.4). These assessments were carried out at local microtopography, regional mesotopography and water surface levels (Chapters 6), and integrated local microtopography and regional mesotopography levels (Chapter 7).

**Microtopographic Model:** The vertical accuracy of optical models (Test sites 1 & 2) was assessed by GPS measurements (Sections 6.2.3 & 6.3).

**Mesotopographic Models:** The vertical accuracies of GPS-based model was assessed using independent GPS measurements (Section 6.4.1), airborne profiling radar model by GPS measurements (relative to physiographic regions) (Section 6.4.2), and spaceborne imaging radar and spaceborne optical stereo models were assessed using GPS and profiling laser observations (Sections 6.4.3 and 6.4.4, respectively). Spaceborne imaging radar model was assessed relative to physiographic regions and land cover types. The vertical accuracies of spaceborne imaging radar and optical stereo models were assessed with profiling laser observations because laser measurements provided a large number of samples compared to GPS.

**Water Surface Elevation:** The water surface elevations from airborne profiling and spaceborne imaging radar, and spaceborne profiling laser observations were assessed using GPS measurements (Section 6.5). Airborne profiling water level was assessed along the main channels while imaging radar water level was assessed along the main channels and on the delta water surface. The profiling laser water level was assessed on the delta water surface.
Table 3.4 Elevation data products and reference data for accuracy assessment.

<table>
<thead>
<tr>
<th>Elevation products</th>
<th>Reference data</th>
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<tbody>
<tr>
<td>Microtopography</td>
<td></td>
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<tr>
<td><em>Airborne optical stereo</em></td>
<td>GPS GCPs</td>
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<tr>
<td><em>Spaceborne optical stereo</em></td>
<td>GPS GCPs</td>
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<tr>
<td>Mesotopography</td>
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<tr>
<td><em>Global positioning system</em></td>
<td>GPS GCPs</td>
</tr>
<tr>
<td><em>Airborne profiling radar</em></td>
<td>GPS postings</td>
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<tr>
<td><em>Spaceborne imaging radar</em></td>
<td>GPS postings, laser footprints</td>
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<tr>
<td><em>Spaceborne optical stereo</em></td>
<td>GPS postings, laser footprints</td>
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<tr>
<td>Water surface elevation</td>
<td></td>
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<tr>
<td><em>Air and spaceborne radar</em></td>
<td>GPS postings</td>
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<tr>
<td><em>Spaceborne laser</em></td>
<td>GPS postings</td>
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<tr>
<td>Integrated models</td>
<td></td>
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<tr>
<td><em>Fused models</em></td>
<td>Photogrammetric DEM</td>
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<tr>
<td><em>Merged data/models</em></td>
<td>GPS GCPS/postings</td>
</tr>
</tbody>
</table>

**Integrated Models:** The vertical accuracy of constructed integrated (fused and merged) models was assessed using higher quality reference data. The quality of fused models: 1) fused airborne and spaceborne radar model and 2) fused spaceborne radar and GPS-based model was assessed using airborne optical stereo-photogrammetric DEM. The quality of the merged models: 1) merged imaging radar and profiling laser, 2) merged optical stereo and profiling laser, 3) merged profiling radar and laser, and 4) merged profiling laser and radar and GPS was assessed by independent GPS measurements (Section 7.4).

This step addresses the question 3: To what extent does physiography and land cover acts as a determinant of vertical errors in elevation data (e.g. SRTM DSM)?

### 3.3.5 Integrating Elevation Observations

Approaches and methods to integrate elevation data were investigated to improve the wetland topographic modeling with remotely-measured multi-source elevation datasets (Chapter 7). Two approaches were used based on the availability of appropriate datasets and their characteristics: 1) frequency domain fusion of elevation data at a test site, and 2) merging elevation data through bias calibration at the regional level.

**Fusion of Elevation Data:** The data used for fusion (Test site 1) are airborne and spaceborne radar models, and GPS-based model (MDEM). The fusion was carried out in the frequency domain using two sets of data: 1) airborne and spaceborne radar models, and 2) spaceborne radar and MDEM models (Section 7.2). Airborne optical stereo-photogrammetric DEM was used to assess the vertical accuracy of fused models.

**Merging Elevation Data:** The datasets used for merging are spaceborne imaging radar and optical stereo, spaceborne profiling laser and radar, and GPS at the regional (delta) level. To calibrate elevation bias in imaging radar and optical stereo models and profiling radar observations, laser observations were used. The elevation bias in profiling radar and laser data
was calibrated by GPS. The bias in imaging radar model was calibrated at three spatial levels (delta, wetland and land cover; land cover data derived from Landsat 7 multispectral image). The merged models comprise: 1) imaging radar and profiling laser, 2) optical stereo and profiling laser, 3) profiling radar and laser, and 4) profiling laser and radar and GPS (Section 7.3). Independent GPS measurements were used for evaluation of merged models.

This step addresses two science questions: 4) How far does integration (fusion and merging) of multisource elevation data increases accuracy and reliability of elevation models? and 5) To what extent does bias calibration in elevation data (e.g. SRTM and ASTER DSMs) improve vertical accuracy?

3.3.6 Mapping Error Budgets
The state of error budget of elevation datasets (of Chapters 4 and 7) was created to provide alternate scenarios. This part describes the error budgets of elevation datasets at a test site and at regional levels (see detail in Chapter 8, Section 8.1.6).

**Microtopography:** The error budgets of test site elevation data products were analysed. The data products are air and spaceborne optical stereo models.

**Mesotopography:** The error budgets and trends of error in elevation data products were presented and statistically analysed. The mesotopographic data products are spaceborne imaging radar, merged imaging and profiling laser, optical stereo imaging, merged optical stereo imaging and profiling laser, positioning system, integrated profiling laser and radar, and integrated profiling laser & radar and positioning system models.

**Water Surface Mesotopography:** The error budgets on water surface elevation products were presented and analysed. The data products are airborne profiling radar and spaceborne profiling laser water elevation, and spaceborne imaging radar water surface model.

3.4 Conclusion
The experimental steps presented here enables measuring and modeling wetland landscape topography from diverse platform observations. The multiplatform approach leads to the construction of 1) high spatial resolution microtopographic models (test sites) from air- and spaceborne optical stereo-observations using photogrammetric technique, 2) mesotopographic models (regional) from GPS measurements, profiling and imaging radar, and optical stereo imaging observations, and 3) water surface mesotopographic models from imaging radar and water surface elevation from profiling and imaging radar and profiling laser observations. Assessment of these elevation data/models was done by higher accuracy reference elevation data. Appropriate (measured/constructed and available) elevation datasets were fused and merged to produce vertically improved topographic models at the local and regional levels and finally, error budgets of elevation data products are mapped. The approach developed here provides a comprehensive design to measure landscape topography in general and wetland topography in particular, which can be applied in other situations, regionally and globally.
Chapter 4

Measuring and Modeling Landscape Topography

Measure what is measurable, and make measurable what is not so.
– Galileo Galilei (1564-1642)

This chapter measures and constructs topographic models from various platform observations on contrasting physiographic and wetland landscapes. Optical stereo imaging-based micro- and mesotopographic models, and GPS, profiling and imaging radar-based mesotopographic models are presented. Imaging radar (SRTM) and optical stereo-imaging (ASTER) elevation models are presented in detail, as they provide consistent coverage over the study region. Finally, radar and laser-based water surface elevations are presented.

Keywords: Multiplatform; remote observation; landscape topography; elevation modeling; optical stereo-imaging; photogrammetry; global positioning system; profiling radar; imaging radar; profiling laser; microtopography; mesotopography; water surface topography; model characterization.

4.1 Measuring and Modeling Elevation

The earth’s landscapes are too complex to be measured and modeled analytically, thus the information is most often recorded as samples. There are several well-established techniques for measuring samples of surface position (either discrete or continuous) in remotely sensed/measured observations or on the ground to create landscape topographic models. Topography is defined in terms of terrain elevation (i.e. DEM), which is an important product to derive several primary attributes such as slope, aspect and drainage. DEMs form the three dimensional (3D) representation (elevation matrix) of the terrain surface, where the elevation \( z \) is defined by \( z = f(x,y) \), where \( x \) and \( y \) are spatial coordinates (e.g. in a UTM projection, \( x \) and \( y \) are the easting and northing components, in meters). Digital elevation modeling was first introduced in the 1950s (Miller, 1958; Miller and Laflamme, 1958) and the field has advanced significantly during the last few decades. DEMs are increasingly used by scientists and engineers for mapping the earth (USGS, 1993; Ackermann, 1994, 1996; Lohr, 1998; Mikhail et al., 2001; Maune, 2007) and planetary surfaces (Smith et al., 1998, 1999, 2001; Parker and Curry, 2001; Araki et al., 2009), and for mathematical analysis of landscapes (Zevenbergen and Thorne, 1987; Lane et al., 1998; Pike, 2000; Wilson, and Gallant, 2000; Hengl and Reuter, 2009; Florinsky, 2012). The earth’s topography is an essential constraint and boundary condition in hydrologic models of flooding and runoff to atmospheric boundary layer friction theories (Farr et al., 2007). Topography defines the effects of gravity on the movement of water in a watershed, and therefore it influences many aspects of the hydrologic system (Wolock and Price, 1994). Accurate and reliable DEMs provide vital information to
model landscape processes and for improved representation of landscapes, e.g. channel networks, catchment areas, and other hydrological aspects. The resolution (horizontal and vertical) of data points sampled is fundamental in determining the usefulness of a DEM. Available DEMs often have insufficient resolution and vertical accuracies for the applications they are used for. In a developing country like Botswana, this issue is significant due to the lack of high resolution and accurate DEM over the Okavango Delta (see review Chapter 1, Section 1.3). Elevation data at a higher quality than currently available could provide critical information to understand the dynamics of the delta.

Observations from various platforms are being used to produce digital elevation data. However, in many areas single platform observations are inadequate to construct high spatial resolution and vertically accurate elevation models. A multiplatform observation approach has been developed to produce variable scale and resolution elevation models on the Okavango Delta (see Section 3.2, Chapter 3). This research attempts to measure and construct DEMs at two scales: microtopography of test sites and mesotopography of the Okavango Delta (Figure 4.1), a gently-sloping alluvial fan in the Okavango River basin (Figure 4.2). Elevation modeling of test sites demonstrates the potential of photogrammetric techniques in creating microtopography from aerial and spaceborne optical stereo-observations. Regional modeling tries to create alternate scenarios of topographic models from sparse GPS postings, airborne profiling radar, spaceborne imaging radar and spaceborne optical stereo-imaging derived elevation data at an increasing spatial resolution. Further, this study attempts to measure the delta water surface elevation from spaceborne imaging radar and laser altimetry observations (Figure 4.1). The goal of elevation modeling at various resolutions is to advance the scientific understanding of wetland topography, especially the Okavango wetland. This is essential for assessing the impact on the Okavango Delta water resources because of

![Figure 4.1 Outline of a multiplatform approach for measuring and modeling wetland landscape topography. Datasets are defined as:](image)

- Spaceborne optical stereo = IKONOS
- Airborne profiling radar = AGS
- Spaceborne imaging radar = SRTM
- Spaceborne optical stereo imaging = ASTER
- Spaceborne profiling laser = ICESat

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Figure 4.1 Outline of a multiplatform approach for measuring and modeling wetland landscape topography. Datasets are defined as:
abstraction, evapotranspiration, land use/land cover and climate changes. This chapter addresses the science question (of Chapter 1): What is the advantage of a multiplatform observation approach to measure and construct landscape topographic models of a wetland environment? The following sections deal with measuring elevations and constructing micro- and mesotopographic and water surface elevation models.

Figure 4.2 Topography of the Okavango River Basin measured by the SRTM C-radar (3 arc-sec grid [-90 m]). The image covers an area of 1404 km x 1404 km (between 12° S to 25° S latitudes and 15.5° E to 28.5° E longitudes). This US Geological Survey hydrologically conditioned elevation surface is produced by iterative conditioning and correction process (see details in Lehner et al., 2006). The Okavango basin boundary (in blue) is adapted from the HydroSHEDS data; the basin covers 692,220 km² area (Elevation and basin data source: http://hydrosheds.cr.usgs.gov/index.php). National boundary (in black) data source: U.S. Department of State, Humanitarian Information Unit (https://hiu.state.gov/data/data.aspx).
4.2 Microtopography

A finer resolution elevation model accurately represents topographic parameters (e.g. elevation, slope, and aspect) and consequently contains higher topographic information content. The resolution requirement is, however, a function of topographic variability of the landscape. The landscape processes in a wetland environment occur at finer-scales and produces short-wavelength topography. Thus, it requires a high resolution DEM (both horizontally and vertically) to derive topographic parameters. This section describes measurement and modeling of microtopography (of test sites) from air- and spaceborne optical stereo-observations (Figure 4.1) using photogrammetry.

4.2.1 Airborne Optical Stereo Imaging

This section measures an elevation model of the Maunachira test site from airborne stereo-panchromatic observations using analytical photogrammetry (see Chapter 2, Section 2.4.2 and Appendix I for details about data).

Data and Method

An airborne stereo image pair (about 60% overlap) of the Maunachira test site in the Okavango Delta was used to derive a high resolution DEM. The site is located (upper-left X,Y: 732584 E, 7888831 N and lower-right X,Y: 738868 E, 7878231 N) in the north-eastern part of the delta (see Chapter 2, Figure 2.17) and is characterised by seasonal swamps. The stereo image (Figure 4.3) shows the physiographic characteristics of the site, as acquired from an aerial platform in 1991. The site comprises diverse landscape features such as open water, lagoons, swamp, and land-vegetation.

Figure 4.3 Airborne stereo-image pair (024/023 [scanned diapositives]) of Maunachira test site in the Okavango Delta, acquired on 29 August 1991 (1:50000 scale). The image (spatial resolution 0.76 m) comprises open water/lagoons (dark), swamp (gray), and land-vegetation (gray-white). The stereo-model (overlapping image area) is within white lines.
Digital and analytical photogrammetric techniques were used to generate wetland elevation models from aerial stereo images. Photogrammetry is a fast and relatively cost-effective way to generate DEMs and it provides reliable geometric measurement. First, an attempt was made to generate a DEM with a digital photogrammetric technique. Poor image texture resulted in poor image matching, and consequently the digital photogrammetric system (VirtuZo software, Supersoft Inc.) failed to produce reliable elevation measurements. For automatic (or digital) DSM/DTM generation through image matching, a number of approaches have been developed. The performance of image matchers, however, has not achieved the quality of manual DSM/DTM measurement (Gruen et al., 2000). However, progress has been made during the last decade, also in combination with digital aerial cameras. A classical analytical photogrammetric approach was used to measure the elevation postings (on the stereo-model) using WILD AVIOLYT AC3 analytical plotter and AVIOSOFT photogrammetric software (DIO program for creating, editing, and output of the control points and camera calibration files; ORI program for orientation of the pairs of stereophotographs (diapositives at 1:50,000 scale); and DTM program for the data acquisition for digital elevation models). The advantage of the analytical technique in digital terrain model (DTM) generation is that exact ground elevation can be measured with a floating mark method by careful selection of points, avoiding canopies and other obstructions. To set up the model in the analytical plotter, three tasks were performed: the inner, relative and absolute orientations. For absolute orientation of the model, aerotriangulation was done manually on the analytical plotter using AVIOSOFT ATP software to measure tie points (following the von Gruber scheme [von Gruber, 1932]) and control points in the aerial images. The model was orientated using 15 control points: five GPS GCPs and 10 tie points from results of block adjustment done with the PATB program (a program for block adjustment). Control points were in UTM Zone 34 S, Clarke 1880 ellipsoid and Cape datum reference system. The AVIOSOFT DTM software was used to measure elevation points on the oriented stereo-model. The elevation postings were measured in parallel profile mode with a profile distance of 100 m and point distance of ~100 m on the ground. Additionally, channels and islands features were measured and incorporated as breaklines to improve the data structure and topographic representation. The model comprises 68 profiles and roughly 80 elevation points per profile that resulted in 6724 points, plus 904 break points of channels and islands. As the DEM resolution determines the level of details of the surface, the measured elevation points (including break points) were interpolated to a regular grid model using the DTMZ software (based on bilinear finite elements method) developed by the Institute of Geodesy and Photogrammetry (IGP, ETHZ). Spatial interpolation was needed to estimate elevation values at unknown locations using the measured elevation points.

Results and Discussion

Figure 4.4 presents the analytical stereo-photogrammetry measured elevation points \((x,y,z)\) of the Maunachira site. These points were interpolated to construct an elevation model with high spatial resolution (5 m). Figure 4.5 shows the Maunachira test site DEM, which covers an area of 8 km x 6.8 km with 15 m height deviations. The elevation ranges from 947 m to 962 m above msl; the average elevation is 952.44 m with a local relief of 2 m \((\sigma)\). Visual inspection of the elevation model (Figure 4.5) and contour patterns and shapes (Figure 4.6) shows realistic representation of topographic structure; even small morphological features (e.g. island sizes and shapes) are recognizable. The vertical accuracy of the model is evaluated in Chapter 6 (Section 6.2). The elevation points were interpolated to a 5 m grid using the DTMZ software for representation of micro-topographic structure. High spatial resolution is also needed to derive topographic attributes such as the slope and aspect. Several authors
Figure 4.4 Airborne stereo-photogrammetry measured elevation points over Maunachira site in the Okavango Delta (~100 m sample distance, along north-south profile and across profile).

Figure 4.5 Airborne stereo-photogrammetry derived micro-DEM of the Maunachira site in the Okavango Delta (5 m spatial resolution). [Orange/white = islands/land areas, blue = water and swamps]. The model covers an area of 8 km x 6.8 km (~55 km²).
found the sensitivity of estimated topographic attributes to DEM spatial resolution (Zhang and Montgomery, 1994; Garbrecht and Martz, 1994; Band and Moore, 1995; Florinsky, 1998). Figure 4.6 presents the contour map of this model, which revealed 3D landscape topography and its structure. This analytical photogrammetry-generated elevation model, for the first time, provided understanding of the detailed landscape microtopography in the Okavango Delta. It will be a base for future research on wetland microtopographic modeling and wetland landscape processes in general, and the Okavango wetland in particular.

**Figure 4.6** Contours derived from airborne stereo-photogrammetry generated micro-DEM, Maunachira site. Contour color (1 m interval) shows the elevation that represent topographic features. The range of elevation (minimum and maximum) differs from the Figure 4.4 model as edges are removed.

### 4.2.2 Spaceborne Optical Stereo Imaging

This section measures an elevation model from high resolution stereo-panchromatic observations, acquired by the IKONOS satellite, using digital photogrammetry (see Chapter 2, Section 2.4.2 and Appendix II for details).

**Data and Method**

The IKONOS stereo-image pair of the Jao test site is located (upper-left X,Y: 654142 E, 7898518 N and lower-right X,Y: 659642 E, 7889278 N) in the mouth of the panhandle when it is spreading into the wetland (see Chapter 2, Figure 2.19). Figure 4.7 shows the physiographic characteristics of the site, as observed from the IKONOS platform on 11
October 2003. The site comprises permanent swamps, two major islands (Xhamogo and Geranendi) and numerous smaller islands. The white patches in the islands are salt crusts.

To improve the radiometric quality and optimize the images for subsequent processing, a series of filters were applied to the IKONOS stereo-images (11 bit). The preprocessing comprises noise reduction, contrast and edge enhancement. The purpose of noise reduction filter was to reduce noise and sharpening edges in the image. After reducing noise, a Wallis filter (Wallis, 1974) was applied on each individual image to enhance the contrast of stereo-pair images and equalize the radiometric differences between the imagery. The Wallis filter performs a non-linear, locally adaptive contrast enhancement that results in a good local contrast throughout the image and normalizes the radiometry between the images (Baltsavias, 1991).

![Figure 4.7 IKONOS panchromatic image of Jao test site in the Okavango Delta, acquired on 11 October 2003 (1 m spatial resolution). Image area is 9.24 km x 5.5 km (~51 km^2) and comprises swamp (gray-dark), islands/land vegetation (gray-white) and salt crusts (white). (See IKONOS multispectral image of the area in Chapter 5, Section 5.5.2).](image)

The stereo-images were orientated with six GPS measured GCPs; the orientation accuracy was about 0.43 m for planimetry and 0.58 m for elevation. The elevation data were generated using an image matching algorithm (Zhang and Gruen, 2004). The matching was done using cross-correlation in image pyramids, and a DSM (5 m grid) was derived from the matched mass points and the edges (Figure 4.8). Note, a DSM presents elevation at the top of
objects on the ground, i.e. the highest reflective surface captured by the sensor (NDEP, 2004). Generally, several problems occur in automated DSM/DTM generation such as absence of sufficient texture, distinct object discontinuities, local object patch not being planar, repetitive objects, occlusions, moving objects including shadows, multi-layered and transparent objects, radiometric artifacts including specular reflections, and reduction from DSM to DTM (Zhang and Gruen, 2004). Because of complexity and near-flat topography of the Okavango wetland and consequent poor image texture, additional challenges were faced in automatic generation of the DSM. For improving the DSM quality (vertical accuracy), filtering was essential to reduce erroneous elevation values, and thereby improving the geomorphic resemblance of the model.

![Figure 4.8 IKONOS stereo-image based digital photogrammetry derived elevation model of Jao site (5 m spatial resolution). The elevation ranges from 960 m to 1007 m, with an average height of 973 m.](image)

Erroneous values are height points much higher than their surrounding pixels, which result from the measurement of high objects (e.g. trees). To remove these erroneous values, two filters were applied: a nonlinear median filter and a spectral ideal lowpass filter (ILPF). Filtering IKONOS stereo-image derived DSM was needed to reduce erroneous values, i.e. the surface heights objects (e.g. trees), which are hiding the actual topography, to approximate the terrain heights. Median filtering (5 x 5 windows) was done to remove erroneous or extreme values from the elevation models. This filter is based on neighborhood ranking and uses the median of the pixel (here elevation) values in the filter window. It is well-suited to eliminate point error, i.e. individual pixels that are corrupted or missing (Schenk, 1999); it also preserves edges and less sensitive to errors or extreme data values (Mather, 2004).

The results of filtering of erroneous elevation points show that median filter reduces some erroneous surface elevation points (Figure 4.9b), while the spectral filter performed better (Figure 4.9c). For example, many extreme points with height about 975 m remains after
median filtering, while very few extreme values with same height remains after spectral filtering.

Figure 4.9 IKONOS elevation models (original and filtered). a) IKONOS original model, b) median filtered model (5 x 5 window), and c) spectral filtered model. The model filtered in the frequency domain improved the quality by removing high frequency (erroneous) values (compared to median filtered model).

Results and Discussion

The elevation values in the IKONOS surface model (Figure 4.8) range from 960 m to 1007 m, with an average height of 973.14 m and local relief of 1.82 m (σ). This model was filtered to improve the model quality by removing erroneous (high-frequency) values. The minimum and maximum elevation in median and spectral filtered IKONOS elevation models (Figures 4.10a and b) show that a spectral filter produced better results than the median filter in reducing erroneous elevation points. Frequency domain filtering significantly removed the extreme values in the IKONOS DSM, resulted in improved topographic structure. The vertical accuracy of the model was evaluated in Chapter 6 (Section 6.2). Visual inspection of the result shows that even minor geomorphological features (in a wetland environment) are measured and surface discontinuities are well preserved. This digital photogrammetric-generated elevation model, for the first time, provided understanding of the detailed landscape micro-topography (of a test site) of the Okavango Delta (in a permanent swamp area). This
result will encourage further research on spaceborne optical stereo-photogrammetry for wetland microtopographic modeling and landscape processes.

Figure 4.10 IKONOS stereo-photogrammetric derived elevation models (5 m spatial resolution) after filtering. a) Median filtered and b) spectral filtered. The spectral filter performed better in removing erroneous elevation values than the median filter. Reduced high frequency values resulted in more realistic topography.

4.3 Mesotopography

Digital elevation models at medium spatial resolution (30 m to 100 m) provide the coarse topographic structure for understanding landscape patterns and processes, and reveal the medium-wavelength topography (i.e. medium resolution topographic structure). This section maps the regional topography of the Okavango Delta from 1) global positioning system, 2) airborne profiling radar, 3) spaceborne imaging radar, and 4) spaceborne optical stereo-imaging observations (Figure 4.1). The purpose was to create alternate mesotopographic models of the delta.

4.3.1 Global Positioning System

In regions that lack traditional topographic data (e.g. up-to-date topographic map with elevation contours) such as the Okavango Delta, GPS provides a powerful surveying tool to measure elevation points to produce a generalized but valuable topographic model. As a global system, GPS provides all time 3D position, velocity and time information with appropriate ground-receiving equipment (Van Sickle, 2001).

Generally, GPS measurements (x,y,z coordinates) are used as check points for validation of lower accuracy elevation datasets (Harding and Carabajal, 2005; Rodriguez et al., 2005,
2006). To produce denser samples by GPS over large areas is time-consuming and expensive. GPS, however, provide a powerful means to produce elevation models through interpolation of sparse postings. For example, the sparsely measured GPS postings in the Okavango Delta were used to create an elevation model (Modisi et al., 2000; Gumbricht et al., 2005). However, these authors used GPS data referenced to the provisional EGM96 and they provide about half a meter higher elevation than with the final EGM96. The vertical correction factor of final EGM96 was −0.53 m (Lemoine et al., 1998). The present study constructs a DEM from GPS-measured elevation postings (plus a few GPS-calibrated SRTM points to fill data gaps) on the Okavango Delta to demonstrate the practicality of GPS technology for topographic mapping.

Data and Method

Data

Poseidon Geophysics (a geophysical surveying company) carried out a regional gravity survey over northern Botswana for the Department of Geological Survey, Government of Botswana in the 1990s. The main objective of this survey was to generate a regional gravity data coverage for improving the geological understanding of the northern Botswana, as an incentive to private sector mineral exploration. As part of this survey, 4003 stations at a spacing of −7.5 km were established during October 8, 1998 to May 24, 1999 (Poseidon Geophysics, 1999) over the Okavango Delta and its surrounding regions using differential GPS (DGPS). These measurements were processed relative to the WGS84 datum, and the resultant GPS co-ordinates were referenced to the International Terrestrial Reference Frame (ITRF) with a long baseline tie to ITRF96 datum stations in South Africa (Poseidon Geophysics, 1999). Finally, data were transformed to the Clarke 1880 (modified) datum using a Bursa-Wolfe transformation. This survey resulted in high quality point elevation data (x,y,z); the station positions have an estimated height precision of ± 0.15 m (Poseidon Geophysics, 1999).

This study used GPS elevation postings surveyed by Poseidon Geophysics (989 postings), UCT (50 postings) (Figure 4.11) and 114 GPS-calibrated SRTM C-radar data points over the Okavango Delta to construct a DEM. The ETHZ surveyed 47 GPS GCPS and Poseidon Geophysics surveyed 13 postings were used as check points to assess the GPS-based DEM (Chapter 6). On the Poseidon Geophysics surveyed GPS data, a vertical correction factor −0.53 m of final EGM96 (Lemoine et al., 1998) was applied to adjust the offset.

Method

Elevation models from GPS postings were created by two interpolation methods: 1) inverse squared distance weighting (IDW) and 2) ordinary kriging. An IDW technique (12 neighbours, \( p = 2 \), where \( p \) is the power of weight) was used to interpolate 1098 elevation postings for creating a grid-based model. This method assigns weight inversely proportional to the squared distance that a particular sample is separated from the point of estimation. The equation for the IDW interpolation is defined as:

\[
z(x,y) = \frac{\sum_{i=1}^{n} \frac{z_i}{d_i^p}}{\sum_{i=1}^{n} \frac{1}{d_i^p}}
\]

(4.1)
where $z(x,y)$ is the estimated $z$ value at the location $(x,y)$ while $z_i$ is the elevation value at the $i$th reference point located at $(x_i,y_i)$, $d_i$ is the distance between the reference and interpolation points, and $p$ is the power to which the distance is raised (El-Sheimy et al., 2005). The selection of $p = 2$ produces better result (found by experiments), as close points are heavily weighted, and more distant points lightly weighted (El-Sheimy et al., 2005). The IDW method is suitable for the interpolation of elevation points on topographically flat areas (e.g. Okavango Delta). But, IDW creates bumps or bulls eyes in the interpolated surface. Kriging, a geostatistical method, uses a similar approach but rather than simply considering distances to control points independently of one another, it uses the spatial autocorrelation in the data, both between the grid point and the surrounding control points and among the control points themselves (Slocum et al., 2009). Ordinary kriging (Matheron, 1962) with exponential semivariogram model (found to provide best fit) was used to interpolate the GPS dataset (as used in the IDW interpolation) to construct an elevation model.
Results and Discussion

From GPS elevation postings on the Okavango Delta, a medium spatial resolution DEM (90 m) was generated by IDW and ordinary kriging interpolation (Figure 4.13). The elevation ranges from 921.81 m to 1042.59 m, with an average elevation of 959.23 m. This GPS-based DEM of the delta presents coarse-resolution topography and regional relief ($\sigma = 19.06$ m, relief is defined by standard deviation). However, this model has provided accurate regional topographic structure (gradients and shapes) of the delta, as revealed by the contours. The model is limited by its coarse surface structure, because of sparse sampling. The interpolation of these sparse postings into a medium resolution (90 m) model resulted in bloating effects around postings.

Figure 4.14 presents the GPS-based elevation models (IDW and kriging-interpolated) with contours (5 m interval). Kriging has created a natural-looking topographic surface with contour shapes and directions (Figure 4.14b), while IDW interpolated surface’s geometry is limited by circular bulls-eye features.

Figure 4.15 presents the kriging-based GPS elevation model of the Okavango Delta, with 2.5 m interval contours. Regular pattern of GPS sample distribution (Figure 4.12) minimised the interpolation error, and thus has created a natural-look landscape topographic model. At a higher contour interval, this model reveals realistic mesotopographic structure (shapes and gradients). This model was used as a basis for further work on mesotopographic modeling of the Okavango Delta.
Figure 4.13 GPS-based elevation models of the Okavango Delta (90 m spatial resolution, 2534 x 2782 pixels). The height deviation on both models is $-121$ m, revealing the gentle nature of the delta topography. a) IDW-based elevation surface, b) ordinary kriging-based elevation surface. IDW produced bulls-eye like features around elevation samples, while kriging created a natural-looking elevation surface.

Figure 4.14 Contours (5 m interval) of the GPS-based elevation models (90 m spatial resolution) of the Okavango Delta. a) IDW-based elevation surface, b) Kriging-based elevation surface.
Figure 4.15 Kriging-based GPS elevation model (90 m) of the Okavango Delta, with contours (2.5 m interval). Regular distribution of GPS samples (see Figure 4.12) minimised the kriging error, and thus has created a natural-look landscape topographic model.

Table 4.1 shows the structural characteristics of the elevation models by IDW and kriging methods. Kriging has created better topographic structure ($\sigma = 18.61$ m) in the model than the IDW ($\sigma = 18.36$ m).

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>Interpolated elevation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IDW-based model</td>
</tr>
<tr>
<td>Minimum elevation</td>
<td>921.277</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>1042.063</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>958.218</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>18.359</td>
</tr>
</tbody>
</table>
4.3.2 Airborne Profiling Radar

This section maps the mesotopography of the Okavango Delta from observations acquired by an airborne profiling radar, which measures altitude above the terrain beneath an aircraft.

Data and Method

An airborne geophysical survey (AGS) that included a radar altimeter was carried out on the Okavango Delta region in 1996 by the Department of Geological Survey, Government of Botswana. This aerial survey was done using 80 m ground clearance along north-south lines, 250 m spaced traverses on 345°-165° reciprocal bearings and 2500 m spaced orthogonal control lines (Sefofane Geophysics, 2003). The elevation data \((x,y,z)\) were derived from differences between the GPS altitude and the radar altimeter trace, and the leveling was done with Intrepid’s loop closure algorithm. The elevation precision of these measurements was 2-3 m (personal communication with Luc Antoine, Sefofane Geophysics, 2003). The leveled data (250 m profile spacing and 7 m sample distance elevation postings) were converted into grids using Intrepid Geophysics minimum curvature bi-cubic spline interpolation algorithm with a 50 m grid mesh (Sefofane Geophysics, 2003). The dataset was referenced to UTM zone 34 S, Clarke 1880 (modified) ellipsoid and Cape datum. The final grid product was merged with the surrounding contiguous surveys, the Western Ngamiland and Maun airborne magnetic surveys to cover the Okavango Delta to produce an elevation model. For geometric consistency, this airborne radar model (hereafter AGS) was co-registered with a rectified Landsat 7 ETM+ panchromatic image (see Appendix VII) to make the dataset compatible with GPS measurements for error assessment.

Results and Discussion

Figure 4.16 presents a mesotopographic model of the Okavango Delta generated from airborne radar altimetry measurements, with elevation ranging from 923 m to 1023 m. Since the AGS model was constructed from radar altimetry profiles, it contains erroneous elevation values (speckles) (see Figure 4.17, 5 m interval contours). A better representation of topography was obtained by spectral filtering (lowpass) of high-frequency erroneous values from the AGS model (Figure 4.18).

Since the AGS radar elevation model over the delta was derived from a dataset having 250 m spaced profiles and 7 m sampling distance (along-profile), it presents a smoother topographic surface with low regional relief \((\sigma = 17.38 \text{ m})\) than the model generated from GPS postings (see Figure 4.12) with a 19 m regional relief. Relief describes the vertical dimension or amplitude of topography, which can be measured by the standard deviation of elevation (Evans, 1980). The elevation ranges from 923 m to 1023 m over the delta (unfiltered model), with an average elevation of 957.18 m. For the filtered DEM of the main delta, the elevation ranges from 931 m to 1010 m, less than 20 m from the unfiltered one. This is due to exclusion of areas such as sand hills in the south-east corner, Lake Ngami in the south, and Mababe depression in the east as well as filtering of trees and other object surface heights. The accuracy of the airborne radar elevation model has been evaluated against the GPS postings and is presented in Chapter 6 (Section 6.5.2). This model has provided general characteristics of the topography (structures and shapes) of the delta and increased understanding of its landscape. After removal of speckles, the model represents improved topographic structures, as revealed by contour shapes (Figure 4.18).
Figure 4.16 Airborne radar altimetry-based elevation model of the Okavango Delta (50 m spatial resolution). Elevation ranges from 923 to 1023 m, with 100 m height deviation.

Figure 4.17 Airborne radar altimetry-based elevation model of the delta (50 m spatial resolution) with contour overlay (5 m interval). Contouring reveals speckles in the dataset.
4.3.3 Spaceborne Imaging Radar

The topographic mapping from InSAR technology can be of single pass type or two pass type. In single pass type, two (or more) antennas simultaneously image the scene such that the temporal baseline is zero, while in two pass type, separate passes with a single antenna is used (Madsen and Zebker, 1998). Single pass systems like two pass ones, can either be airborne (e.g. JPL Topographic Synthetic Aperture Radar, TOPSAR) or spaceborne (e.g. SRTM). This section maps the topography of the Okavango Delta using elevation observations measured by SRTM C-band radar, which was a distinct milestone in the history of topographic mapping from space as the first spaceborne implementation of single-pass interferometry (Farr et al., 2007). The platform characteristics and topographic product specifications are given in Chapter 2 (Tables 2.2 and 2.6, respectively).

Data and Method

Imaging radar elevation data acquired by the SRTM C-band sensor (for site location, see Chapter 2, Figure 2.7) was used to map the Okavango regional topography (see details about data in Chapter 2, Section 2.4.2). Figure 4.19 shows the 30 m spatial resolution (downscaled from original 90 m) SRTM model of the Okavango Delta. The elevation ranges from 918 m to 1341 m, with a height deviation of 423 m.

Void Characterization and Filling

Inherent in radar technology-derived elevation information is the data void (e.g. SRTM data) and erroneous (or noisy) elevation values. Few voids exist in the SRTM data on the Okavango Delta region and they are mainly found in terrain slopes (e.g. sand hills) and in lakes and water bodies. These voids were identified by comparing void locations with topographic and
Figure 4.19 SRTM elevation model of the Okavango Delta (30 m spatial resolution, resampled from 90 m void corrected data), acquired from Space Shuttle Endeavour platform in February 2000. Few higher elevation points on the Tsodilo Hills (north-western part) produced the height deviation of about 420 m, otherwise a gently-sloping topography of the whole delta region.

Land cover features using Landsat 7 multispectral image and topographic maps. Figure 4.20 shows the voids in the SRTM elevation data on the delta water bodies and their corresponding location on the Landsat 7 multispectral image. These voids were filled by interpolating neighbouring pixels using the IDW function with one pixel radius around void pixels. Voids are caused by two main mechanisms: steep slopes facing away from the radar (shadowing) or toward the radar (foreshortening or layover) and smooth areas such as smooth water or sand which scattered too little energy back to the radar to create an image (Hall et al., 2005; Slater et al., 2006).

Rectification and Georegistration

The SRTM elevation measurements are in geographic coordinates with WGS84 ellipsoidal heights. These heights were transformed into UTM coordinates (Zone 34 S, Clarke 1880 ellipsoid, Cape datum) and orthometric heights. Nine SRTM data tiles covering the Okavango Delta region were mosaicked to create a single elevation image. In case of Global Land Cover Facility (GLCF) SRTM elevation images (University of Maryland at College Park,
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Overlaps were kept to a minimum to minimize differences in elevation values. The GLCF datasets were referenced to WRS-2 (Worldwide Reference System-2). Overlap areas were thoroughly examined and no discernible discrepancies were found. The mosaicking was done using a nearest neighbour resampling technique, which preserved the original values.

![Image](http://www.landcover.org/)

**Figure 4.20** Voids (black) in uncorrected SRTM elevation data on the Okavango Delta. a) Permanent swamp SRTM data, b) SRTM void enlarged, c) void (water) as seen in Landsat 7 ETM+ multispectral image.

The SRTM DSM mosaic (90 m) of the delta was rectified using a georegistered Landsat 7 ETM+ panchromatic image at 15 m spatial resolution (see Appendix VII, Landsat image rectification). The well-distributed 24 GCPs were used to rectify the SRTM model. GCPs were selected on diverse features such as the bend of dry river channels, intersection of two channels, corners of sand dunes and hill peaks. The registration error resulted in 0.24 pixel $X$ residual (21.30 m object space) and 0.25 pixel $Y$ residual (22.83 m), and 0.34 pixel total residual (30.62 m). The first order polynomial transformation and nearest neighbour resampling were performed. The residual distribution for a first degree polynomial fit (Figure 4.21) shows that the model describes the data well, as residuals are randomly scattered around zero.
Downscaling

Downscaling rescales data from low to high spatial resolution. In elevation estimation, downscaling determines sub-pixel elevation values within pixels of a lower spatial resolution model. Downscaling was required to make the dataset compatible with other remote sensing (e.g., Landsat 7 images, 30 m spatial resolution) and geospatial data. Also, this was required in filtering as higher spatial resolution enables better filtering. Here, the SRTM model (90 m) on the delta was downscaled to 30 m grid using an inverse distance squared weighting (IDW) interpolation method (12 neighbours, power = 2). Downscaling resulted in slight reduction of topographic relief (σ) but retains the integrity of data because of relative flatness of the area. Note, the accuracy loss by interpolation is a function of the variation of the terrain inclination.

Filtering

The presence of speckle in an imaging system reduces its resolution, particularly for low-contrast images (Jain, 1989). For purposeful use, noise in such images needs to be suppressed or minimised by filtering.

The speckle in the SRTM data persists even after selective use of boxcar filtering during processing at the JPL (Smith and Sandwell, 2003); this uncertainty is due to short-wavelength random speckle that is common in SAR products (Falorni et al., 2005). These models do not represent terrain surface but the surface height of objects. Thus, the topographic data provided by the SRTM cannot be used directly. It requires a significant amount of processing to ensure that there is no spurious information in the data, which would cause problems in deriving topographic attributes such as slope, aspect and drainage. Here two filters – a non-linear median filter and a spectral filter were used to reduce noise in the SRTM data. Figure 4.22 presents noisy contours of the SRTM model at 10 m and 5 m intervals, which contains erroneous elevation values.

Figure 4.21 Residual distribution of georegistered SRTM mosaicked elevation model (90 m resolution). Most residuals lie between ±0.4 m (less than half-pixel) from zero, which resulted in a relatively well-fit model.
Figure 4.22. Contours derived from SRTM model of the delta (30 m spatial resolution). a) Contours at 10 m interval, b) contours at 5 m interval. Contouring reveals high magnitude speckle in the SRTM elevation data, which obscured the terrain surface.

Median Filtering: To minimize erroneous elevation values from the SRTM model of the delta (Figure 4.23a), a median filter (5 x 5 windows) was used. Median filtering did not improve

Figure 4.23 a) SRTM median filtered (5 x 5 windows) elevation model of the delta (30 m spatial resolution); b) contours derived from median filtered SRTM model (5 m interval). Contouring of median filtered model shows marginal reduction of extreme values, when compared with contours from the original elevation data (see Figure 4.22b).
the model much, the high magnitude noise remains in the model (contour interval = 5 m) that obscures terrain features (Figure 4.23b).

*Spectral Filtering:* A frequency domain filter (ideal lowpass filter, ILPF) was used for removing or minimizing speckle in the SRTM data, which obscured the actual topographic surface. We investigated various cut-offs and choose radius 90 as the optimal cut-off frequency for this dataset (Table 4.2).

**Table 4.2 Characteristics of SRTM elevation model (30 m) filtering with various cut-off frequencies.**

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>Radius of cut-off frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>90</td>
</tr>
<tr>
<td>Minimum elevation</td>
<td>917</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>1080</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>960.383</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>19.755</td>
</tr>
</tbody>
</table>

**Results and Discussion**

Figures 4.24-27 present the results of spectral filtered SRTM elevation data over the Okavango Delta region and wetland area. Filtered model clearly delineated the elevation surface. Figures 4.24 and 4.25 show that contours with 5 m and 2.5 m intervals captured topographic structure realistically. The elevation ranges from 917 m to 1080 m (at cut-off frequency 90). Visual observation of the model with 2.5 m contour intervals (Figure 4.25) shows that finer details of the topography and varied geomorphic features can be delineated from spectrally filtered SRTM elevation model.

Figure 4.26 presents the 3D Visualization of the SRTM elevation model of the delta, with 150 times of vertical exaggeration. It clearly depicts the flatness of the topography, with lowest elevation areas running from Lake Ngami in the south-west through Mababe depression in the north-east. Figure 4.27 presents SRTM elevation models of the Okavango wetland. The elevation ranges from 929 m to 1013 m for the SRTM original model (Figure 4.27a), while for filtered SRTM model elevation ranges from 935 m to 1009 m (Figure 4.27b). The SRTM filtered model with 1 m interval contour overlay (Figure 4.27c) shows the gently-sloping character of the wetland topography, with an elevation deviation of only 74 m. This model shows the detailed structure of landscape topography over the wetlands, and improves understanding of its internal structures such as gradients and the flow direction.
Figure 4.24 SRTM spectral filtered elevation model of the delta (30 m spatial resolution) with
contour overlay (5 m interval). Filtering significantly removed erroneous (high-frequency) values,
which resulted in realistic representation of the landscape topography. The 163 m height deviation
resembles the deviation in the GPS-based model (121 m).

Figure 4.28 shows the representation of elevation distribution in the SRTM filtered
elevation model (30 m) of the delta. About 61% pixels lie below mean elevation of the delta
(960 m), while 39 percent pixels are above the mean elevation. Nearly two-thirds of the delta
topography lies between 917 m and 960 m elevation, a height difference of 43 m. Within the
wetland the average reduction due to filtering was 10 m, which means most reduction
occurred outside the wetland areas as average relief (difference between maximum and
minimum elevation) decreases from 423 m (SRTM model) to 163 m (SRTM filtered model).
Several factors contributed this such as wooded vegetation and buildings and other man-made
structures in Maun and other inhabited areas.
Figure 4.25 SRTM spectral filtered elevation model of the delta (30 m spatial resolution) with contour overlay (2.5 m interval). Dense contours reveal the realistic topographic surface.

Figure 4.26 The perspective view of SRTM spectral filtered elevation model of the delta (30 m spatial resolution; elevation range: 917 m to 1080 m) with 150x vertical exaggeration.
Figure 4.27 SRTM topography of the Okavango wetland (30 m spatial resolution). a) SRTM original wetland model, b) SRTM spectral filtered wetland model, c) SRTM filtered wetland model with contour overlay (1 m interval). Contours at 1 m interval reveal the detail landscape topographic structure on the wetland. Elevation deviation of 74 m from the apex of the wetland (north-west) to the margin (south-east). SRTM data contains speckle, filtering in the frequency domain removes these high-frequency speckles and thereby presented realistic topographic structures (b&c).

Figure 4.28 Elevation histogram of SRTM spectral filtered elevation model (30 m) of the delta. Nearly two-thirds of data values lie below mean elevation (960 m).
The SRTM filtered data produced a better topographically representative elevation model of the Okavango Delta compared to the AGS radar model (Figure 4.16) and GPS-based model (Figure 4.13) in terms of structure and shapes (as revealed by contours). This was further confirmed by observing contour patterns and shapes of elevation models at 5 m, 2.5 m and 1 m intervals (Figures 4.24, 4.25 and 4.27c, respectively). Several depressions are evident in the model, notable are the Lake Ngami in the south-west part and part of Mababe depression in the eastern part (Figure 4.25).

The elevation difference between SRTM original and filtered models shows that the minimum elevation almost remain the same (SRTM original = 918 m, and SRTM filtered = 917 m). However, a large difference arises between the two models in maximum elevation (SRTM original = 1341 m, and SRTM filtered = 1080 m). This is because a few higher elevation pixels are located in the north-western edge of the delta (e.g. Tsodilo Hills), which are considerably minimised by filtering. This can explains the mean difference of 0.07 m, between two models.

Figure 4.29 presents the topographic transects from end of the Panhandle (~980 m) to six gradient directions (A to E and P). They represent complex interaction of physical processes that operate on a wide range of (length) scales; thus topography can be generalised over many spatial scales (Gilbert 1989). Figure 4.30 shows the variation of topographic relief from end of Panhandle to SW, S, SE, E and NE-ward directions in the delta. There exists little difference in relief variations and gradients along transects B (towards lake Ngami), C (towards Maun) and D (towards Mababe depression). Within ~150 km from end of the Panhandle, these profiles show ~40 m elevation difference. The gradients are steeper in B,C,D directions than in transects A and E. The Panhandle (>100 km) shows an elevation difference of ~20 m (transect P).

![Diagram](image_url)

**Figure 4.29** SRTM filtered elevation model with transects (from Panhandle end towards the wetland).
Figure 4.30 Topographic relief variations from Panhandle end to SW, S, SE, E and NE-ward directions in the Okavango Delta. a) Transect A towards south-west, b) transect B towards lake Ngami, c) transect C towards Maun, d) transect D towards Mababe depression, e) transect E towards Linyanti, f) transect of Panhandle (P). Highest relief variations are towards the Mababe depression and the Lake Ngami, while lowest on the Panhandle and south-west of the delta.

Table 4.3 shows the regional variation of topographic relief along six transects from the Panhandle end point. The delta has the maximum relief towards the Mababe (~57 m) and
Lake Ngami (~53 m) while Maun and Linyanti directions shows near-uniform relief (~37 m). The Panhandle has the minimum relief (~20 m), followed by the south-west direction (~27 m). The south-west direction is gentler with 1 m height deviation per 6.85 km, followed by the Mohembo, Linyanti and Maun transects. The Mababe transect have the highest slope (1 m per 2.8 km) followed by Lake Ngami transect (1 m per 3.3 km).

Table 4.3 Regional topographic relief characteristics of the Okavango Delta.

<table>
<thead>
<tr>
<th>Transects (from Panhandle end to outwards)</th>
<th>Transect distance (~km)</th>
<th>Relief along transect (~m)</th>
<th>1 m height variation for a distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>South-west (A)</td>
<td>185</td>
<td>27</td>
<td>6.85</td>
</tr>
<tr>
<td>Lake Ngami (B)</td>
<td>175</td>
<td>53</td>
<td>3.3</td>
</tr>
<tr>
<td>Maun (C)</td>
<td>154</td>
<td>37</td>
<td>4.16</td>
</tr>
<tr>
<td>Mababe depression (D)</td>
<td>162</td>
<td>57</td>
<td>2.84</td>
</tr>
<tr>
<td>Linyanti (E)</td>
<td>168</td>
<td>37</td>
<td>4.54</td>
</tr>
<tr>
<td>Mohembo (P)</td>
<td>102</td>
<td>20</td>
<td>5.1</td>
</tr>
</tbody>
</table>

The accuracy of the SRTM data has been evaluated against GPS postings and ICESat laser elevation, and is presented in Chapter 6 (Section 6.5.3). The SRTM model for the first time presented a thorough mesotopographic model of the Okavango Delta and increased understanding of the regional landscape topographic characteristics.

### 4.3.4 Spaceborne Optical Stereo Imaging

Several spaceborne optical-stereo imaging technologies had been implemented to generate topographic models in the last three decades (e.g. instruments on SPOT, IKONOS and CartoSat). However, ASTER global DEM (GDEM) has created a landmark in the history of topographic mapping from space as the first spaceborne optical-stereo implementation at a global scale (between 83°N and 83°S latitudes, covering 99% landmass). ASTER collected in-track stereo-images using nadir- and aft looking near-infrared sensors on Terra spacecraft, from an altitude of 705 km during 2000 to 2011. These stereo-pairs were used to produce single scene elevation model (60 km x 60 km) using digital photogrammetry. ASTER GDEM is a joint contribution of NASA/JPL and the Ministry of Economy, Trade, and Industry (METI) of Japan. For details about ASTER GDEM see Abrams et al. (2010) and Tachikawa et al. (2011). This section maps the mesotopography of the Okavango Delta from elevation data derived from ASTER stereo-observations.

### Data and Method

The ASTER elevation data (GDEM Version 2) on the Okavango Delta was acquired from the NASA/JPL site (http://asterweb.jpl.nasa.gov/gdem.asp), and are used to map the regional topography (see details about data in Chapter 2, Section 2.4.2). Figure 4.31 shows the ASTER surface model (30 m spatial resolution) of the Okavango Delta, the elevation ranges from 901 m to 1348 m, with a mean elevation of 961 m. height deviation of 447 m. This model was generated from ASTER’s along-track stereoscopic capability using its near-infrared band and
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its nadir-viewing and backward-viewing telescopes to acquire stereo-images with a base-to-height ratio of 0.6 (Fujisada et al., 2005; Tachikawa et al., 2011). ASTER acquired stereo-images at 15 m spatial resolution and swath width of 60 km. The platform and sensor characteristics are given in Chapter 2 (Table 2.2) and Appendix III, respectively.

ASTER model provides surface height of objects (and not terrain height) because it was generated by digital photogrammetry. To remove extreme (high frequency) values, this model was filtered in the frequency domain (using a low pass filter, ILPF). We investigated various cut-offs and choose radius 99 as the optimal cut-off frequency for this dataset.

![Figure 4.31](aster_elevation_model.png)

**Figure 4.31** ASTER elevation model of the Okavango Delta (Version 2, 30 m spatial resolution; 7772 x 9313 pixels). Strips (north-south) on the model reveal the mismatch in mosaicking elevation images (60 km x 60 km) and the issues related with mass-production using digital photogrammetry (with poor image-matching). Also note, paired-images of ASTER were acquired in various periods (during 2000 – 2011).

**Results and Discussion**

Figure 4.32 presents the ASTER filtered elevation model (30 m spatial resolution) with contour overlay (5 m interval) of the Okavango Delta. Filtering has removes the high elevation edge pixels (north-west part of the delta) and sinks in the dataset. The elevation ranges from 918 m to 1072 m, with a mean elevation of 960.93 m and regional relief of 19.87
m (slightly lower than the unfiltered data). Filtering produced a more realistic topography (as revealed by contour patterns and shapes) than the unfiltered model.

Figure 4.32 ASTER filtered elevation model of the delta with contour overlay (5 m interval).

Figure 4.33 presents the ASTER spectral filtered elevation model (30 m spatial resolution) with contour overlay (2.5 m interval) of the Okavango Delta. Contours at higher interval reveal terrain shapes and gradients, and thereby reveal the structural quality of an elevation model. ASTER model contains artefacts and anomalies, which clearly revealed by contours at 2.5 m interval (see north-south elongated structures, as revealed by contour patterns and shapes). Figure 4.34 shows the elevation histogram of ASTER elevation model on the delta. Finally, ASTER GDEM provides high spatial resolution elevation data over the delta region, but data contains artefacts and anomalies that impede effectiveness for its use in hydrological and environmental applications.
Figure 4.33 ASTER filtered elevation model of the delta with contour overlay (2.5 m interval). North-south strips on the dataset resulted elongated structures in the wetland area, as revealed by contour patterns and shapes.

Figure 4.34 Elevation histogram of ASTER elevation model on the delta. Most data value lies between 900 m and 1100 m elevation; 0.004% data values are above 1100 m elevation. Only 179 out of 72,363,552 data values are above 1300 m elevation, and these points are located in the north-western edge of the model.
4.4 Water Surface Topography

Measurements of water levels in main channels of rivers, upland tributaries and floodplain lakes are necessary for understanding flooding hazards, methane production, sediment transport and nutrient exchange (Alsdorf et al., 2000, 2007). Observations of water surface from remote sensing provide an alternate technique to permanent gauging. This is especially important for developing countries where most rivers either have sparse or no gauges (e.g. Okavango River, Africa). This section measures the Okavango Delta water surface topography (WST) from spaceborne imaging radar (SRTM), and water surface elevation (WSE) from profiling laser (ICESat) observations (Figure 4.1).

4.4.1 Spaceborne Imaging Radar

Spaceborne radar altimetry observations are used to measure water surface elevation, especially ocean surface (Townsend and Fellous, 1987; Tapley et al., 1994; Fu et al., 2003) and large rivers, water bodies and wetlands (Birkett, 1998; Alsdorf et al., 2000, 2007; Birkett et al., 2002). These observations are limited by their large footprints (e.g. 5 km footprint of TOPEX/Poseidon). Satellite-borne InSAR (e.g. ERS 1/2 and Envisat) provides grid-based elevation models; but they are limited by data coverage in many parts of the world (e.g. Okavango region) and not suited for constructing high vertical accuracy elevation models. SRTM C-band imaging radar was the only spaceborne mission with global observations that measured the water surface elevation/topography (Farr et al., 2007). WST is an important parameter for modeling hydrological and environmental processes.

Data and Method

Data: Datasets used in constructing and evaluating water surface topographic models are: SRTM data, Landsat 7 multispectral image-derived water surface mask, and GPS postings (for details about data, see Chapter 2, Section 2.4.2).

Approach: A combined radar-optical approach was developed (Figure 4.35) for mapping water surface topography of the Okavango Delta at two levels: 1) water surface (including aquatic vegetated areas), and 2) open water surface. A frequency domain filter (ILPF) was used to minimize speckles in the SRTM water surface data. We found radius 99 as the best cut-off frequency for this dataset (Table 4.4).

Results and Discussion

Figure 4.36 presents the SRTM water surface topographic models (original and filtered) of the Okavango Delta. The elevation ranges from 934 m to 1009 m over the delta water surface, with a mean elevation of 960.4 m and regional water surface relief (σ) of about 12 m (Table 4.4). Filtering did improve the model quality: it slightly reduced the range deviation, but retained the regional water surface relief.
Figure 4.35 Combined radar-optical approach to water surface topographic modeling. The details on observation from various space platforms are given in Chapter 2 (Section 2.4.2 and Table 2.2).

Figure 4.36 SRTM water surface topographic models of the Okavango Delta. a) SRTM original water elevation, b) SRTM filtered water elevation. This model covers open water surface and aquatic vegetated water areas. The model covers an area of 8864 km² (~59% of total wetland area, i.e. 15047 km²).
Table 4.4 Characteristics of SRTM water surface (including aquatic vegetated areas) topographic models on the Okavango Delta.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>SRTM water surface model (m)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original</td>
<td>Spectral filtered</td>
</tr>
<tr>
<td>Minimum elevation</td>
<td>934</td>
<td>935</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>1009</td>
<td>1007</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>960.43</td>
<td>960.43</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>12.31</td>
<td>12.36</td>
</tr>
</tbody>
</table>

Figure 4.37 presents the SRTM open water surface topographic models (original and filtered) of the Okavango Delta. The elevation ranges from 934 m to 1008 m over the delta open water surface, with a mean elevation of ~962 m. Over the open water surface, the regional relief is about 10 m (Table 4.5), which is 2 m lower than the regional water surface (see Table 4.4). Like the delta water surface, filtering has improved the delta open water surface model (Table 4.5) with a range deviation between 935 m to 1005 m and regional relief of about 10 m. These improvements occurred because of removal of aquatic vegetated cover and other erroneous height values.

Table 4.5 Characteristics of SRTM open water surface topographic models on the Okavango Delta.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>SRTM water surface model (m)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original</td>
<td>Spectral filtered</td>
</tr>
<tr>
<td>Minimum elevation</td>
<td>934</td>
<td>935</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>1008</td>
<td>1005</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>961.69</td>
<td>962.05</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>10.35</td>
<td>10.27</td>
</tr>
</tbody>
</table>

Figure 4.38 presents the subset SRTM open water surface models (original and filtered) of the delta (see S1 and S2 sites in Figure 4.37). This subset (405 km²) mostly comprises permanent swamp with open water surface. On the main channel (36 km), the SRTM water elevation ranges from 988 m to 967 m (along the flow direction A1 to B1) with a mean elevation of 976 m (and water relief ~1.5 m). This gives 1 m water height deviation for every 1.7 km on the SRTM water topography. Generally, there are 1 m height deviations for every ~4.5 km distance over the delta topography. This means the deviation in the SRTM water topography was caused by speckles. Filtered SRTM data gave 7 m elevation range deviation (Figure 4.38b) along the flow direction B1 to B2. Thus, it gave 1 m water height deviation for every 5 km, which is realistic. The SRTM water topographic models were assessed in Chapter 6 (Section 6.6.1).
Figure 4.37 SRTM open water surface topographic models of the Okavango Delta. a) SRTM original open water elevation model, b) SRTM spectral filtered open water elevation model. The open water surface elevation model covers an area of 3118 km$^2$ (~21 percent of total wetland area, i.e. 15047 km$^2$). See S1 and S2 (black box) in enlarged form in Figure 4.35.

Figure 4.38 SRTM open water surface topographic models in the Okavango Delta. a) Enlarged S1-site (original data, Figure 4.37a) of open water model (elevation ranges from 988 m to 967 m, along flow direction A1 to B1), b) enlarged S2-site (Figure 4.37b) of filtered open water model (elevation ranges from 980 m to 973 m, along flow direction A2 to B2). This site covers an area of 405 km$^2$. 
4.4.2 Spaceborne Profiling Laser

Laser observations from air- and space platforms provide precise measurements of the earth surface topography, which is crucial to derive accurate surface attributes (e.g. elevation, slope, aspect, curvature and relief). The ICESat was the first earth-orbiting satellite that carried a laser instrument (GLAS), and has provided comprehensive measurements of ice, cloud and land topography on most part of the earth surface (for detail see Zwally et al., 2002; Abdalati et al., 2010). The GLAS measured the round-trip time of flight of visible (0.542 μm) and infrared (1.064 μm) laser pulses between the satellite and the earth surface. It has provided high accuracy and precision land surface elevation measurements, about 14 cm and 2 cm, respectively (Zwally et al., 2002; Harding and Carabajal, 2005). Detailed description of the GLAS on board ICESat, a component of the NASA’s Earth Observing System, is given in Zwally et al. (2002). The ICESat platform and sensor characteristics are given in Chapter 2 (Table 2.2) and Appendix IV, respectively. This section measures the Okavango Delta water level dynamics and changes from ICESat laser multitemporal observations (Figure 4.1).

Data and Method

Data: The Global GLAS Laser Altimetry product 14 (GLA14, also called global land surface altimetry data) of ICESat was used for measuring water level elevation and elevation changes. Other datasets used are Landsat 7 multispectral image and GPS postings (see details in Chapter 2, Section 2.4.2).

The ICESat recorded about 150,000 elevation measurements (laser footprints) over the Okavango Delta region during its operation (February 2003 to October 2009). They were recorded by the GLAS’s infrared laser pulses (1.064 μm) at 70 m footprints over 170 m along-track spacing (sampling at 40 Hz) and ~65 km across-track spacing over the delta region (between 18° to 21° S latitudes). Detailed features of ICESat GLAS data and their processing levels over the delta are given in Appendix V. Figure 4.39 shows the distribution of ICESat profiles on the Okavango Delta SRTM elevation surface (discontinuities in some profiles represent gaps in the data). Table 4.6 presents the ICESat data processing level (DPL) with laser campaign period used for estimating water level dynamics, between 2003 and 2009. For estimating the water level change (especially to estimate the historic water level rise in 2009 over 2007, for which ICESat data were available), two laser campaign data were used: L3H (4 April 2007) and L2E (1 April 2009). Note, in this section for estimating water level dynamics and change, we used the ICESat data with WGS84 ellipsoidal heights.
**Table 4.6** ICESat laser data processing levels and campaign period, as available over the Okavango Delta, 2003 to 2009.

<table>
<thead>
<tr>
<th>Data processing level (DPL)</th>
<th>Laser campaign period (month/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L2A</td>
<td>ON2003</td>
</tr>
<tr>
<td>L2B</td>
<td>FM2004</td>
</tr>
<tr>
<td>L3A</td>
<td>ON2004</td>
</tr>
<tr>
<td>L3B</td>
<td>FM2005</td>
</tr>
<tr>
<td>L3D</td>
<td>ON2005</td>
</tr>
<tr>
<td>L3F</td>
<td>MJ2006</td>
</tr>
<tr>
<td>L3G</td>
<td>ON2006</td>
</tr>
<tr>
<td>L3H</td>
<td>MA2007</td>
</tr>
<tr>
<td>L3J</td>
<td>FM2008</td>
</tr>
<tr>
<td>L2D</td>
<td>ND2008</td>
</tr>
<tr>
<td>L2E</td>
<td>MA2009</td>
</tr>
</tbody>
</table>

*FM= February-March, MA= March-April, MJ= May-June, ON= October-November, ND= November-December.*
Approach: A combined laser-optical approach was developed to measure water level elevation and elevation changes in the Okavango Delta (Figure 4.40). The GLAS footprints (February 2003-2009) on the delta water surface were extracted using a water surface mask (derived from Landsat 7 multispectral images, see Chapter 5). Outliers in the ICESat data were visually detected (by creating contours from laser points) and removed using the criterion – elevation values >1400 m as outliers (as there is no elevation point above 1400 m in the Okavango Delta region). We used an altimeter multi-temporal approach (AMA) and estimated the Okavango Delta water level dynamics and elevation change for two periods:

1) water level dynamics, between 2003 – 2009, and
2) water level change, between 2007 – 2009.

The location of the ICESat laser shots on the delta water surface that were used to estimate water level dynamics is shown in Figure 4.41b (box-A, see Figure 4.42 for laser shot distribution), and in Figure 4.41a (box-B) for estimating water level change. Figure 4.42 shows the 11 tracks of ICESat laser shots on the delta surface water, acquired during 2003 – 2009. We used multi-season ICESat data for estimating water level dynamics (see Table 4.6), and flooding season ICESat data for estimating water level change. The selection of site 1 (box-A) was driven by the availability of maximum ICESat tracks and shots on the delta surface water (along 19.303 to 19.320 degree south latitude), while the site 2 (box-B) was selected to cover maximum length of surface water in the delta (along 18.932 to 19.429 degree south latitude).
Figure 4.41 ICESat tracks (red, 2007 and 2009) on the Okavango Delta water surface (blue). The spacing between left (1 April 2009) and right track (4 April 2007) is ~336 m. These tracks are located between 18°55'53" S, 22°30'45" E (989.90 m) and 19°25'43" S, 22°35'5" E (975.72 m). The water surface mask was derived from Landsat 7 multispectral image (see Chapter 5). Box A (red) enlarged with laser tracks in Figure 4.42.

Figure 4.42 ICESat track-wise footprints (red and yellow, 2003-2009) on the Okavango Delta water surface (blue) (see location box-A in Figure 4.41). These datasets were used to estimate water level dynamics see Figures 4.44-47.
Results and Discussion

Water Level Dynamics, 2003-2009

Figure 4.43 presents the water level dynamics in the Okavango Delta between 2003 and 2009, as estimated from ICESat measurements. The estimates from 11 laser campaign period, which covers both flooding and dry season, shows water level fluctuation of ~2 m. The highest water level recorded in March-April 2009 and lowest in May-June 2006.

Figure 4.43 ICESat estimates of water level dynamics in the Okavango Delta, 2003-2009. These ICESat measurements from 11 campaign periods (see legend) are for flooding season (February-April, May-June 2006 also included) and dry season (October-December). FM= February-March, MA= March-April, MJ= May-June, ON= October-November, ND=November-December.

Figure 4.44 presents the mean water level (i.e. average of nine water laser shots) dynamics between 2003 to 2009, with a mean water level 978.8 m and standard deviation 0.37 m (and range deviation of 1.3 m). The maximum water level fluctuations occurred in ON2004, ON2005, MA2007 and FM2008, while the lowest fluctuations occurred in MJ2006, followed by ON2006. In the flooding season (Figure 4.45), the maximum water level fluctuations occurred in 2007 and 2008, followed by 2009 and 2005, and the lowest in 2004. The highest mean water level recorded in MA2009 and the lowest in MA2007, with a mean water level of 979 m during flooding season and water level deviation 0.47 m (and range deviation of 1.12 m).
Figure 4.44 ICESat estimates of mean water level dynamics in the Okavango Delta, 2003-2009. These measurements (average of nine water laser shots along a profile) were acquired in the flooding season (February-April, May-June 2006 also included) and dry season (October-December). For laser campaign period, see Table 4.6 & Figure 4.43.

In the dry season (Figure 4.46), the maximum water level fluctuations occurred in 2004 and 2005, and the lowest in 2006. The highest mean water level was recorded in ND2008 and the lowest in ON2004, with a mean water level of 978.9 m during dry season and water level deviation of 0.3 m (range deviation of 0.85 m).
Figure 4.46 ICESat estimates of mean water level dynamics in the Okavango Delta, 2003-2008. These measurements (average of nine water laser shots along a profile) were acquired in dry season (October-December). For laser campaign period, see Table 4.6 & Figure 4.43.

**Water Level Change, 2007-2009**

Figure 4.47 presents the ICESat estimates of the water level change in the Okavango Delta, between 2007 (4 April) and 2009 (1 April). The ICESat recorded the historical water level rise of 2009 in the delta (since 1960s), with a water level rise of 0.8 m over 2007 (and -1.3 m over May-June 2006, see Figure 4.44). The mean water level in 2009 was -982.6 m and -981.8 m for 2007, with deviation of water levels 3.7 m and 3.8, respectively (Table 4.7). About 1.6 m water level change occurred for maximum water levels between 2007 and 2009, the minimum water levels remained same (estimation based on 41 laser samples). Note, variations in the water level depend on the location and openness of water bodies in the wetland.
Table 4.7 ICESat measured water level change (m) on the Okavango Delta, between 2007 and 2009 (as estimated along a 56 km north-south transect).

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>Water level (m)</th>
<th>Water level change, (2009 – 2007)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2007</td>
<td>2009</td>
</tr>
<tr>
<td>Minimum elevation</td>
<td>975.724</td>
<td>976.083</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>989.898</td>
<td>990.105</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>981.772</td>
<td>982.571</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>3.827</td>
<td>3.680</td>
</tr>
</tbody>
</table>

Note: Median water level elevation change between 2007 and 2009 is 0.784 m.

4.5 Characterisation of Multi-technology Models

This section describes the broad characteristics of topographic models constructed in the preceding sections: microtopographic, mesotopographic and water surface elevation.

Microtopographic Models

Figure 4.48 presents the micro-DEMs derived from air- and spaceborne optical stereo-observations by photogrammetry of the Okavango wetland. Two test site stereo-photogrammetric models, derived from air- and spaceborne optical observations, provided contrasting levels of topographic details. This is occurred due to physiographic difference of test sites, data acquisition techniques and elevation data capture methods. Although a direct comparison is not possible, both models provided detailed structure of wetland topography.

Figure 4.48 Micro-DEMs derived from air- and spaceborne optical stereo-observations by photogrammetry on the Okavango Delta. a) Airborne elevation model of Maunachira site, and b) spaceborne elevation model of Jao site.
Mesotopographic Models

The general trends of all mesotopographic models: minimum elevation ~920 m (except ASTER original) for all models (Table 4.8). The differences in technology have no significant effects in measurement of minimum elevation. The maximum elevation ranges between 1023 and 1080 m (except SRTM and ASTER original models). The maximum elevation differences are due to differences in technology, biophysical aspects (e.g. land/vegetation cover), sand dunes and hilly terrain. AGS model does not cover the Tsodilo Hills (1348 m), the highest elevation points in SRTM and ASTER models (located in the north-western edge of the study site). Topography, land cover, and time (i.e. data acquisition date) variation affected the sensors reflectance properties on sand dunes, wetlands, and water. This explains part of the reasons of variability (the other being instrumental) of elevation in mesotopographic models.

Table 4.8 Characteristics of mesotopographic models (m) on the Okavango Delta.

<table>
<thead>
<tr>
<th>Models</th>
<th>Spatial resolution</th>
<th>Elevation range</th>
<th>Standard deviation</th>
<th>Mean elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Minimum</td>
<td>Maximum</td>
<td></td>
</tr>
<tr>
<td><strong>GPS</strong></td>
<td>90</td>
<td>921</td>
<td>1042</td>
<td>18.61</td>
</tr>
<tr>
<td><strong>AGS</strong></td>
<td>50</td>
<td>923</td>
<td>1023</td>
<td>18.58</td>
</tr>
<tr>
<td><strong>SRTM</strong></td>
<td>90</td>
<td>918</td>
<td>1341</td>
<td>20</td>
</tr>
<tr>
<td>Original</td>
<td>30'</td>
<td>919</td>
<td>1328</td>
<td>19.89</td>
</tr>
<tr>
<td>Median filtered</td>
<td>30'</td>
<td>917</td>
<td>1080</td>
<td>19.77</td>
</tr>
<tr>
<td>Spectral filtered</td>
<td>30'</td>
<td>901</td>
<td>1348</td>
<td>20.33</td>
</tr>
<tr>
<td><strong>ASTER</strong></td>
<td>30</td>
<td>918</td>
<td>1072</td>
<td>19.87</td>
</tr>
<tr>
<td>Original</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectral filtered</td>
<td>30</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Resampled from 90 m.

Figure 4.49 presents the mesotopographic models from air- and spaceborne observations on the Okavango Delta with 5 m interval contours. The GPS-based model provided reference for other models in terms of topographic structure (i.e. roughness, relief, gradients and shapes, as shown by contours). Four elevation models (Figure 4.49), though constructed from various technologies, show similarities (to a great degree) of the Okavango Delta landscape topography at different scales (30 m [ASTER], 50 m [AGS] and 90 m [GPS and SRTM] spatial resolution). Contours (5 m interval) derived from various scale (resolution) elevation models exemplify these similarities. Furthermore, the multi-technology models provided comprehensive understanding of the Okavango Delta topography through complementary information.
Figure 4.49 Mesotopographic models from air- and spaceborne observations on the Okavango Delta, with contour overlay (5 m interval). a) GPS-based (90 m), b) airborne profiling radar (50 m), c) spaceborne imaging radar (spectral filtered) (30 m), and d) spaceborne optical stereo-imaging (spectral filtered) (30 m).

Figure 4.50 shows the characteristic of mesotopographic models, with mean elevation ranges between 957 m 961 m. This small mean difference (4 m) shows that most elevation points over the delta landscape are between ~920 m and ~1050 m (also see Figure 4.51). Few high elevation points (above 1100 m) in SRTM and ASTER datasets are located in the northwestern edge of the study area (i.e. Tsodilo Hills, 1348 m).
Figure 4.50 Elevation characteristics of multiplatform mesotopographic models. Mean elevation correlation of these models is significantly high ($R^2=0.665$). Minimum elevation correlation of these models are relatively high ($R^2=0.332$), while insignificant correlation exists for the maximum elevation ($R^2=0.058$).

The mean elevation correlation of these models is significantly high ($R^2=0.668$). Maximum and minimum elevation correlations of GPS, AGS, spectral filtered SRTM and ASTER models are moderately high ($R^2=0.513$ and $R^2=0.455$, respectively). Four selected mesotopographic models present roughly similar elevation characteristics (Figure 4.51). The average elevation ranges from about 957 m (AGS) to nearly 961 m (ASTER filtered), with a difference of 4 m. Filtered SRTM and ASTER provided roughly similar minimum and maximum elevations, while the AGS provided lower maximum elevation compared to other models. The GPS-based model provided more realistic elevation range (between minimum and maximum, i.e. 921 m to 1042 m).

Figure 4.51 Elevation characteristics of selected multiplatform mesotopographic models.
The water surface topography from SRTM C-band radar and water level dynamics from ICESat laser altimetry observations for the first time revealed the Okavango Delta water surface structure and water level dynamics. SRTM water surface topographic models: 1) water surface including aquatic vegetated areas and 2) open water surface models, characterised the patterns and directions of water flow in the delta. The high precision measurements (~ 3 cm [Zwally et al., 2002]) from ICESat laser altimetry made it possible to estimate the water level dynamics in the Okavango Delta and thereby demonstrated the potentiality of spaceborne laser altimetry. ICESat measurements revealed the internal structure and dynamics of the delta water level, distinguishing flooding season dynamics from the dry season, and fluctuations within each season. As mentioned earlier, ICESat recorded the historical flooding (since 1960s) over the delta in 1 April 2009. Both SRTM and ICESat complemented information for better understanding of the delta surface water topography and water level dynamics.

4.6 Conclusion

A multiplatform observation approach can effectively be used to construct variable resolution and landscape scale topographic models, especially in regions that lack reliable topographic data. Since the diverse platforms provide disparate but complementary observations, they can be used to produce multi-resolution elevation models (this chapter) as input to modeling hydrological and environmental processes. We measured and modeled topography at high and medium resolution from air, space and ground-based observations. The models from air and spaceborne (IKONOS) stereo-observations by photogrammetry (analytical and digital, respectively), for the first time, mapped the microtopography of the Okavango wetland (test sites) at high spatial resolution. To map the Okavango Delta regional topography, we constructed variable resolution mesotopographic models using GPS, profiling and imaging radar (AGS and SRTM), and optical stereo imaging (ASTER) observations. Further, we constructed water surface topography from imaging radar, and measured for the first time the water levels in the delta from profiling laser (ICESat) observations.

Both microtopographic models provided detailed topographic structure and thereby advanced understanding of the wetland landforms and the processes that shaped them. Mesotopographic models, through their complementary information, has provided regional topographic structure and advanced understanding of the contrasting Kalahari landforms (wetlands and non-wetlands) and the processes that shaped them. The Okavango Delta water topographic model constructed from a combined radar-optical (SRTM and Landsat 7) approach advanced understanding of the wetland water surface structure and flow patterns. Further, through a combined laser-optical (ICESat and Landsat 7) approach, we measured the precise water level elevation and elevation changes (2003-2009). Significantly, we found that ICESat laser observations recorded the historical flooding in the Okavango Delta (since 1960s) with 0.8 m water level rise in April 2009 over 2007.

The results of this study have significant implications in understanding the topographic and hydrological characteristics of the Okavango Delta. We demonstrated the advantage of a multiplatform approach to measure and construct variable resolution topographic models in a wetland environment. The quality of these elevation data products will be assessed in Chapter 6, and further analysed in Chapter 7.
Chapter 5

Mapping Land Cover from Optical Observations

I saw clouds and their light shadows on the distant dear earth.... The water looked like darkish, slightly gleaming spots.... When I watched the horizon, I saw the abrupt, contrasting transition from the earth's light-colored surface to the absolutely black sky. I enjoyed the rich color spectrum of the earth.

– Yuri Gagarin (1934–1968)

This chapter explores approaches to classify land cover from dual resolution optical observations and assesses the potential of single-band information content over multispectral channels in wetland mapping. These land cover products are used as determinant of elevation data assessment and bias calibration in succeeding chapters.

Keywords: Satellite remote sensing; optical observations; spectral characteristics; multispectral; mid-infrared; near-infrared; classification; land cover; water mask; determinant; wetlands.

5.1 Land Cover as Determinant

The core of earth observation from space is the information from images (Landgrebe, 1976) such as topographic, biophysical and atmospheric information. As a critical biophysical parameter, land cover determines the functioning of terrestrial ecosystems in biogeochemical cycling, in hydrological processes, and in the interaction between the surface and the atmosphere (Cihlar et al., 2000b). It is also one of the major factors in determining the measurement accuracy of terrain elevations by devices on air- and space platforms. Remote sensing provides direct observations to map and characterise land cover; in fact land cover map resulted from the development of this technology, initially through aerial photography (Colwell, 1960). Land cover products are key inputs to diverse applications such as hydrological modeling (Matheussen et al., 2000; Bauer, 2004; Bauer et al., 2006; Wolski et al., 2006), elevation data assessment (Carabajal and Harding, 2006; Hofton et al., 2006), and climate change (Feddema et al., 2005; Pielke Sr., 2005; Turner II et al., 2007; Pitman et al., 2011). Today, we have several remote sensing technologies available to map land cover (e.g. optical, radar and laser); however, optical technology remains the principal one. This study uses spaceborne optical observations to map land cover on the Okavango wetland (as designed in Chapter 3, Section 3.2.2), which will be used as a determinant of elevation data accuracy.

The wetland landscape is complex to be mapped in detail, thus land cover information from remote sensing images is extracted in classes. Mapping wetland land cover from an
Mapping Land Cover from Optical Observations

The Okavango wetland comprises mixtures of various features such as open water, shallow water areas with aquatic vegetation, saturated soil zones, islands of various size and shapes. Several approaches exist to extract information from remote sensing observations such as classification (e.g., land cover), physical property extraction (e.g., terrain elevation), change detection (e.g., land cover change) and extraction of spectral indices (e.g., vegetation index). Each approach has its own purpose, and merits and demerits. This study devises a single-band observation approach to classify wetlands, with an aim to extract reliably land cover information from spectral images. This simple yet effective approach is based on the selection of an appropriate band, which can equally provide important information compared to multispectral observations. A combination of an appropriate band and a classification method can produce better land cover information. This study assesses the multispectral bands (of Landsat 7 and IKONOS) using spectral characteristics of wetland land cover, then an appropriate band is selected from each multispectral image that can maximise classification accuracy. The research addresses the question: How significant is single-channel spectral information (e.g., Landsat 7 mid-infrared) content compared to multispectral observations for mapping wetland land cover?

Remote sensing of topography (terrain elevation) is hampered by land cover effects on spectral signatures, as this biophysical parameter affects the measurement accuracy of object elevation. Thus, several authors used land cover data to assess vertical errors in remotely-measured elevation data (Carabajal and Harding, 2006; Hofton et al., 2006). Also, remote sensing of high relief landscape is hindered by topographic effects on spectral signatures (Prox et al., 1989; Dozier and Frew, 1990; Colby, 1991). Thus, DEMs are used to improve image-based land cover classification, as topographic effects produce low accuracy (Justice et al., 1981; Ciuco, 1989; Hale and Rock, 2003). The Okavango Delta is characterised by gently-sloping topography, hence insignificant topographic effects on remote sensing observations. This thesis focuses on land cover data as determinant of elevation data accuracy: 1) assessing vertical errors in elevation data/models (in Chapters 6 and 7) and 2) calibrating low accuracy elevation data/models using higher accuracy data (in Chapter 7). For task 1, land cover data was used as control for class-wise assessment of vertical errors in elevation data using higher accuracy GPS measurements at three levels: wetland and non-wetland, broad land cover types, and delta water surface mask. For task 2, land cover data was used as control for class-wise calibration of elevation data using higher accuracy GPS measurements at two levels: wetland and non-wetland, and broad land cover types. The procedure is described in detail Chapters 6 and 7. This chapter produces these land cover data on the Okavango wetland from optical infrared (near- and mid-NIR and MIR) and multispectral observations. The following sections describe the optical sensor’s land cover characteristics and experiments to extract the desired cover types.

5.2 Spectral Characteristics of Land Cover

The key properties of remote sensing observations are four resolutions: spatial, spectral, radiometric and temporal. The observations in different spectral bands from visible to microwave region of the electromagnetic spectrum (Table 5.1) provide information about the radiative characteristics of the surface, from which physical and biophysical characteristics can be derived (Choudhury, 1991). The spectral signature provides useful features for identification and delineation of land cover classes on images. Spectral reflectance curves, or reflectance spectra, record the percentage of incident energy that is reflected by a material as a function of wavelength (Sabins, 1996). Table 5.1 shows the main spectral regions used in remote sensing of the earth and its environment, visible (0.4 to 0.7 μm), infrared (0.7 to 14
Multiplatform Observations for Measuring Wetland Landscape Topography

μm) and microwave (1 mm to 1 m). Infrared region comprises NIR, SWIR, MWIR and TIR/LWIR bands. The detail characteristics of these spectral regions are described in textbooks (Elachi and van Zyl, 2006; Schowengerdt, 2007; Lillesand et al., 2008), and beyond the scope of this research. Figure 5.1 shows the classical reflectance signatures for water, vegetation and bare soil, where reflectance can be characterized as a function of wavelengths.

### Table 5.1 The primary spectral regions used in remote sensing.

<table>
<thead>
<tr>
<th>Spectral region</th>
<th>Wavelength range (μm)</th>
<th>Radiation source</th>
<th>Surface property of interest</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Visible</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visible (VIS)</td>
<td>0.4 – 0.7</td>
<td>Solar</td>
<td>Reflectance</td>
</tr>
<tr>
<td><strong>Infrared</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Near infrared (NIR)</td>
<td>0.7 – 1.1</td>
<td>Solar</td>
<td>Reflectance</td>
</tr>
<tr>
<td>Shortwave infrared (SWIR)</td>
<td>1.1 – 1.35</td>
<td>Solar</td>
<td>Reflectance</td>
</tr>
<tr>
<td></td>
<td>1.4 – 1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 – 2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Midwave infrared (MWIR)</td>
<td>3 – 4</td>
<td>Solar, thermal</td>
<td>Reflectance, temperature</td>
</tr>
<tr>
<td></td>
<td>4.5 – 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal or longwave</td>
<td>8 – 9.5</td>
<td>Thermal</td>
<td>Temperature</td>
</tr>
<tr>
<td>infrared (TIR or LWIR)</td>
<td>10 – 14</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Microwave</strong></td>
<td>Microwave, radar</td>
<td>1 mm – 1 m</td>
<td>Temperature (passive),</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>roughness (active)</td>
</tr>
</tbody>
</table>

Source: adapted from Schowengerdt, 2007.

Mapping land cover from spectral properties of remotely sensed images is a powerful technique for extracting spatial information reliably and consistently over large areas. This study uses multispectral observations from dual spatial resolution optical satellites — Landsat 7 and IKONOS. Landsat 7 provides medium resolution (30 m) while IKONOS provides high resolution (4 m) images. Both satellite sensors have similar spectral windows for multispectral and panchromatic channels (Table 5.2).

### Table 5.2 Spectral characteristics of Landsat 7 ETM+ and IKONOS sensor.

<table>
<thead>
<tr>
<th>Wavelength region</th>
<th>Landsat 7 and IKONOS band no.</th>
<th>Spectral range (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>Landsat 7 ETM+</strong></td>
<td><strong>IKONOS</strong></td>
</tr>
<tr>
<td>VIS Blue</td>
<td>1</td>
<td>0.45 – 0.515</td>
</tr>
<tr>
<td>VIS Green</td>
<td>2</td>
<td>0.525 – 0.605</td>
</tr>
<tr>
<td>VIS Red</td>
<td>3</td>
<td>0.63 – 0.69</td>
</tr>
<tr>
<td>NIR</td>
<td>4</td>
<td>0.75 – 0.90</td>
</tr>
<tr>
<td>MIR</td>
<td>5</td>
<td>1.55 – 1.75</td>
</tr>
<tr>
<td>TIR</td>
<td>6 (High Pass)</td>
<td>10.40 – 12.50</td>
</tr>
<tr>
<td></td>
<td>6 (Low Pass)</td>
<td>–</td>
</tr>
<tr>
<td>MIR</td>
<td>7</td>
<td>2.09 – 2.35</td>
</tr>
<tr>
<td>Panchromatic</td>
<td>8 (Landsat 7)</td>
<td>0.52 – 0.90</td>
</tr>
</tbody>
</table>
Figure 5.2 shows the Landsat 7 multispectral image spectral characteristics (in digital numbers, DNs) of the wetland landscapes in channels 3 (red), 4 (NIR) and 7 (MIR), for each channel on a north-south transect. Each pixel’s radiance value is represented by a DN (between 0-255 for Landsat 7) that correspond to a surface object in that pixel (e.g. water, bare soil). Here, the spectral radiance for each channel is derived by averaging DN values over five columns on a north-south (N-S) transect as representation of land cover. Three ETM+ spectral bands are plotted along a transect (Figure 5.2c). These spectral features are valuable clues for recognizing and delineating land cover types on images, either visually or digitally. For example, spectral reflectance of water shows the distinctive characteristic of energy absorption at Landsat 7 MIR wavelength (2.09 to 2.35 μm) (see Figure 5.2, CH7). This band is best suited for locating and delineating water bodies and wetlands. Figure 5.3 shows the IKONOS multispectral image spectral characteristics (in DNs) of the permanent wetland landscapes in channels 2 (green), 3 (red) and 4 (NIR), for each channel on a north-south transect. Each pixel’s radiance value is represented by a DN (between 0-255, rescaled from original 0-2047) Spectral features in the IKONOS channels on a north-south (N-S) transect show the representation of land cover. Because of absorption property, IKONOS NIR wavelength (0.757-0.853 μm) (see Figure 5.3, CH4) is best suited for delineating water bodies and wetlands.

![Figure 5.1 Representative reflectance signatures for water, vegetation and bare soil (after Jones, 1997). The shape of the spectral reflectance curve provides clue to differentiate surface features (water, vegetation and bare soil). For example, water shows a reduction in reflectance with increasing wavelengths, and in the infrared region it becomes almost zero.](image-url)
Figure 5.2 Spectral characteristics of wetland landscape in Landsat 7 ETM+ multispectral image (30 m resolution), acquired in April 2000. a) Multispectral image (band 5,4,2 false color combination) with 15 km N-S transect (white), b) land cover classes derived from the multispectral image (transect in white), c) spectral characteristic of channels 3 (red), 4 (NIR) and 7 (MIR) on the N-S transect (from west to east on the graph) showing distinction among wetland features such as open water, swamp, land-vegetation and bare soil.

Figure 5.3 Spectral characteristics of wetland landscape in IKONOS multispectral image (4 m resolution), acquired in October 2003. a) Multispectral image (band 1,2,3 false color combination) with 9.2 km N-S transect (yellow), b) spectral characteristic of channels 2 (green), 3 (red), and 4 (NIR) on the N-S transect (from west to east on the graph) showing distinction among wetland features (e.g. swamp and land-vegetation).
5.3 Image Classification

All remotely sensed image processing operations are aimed at a better recognition of spatial objects of interest (Jahne, 2002) such as land cover types. Several approaches exist, however, supervised and unsupervised are two major methods used in remotely sensed image classification. Both these methods have advantages and disadvantages. The difficulty in selecting training sites due to variability of spectral response is one of the main disadvantages of the supervised approach. The unsupervised approach reveals distinguishable classes with given spectral attributes, and thus ground data collection requirements are reduced. Additionally, it has the potential advantage of revealing discriminable classes unknown from previous work (Townshend and Justice, 1980). These two methods have been described in detail (Jain, 1989; Jahne, 2002; Mather, 2004; Jensen, 2005; Richards and Jia, 2006; Schowengerdt, 2007; Gonzalez and Woods, 2008) and beyond the scope of this research. The present study focuses on unsupervised approach that addresses the issue of partitioning objects or pixels into categories. This approach is concerned with category coherence, i.e. why some categories are more natural or intuitive than others. In image-based land cover classification, unsupervised approach uses the spectral image properties (in DNs) to define the classes or categories, and then relates the classes to ground areas with known properties. It requires a substantial involvement of the analyst (Townshend and Justice, 1980) and labelling of land cover class requires knowledge of the terrain.

Two steps are used in unsupervised classification – clustering and classification. Clustering is the unsupervised classification of patterns, e.g. an image, into groups or clusters. It arranges samples into groups of maximum homogeneity, while classification allocates samples to a particular cluster (de Moral, 1975). Clustering, however, is a difficult problem combinatorially, and different approaches to this problem have been proposed and studied (Jain et al., 1999). Typical pattern clustering involves the following steps (Jain and Dubes, 1988): 1) pattern representation (optionally including feature extraction and selection), 2) definition of a pattern proximity measures appropriate to the data domain, 3) clustering or grouping, 4) data abstraction (if needed), and 5) assessment of output (if needed).

Several unsupervised clustering algorithms exists such as K-means and ISODATA (Richards and Jia, 2006). The ISODATA (Ball and Hall, 1965) algorithm uses the technique of merging and splitting clusters. A cluster is split when its variance is above a pre-specified threshold, and two clusters are merged when the distance between their centroids is below another pre-specified threshold (Jain et al., 1999). ISODATA is a nonhierarchical, divisive, iterative, and polythetic method based on Euclidean distance (Williams, 1971). The present study uses an unsupervised method based on the ISODATA algorithm to extract land cover from spaceborne optical multispectral observations on the Okavango wetland.

5.4 Spectral Classification of Land Cover

5.4.1 Data and Classification Approach

Data Characteristics

The remote sensing multispectral images used are from Landsat 7 and IKONOS (for detail see, Section 2.4.2); they are categorised into medium (30 m) and high spatial resolution (4 m). Spatial resolution is one of the key properties of images; the radiation recorded by a sensor is dependent on, among other things, the spatial resolution of the sensor relative to the spatial frequency of the terrain (Wulder et al., 2000). The present study adopted medium resolution as images with a spatial resolution between 10 and 30 m, while high resolution as images having a spatial resolution of 10 m and less. Some authors characterized medium resolution
imagery as images with a spatial resolution between 10 and 100 m, while high resolution imagery having a spatial resolution of less than 10 m (Wulder et al., 2008). According to spatial resolution, pixels in images form the discrete objects of varying size as remote observing instruments discretise a continuous natural surface into a uniform grid of equal size and shape pixels (Fisher, 1997). Thus, a high spatial resolution image provides detail information, better object boundaries and shapes, and represent more land cover types than lower resolution image that resulted in generalised object boundaries and shapes. For example, Landsat 7 image is suited for regional studies (e.g. Okavango Delta), while IKONOS image is suited for detailed mapping of smaller areas.

**Classification System**

The basis for land cover classification is the structure (Davis, 1899), i.e. the composition of surface objects. Figure 5.4 presents the classification system of the Okavango wetland land cover features. These classes are devised based on the requirement in this study (i.e. as determinants to elevation data accuracy assessment and model calibration) and extractability through spectral classification of wetland remote sensing images. First, wetland land cover is broadly divided into wet and non-wet areas. At the next level, wet area was sub-classified into open water surface and swamp. Similarly, non-wetland area was sub-classified into land-vegetation and bare soil (or bare earth). Table 5.3 characterises the Okavango wetland land cover classes at two levels. Class I gives general characteristic of land cover, while class II provides specific detail.

![Classification System Diagram](image)

**Figure 5.4** Classification system of major land cover features of the Okavango wetland. This system is designed based on the requirements in this study, and extractability of desired classes from spaceborne optical multispectral observations. Table 5.3 characterises these classes.

**Table 5.3** Characteristics of land cover classes on the Okavango wetland.

<table>
<thead>
<tr>
<th>Class I</th>
<th>Class II</th>
<th>Characterization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wet areas</td>
<td></td>
<td>Open and shallow water surface, aquatic vegetation and saturated land surface</td>
</tr>
<tr>
<td>Open water</td>
<td></td>
<td>Areas with open surface water</td>
</tr>
<tr>
<td>Swamps</td>
<td></td>
<td>Areas with aquatic vegetation and saturated land surface</td>
</tr>
<tr>
<td>Non-wet areas</td>
<td>Land-vegetation</td>
<td>Land-vegetation areas within the general wetland area</td>
</tr>
<tr>
<td>Bare soil</td>
<td></td>
<td>Land areas with part or full vegetation cover</td>
</tr>
<tr>
<td></td>
<td>Bare soil</td>
<td>Land areas with bare earth and no vegetation cover</td>
</tr>
</tbody>
</table>
5.4.2 Data Georegistration

Georegistration is the core of multiplatform observation approach to landscape topographic modeling. Effective integration of diverse topographic and land cover data depend on the accurate georegistration of datasets. Landsat 7 and IKONOS multispectral images are referenced to Clarke 1880 ellipsoid, Cape datum and UTM projection Zone 34 S using nearest neighbour resampling technique with first order polynomial transformations. The detail projection parameters are given in Appendix VIII. Figure 5.5 shows the image rectification procedure and influence of ground control points. Sufficient number of spatially well-

![Diagram of rectification procedure](image)

**Figure 5.5** The procedure of image rectification. Ground control points (number, distribution and location) determines the robustness of the final solution.

distributed control points are required for good solution to a model. The relationship between the original pixel co-ordinates \((x,y)\) and the transformed co-ordinates \((u,v)\) in the new projection is specified by a pair of mapping functions (Rees, 2001):

\[
\begin{align*}
  u &= f(x,y), \\
  v &= g(x,y),
\end{align*}
\]

and by an equivalent pair of inverse functions:

\[
\begin{align*}
  x &= F(u,v), \\
  y &= G(u,v).
\end{align*}
\]
About one pixel accuracy (>30 m in object space) was achieved for Landsat 7 multispectral image registration, while 0.16 pixel (0.6 m in object space) accuracy was achieved for IKONOS multispectral image. The detail results of georegistration of images are given in Appendix IX. After georegistration of Landsat 7 mosaicked delta image, wetland area was masked. The reason for masking wetlands: 1) main focus of this study is the wetland area, 2) to improve land cover classification by masking out non-wetland areas.

5.5 Experiments

5.5.1 Medium Resolution Multispectral vs. MIR Observations

Data and Method

This section uses Landsat 7 ETM+ multispectral images (visible and infrared channels [visible: 1,2,3; NIR: 4; and MIR: 5&7]) on the Okavango wetland (for detail on data, see Section 2.4.2). Figure 5.6a shows the Landsat 7 multispectral image at 30 m spatial resolution (band 5,4,2 [MIR, NIR and green] false color combination) of the wetland, acquired in April 2000. These 8-bit (0-255) images were georegistered to common projection parameters as elevation data (Section 5.4.2) and mosaicked. A wetland mask (previously created by the Okavango researchers) was overlaid on the mosaicked Landsat 7 multispectral image to examine its fit with the wetlands. Visual inspection of the image (5,4,2 band-combination) shows that the mask fits well with the wetland boundary (only a few wet pixels can be found outside the mask). Using this mask, wetland areas are cut out from the mosaicked Landsat 7 multispectral image of the delta (Figure 5.6a). The reason for masking: 1) the main focus of this study is on the wetlands, and 2) it increases classification accuracy of wetland land cover by reducing spectral heterogeneity on the image (that would have arisen from surrounding non-wetland areas).

An unsupervised clustering and classification approach with ISODATA algorithm was used to extract land cover information separately from Landsat 7 1) six-band multispectral (0.45 to 1.75 μm and 2.09 to 2.35 μm), and 2) MIR channel (band-7: 2.09 to 2.35 μm) images on the Okavango wetland. In the multispectral image (six-bands), initially 9 clusters were identified with 6 iterations. In the MIR image of the wetland (Figure 5.6b), initially 5 clusters were identified with 6 iterations as larger clusters (e.g. 10) created spectral mixtures. The resultant clusters of multispectral and MIR images were then assigned to four categories of land cover (Figure 5.4) using the spatial knowledge from Landsat 7 multispectral and Pan images and topographic maps. The assumption is that each cluster falls in one of the four classes (with no inter-class confusion) – open water, swamp/wetland, land-vegetation and bare soil. Open water and swamp/wetland land cover classes, derived from MIR channel observations, are combined to create a water surface mask.

Results and Discussion

Figure 5.7a shows that the wetland area covers nearly 15,050 km². Out of this, swamp comprises 9,900 km² (66%) and land area 5,150 km² (34%). This result is for April 2000, based on Landsat 7 ETM+ six-band multispectral image. The total wetland area may have gone up by about 100 km², if classification would have done without masking wetlands from the delta region. Table 5.4 presents the statistical information of land cover classes and areas in the wetlands. It shows marginal difference in actual wetland (i.e. swamp) and land area between four multispectral channels-based classification (66% and 34%) and classification
based on MIR channel alone (68% and 32%). The MIR channel (Figure 5.6b) alone provides sufficient spectral information for delineation of wetland land-water boundary and other features (Figure 5.7b) as can be seen from the land cover information in Table 5.4. The reason being MIR channel (band-7) has a large dynamic range: within the wetland area DN value ranges from 4 to 251, with a mean of 48.85 and standard deviation of 25.2. The MIR channel shows water in deep dark because of high absorption, and land surface as bright due to high reflectivity. Figures 5.8a and b show the enlarged subsets of multispectral and MIR channel image classification result. The MIR channel, compared to multispectral channels, distinctly separated open water and swamps from land-vegetation and bare soil.
**Figure 5.7** Land cover derived from Landsat ETM+ multispectral and MIR images (3 and 10 April 2000), the Okavango wetland. a) Land cover from six-band multispectral image, b) from MIR channel (band-7) image.

**Figure 5.8** Comparison of land cover derived from Landsat 7 multispectral and MIR images [600 x 633 pixels]. a) Enlarged subset from Figure 5.7a (S1), b) enlarged subset from Figure 5.7b (S2). MIR channel clearly separated wet areas (water and swamps) from non-wet (bare soil and land-vegetation) areas, while multispectral channels misclassified some water/swamp pixels as land-vegetation (e.g. yellow features along the channel). Subset covers an area of 18 km x 19 km (342 km²).
Table 5.4 Land cover statistics on the Okavango wetland, based on Landsat 7 multispectral and mid-infrared (band-7) images.

<table>
<thead>
<tr>
<th>Land cover class</th>
<th>Area (km²)</th>
<th>% of total</th>
<th>Actual wetland vs. land area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MS</td>
<td>MIR</td>
<td>MS</td>
</tr>
<tr>
<td>Open water</td>
<td>3366</td>
<td>2996</td>
<td>22.37</td>
</tr>
<tr>
<td>Swamp/wetland</td>
<td>6530</td>
<td>7186</td>
<td>43.4</td>
</tr>
<tr>
<td>Land-vegetation</td>
<td>4477</td>
<td>3195</td>
<td>29.75</td>
</tr>
<tr>
<td>Bare soil</td>
<td>674</td>
<td>1669</td>
<td>4.48</td>
</tr>
<tr>
<td>Total</td>
<td>15047</td>
<td>15046</td>
<td>100</td>
</tr>
</tbody>
</table>

A mask of the Okavango Delta water surface (Figure 5.9) was extracted from the Landsat 7 multispectral observations (acquired in early-April 2000), which is used to extract water surface elevation from the SRTM model and ICESat profiling laser observations (Chapter 4). This mask (Figure 5.9a) is also used to assess elevation data accuracy (Chapter 6). Figure 5.9b shows the open water surface of the delta, while Figure 5.10 shows enlarged sites of the open water areas (Panhandle [S1] and permanent swamp [S2]). The acquisition date of Landsat 7 observation fits well with the SRTM elevation data acquisition date (i.e. February 2000).

Figure 5.9 Water surface mask from the Landsat 7 multispectral (band 1-5 & 7) observations (3 and 10 April 2000), the Okavango Delta. a) The mask comprises open water surface and swamps (including aquatic vegetated areas), b) mask of open water surface. Note, no field verification was done. See S1 and S2 (red box) in enlarged form in Figure 5.10.
5.5.2 High Resolution Multispectral vs. NIR Observations

Data and Method

This section uses an IKONOS multispectral image (visible and NIR channels) on the permanent swamp of the Okavango wetland (for detail on data, see Section 2.4.2; for location see, Figure 2.17 in Chapter 2). Figure 5.11 shows the IKONOS multispectral image at 4 m spatial resolution (band 1, 2, 3 [blue, green and red] false color combination) of Jao area in the delta, acquired in October 2003. These images (11-bit) were georegistered (Section 5.4.2) to common projection parameters as done for elevation data. An unsupervised clustering and classification approach (ISODATA algorithm) was used to extract land cover information, separately from IKONOS 1) four-band multispectral (0.45 to 0.85 μm) and 2) NIR channel (0.75 to 0.85 μm) images. In unsupervised classification, pixels that exhibit similar characteristics are subdivided into homogeneous spectral regions based on a set of boundary conditions specified by the user (Le Hegarat-Mascle et al., 1997). This method uses clustering approach to establish decision regions based on spectral properties of the corresponding ground covers. The spectral classes were then converted to information classes by identifying the ground cover that corresponds with each spectral class. In the IKONOS multispectral image, initially 10 clusters were specified with 6 iterations. In the NIR channel image, initially 5 clusters were specified with 6 iterations, as more clusters created inapt mixture of spectral land cover information. The resultant clusters of multispectral and NIR images were then assigned to four land cover classes (Figure 5.4) using the spatial knowledge through visual inspection of IKONOS multispectral image and topographic maps. The assumption is that each cluster falls in one of the four classes (with no inter-class confusion) – open water, swamp/wetland, land-vegetation and bare soil.
Figure 5.11 IKONOS multispectral image of Jao area in the Okavango Delta (4 m spatial resolution; band 1,2,3 [blue, green and red] false color combination). This image was acquired on 11 October 2003, and it covers 5.9 km x 9.6 km (56.64 km²) area. Most part of this permanent wetlands comprise aquatic vegetated swamp (red), two large islands (Geranendi and Xhamogo) and numerous small islands (bluish-white), and open water surface. Island margins are ringed with trees.
Results and Discussion

Figure 5.12 presents the major land cover type information derived from IKONOS multispectral and NIR channel images of the Jao area in the Okavango Delta. The area comprises 51 km² area (1376 x 2311 pixels), of which about 70 percent covered by open water and swamps (Table 5.5). The remaining ~30 percent area is composed of land-vegetation and bare soil.

![Figure 5.12](image)

**Figure 5.12** Land cover derived from IKONOS multispectral and NIR images (5.5 km x 9.24 km), Jao area of the Okavango Delta. a) Land cover from four-band multispectral image, b) land cover from NIR channel image.

<table>
<thead>
<tr>
<th>Land cover class</th>
<th>Area (km²)</th>
<th>Area (km²)</th>
<th>Actual wetland vs. land area (km²)</th>
<th>Area (km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MS</td>
<td>NIR</td>
<td>MS</td>
<td>NIR</td>
</tr>
<tr>
<td>Open water</td>
<td>9.92</td>
<td>8.85</td>
<td>35.46 (70%)</td>
<td>37.47 (74%)</td>
</tr>
<tr>
<td>Swamp/wetland</td>
<td>25.54</td>
<td>28.63</td>
<td>62.53 (90%)</td>
<td>66.47 (90%)</td>
</tr>
<tr>
<td>Land-vegetation</td>
<td>11.81</td>
<td>6.89</td>
<td>20.62 (31%)</td>
<td>15.42 (29%)</td>
</tr>
<tr>
<td>Bare soil</td>
<td>3.61</td>
<td>6.51</td>
<td>7.22 (12%)</td>
<td>10.41 (16%)</td>
</tr>
<tr>
<td>Total</td>
<td>50.88</td>
<td>50.88</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
IKONOS NIR channel alone provides better land-wetland discrimination capability (Figure 5.12b and its subset in Figure 5.13b) than four multispectral bands together, which mixes the inapt spectral information (Figure 5.12a and its subset in Figure 5.13a). The classification of inapt mixed multispectral observations resulted in incorporation of wetland pixels into land areas, which NIR channel classification clearly differentiated. Classification results were verified comparing with aerial and IKONOS panchromatic images (1 m spatial resolution) and using field knowledge of the area. The wrong classification of swamps as land-vegetation in the multispectral image (Figures 5.12a and 5.13a) comes from the visible bands (0.4 to 0.7 μm: blue, green and red).

![Figure 5.13](image1.png)  
**Figure 5.13** Comparison of land cover derived from IKONOS multispectral and NIR images [436 x 502 pixels]. a) Enlarged subset from Figure 5.12a (S1), b) enlarged subset from Figure 5.12b (S2). NIR channel clearly separated wet areas (open water and swamp) from non-wet (bare soil and land-vegetation) areas, while multispectral channels mixed-up many water/swamp pixels as land-vegetation (yellow features in wet areas).

### 5.6 Conclusion

Optical remote observations can be effectively used to map wetland land cover by clustering and classification. We classified wetland land cover from dual-resolution optical observations and evaluated the potential of single over multispectral channels. The classification of a single infrared band (e.g. NIR or MIR) produced equally useful products on water surface as multispectral bands.

Landsat 7 MIR (band-7) and IKONOS NIR wavelengths provided suitable spectral information for wetland land cover classification and delineation of the nonwetland-wetland interface because wetlands have very low reflectance in this region of the electromagnetic spectrum. The IKONOS NIR channel alone contains sufficient spectral features of wetland land cover as multispectral observations. The Landsat 7 MIR channel has shown a similar result, as infrared channels (NIR and MIR) have the characteristic of high water absorption and high land surface reflection. For Landsat and IKONOS, multispectral image classification
only marginally improved the quality of land cover mapping over the single-band image classification. The evaluation of these results were limited to visual inspection.

The identification and delineation of wetland land cover types from remote sensing depends on the relative spectral characteristics of surface features (e.g. water, soil and vegetation) and the sensor spatial resolution. For example, Landsat 7 multispectral observations (medium resolution with large swath) produced regional level land cover on the Okavango wetland with little detail, while IKONOS multispectral observations (high resolution with small swath) produced more detailed land cover information, but for a smaller area.
Chapter 6
Assessing the Accuracy of Topographic Data and Models

**Scientific knowledge is a body of statements of varying degree of certainty – some most unsure, some nearly sure, but none absolutely certain.**

– Richard Feynman (1918–1988)

In Chapter 4, we presented elevation models from various platform observations at diverse spatial resolution and levels of detail. This chapter assesses the accuracy of these models against reference elevation data. The comparability of profiling laser (ICESat) and GPS measurements are assessed and geolocation accuracy of datasets are described. The accuracy of imaging radar (SRTM) and optical stereo-imaging (ASTER) elevations are thoroughly evaluated as they provide consistent mesotopographic coverage over the study region. Finally, errors in elevation data are characterized.

Keywords: Accuracy assessment; microtopographic model; mesotopographic model; water surface elevation; reference data; physiographic region; land cover; water surface.

6.1 Assessing Elevation Data

All measurements, however careful and scientific, are subject to some uncertainties (Taylor, 1997). The estimation of accuracy and reliability of digital elevation data and models is a fundamental component of topographic modeling. Accuracy gives the degree of conformity with better quality reference data, while reliability gives the confidence to a dataset based on available metadata and inspections by the users. Mathematical models (e.g. DEMs) have no scientific value until and unless they have been adequately validated with factual data through experience or research (Ghosh, 1988). A DEM is a 3D representation of the landscape topography, where error may come from two fronts – planimetric coordinates \((x,y)\) and vertical heights \((z)\), and can be random or systematic. Error is the difference between the true or established value and the measured value. Knowledge of error characteristics (including spatial distribution and magnitudes) in elevation data are essential before using them as a product or input since they introduce error in applications (e.g. as input to modeling hydrological processes), hence the resultant erroneous information. As the DEM technologies evolve, various approaches are used to evaluate errors in the elevation data (Shearer, 1990; USGS, 1993; Bolstad and Stowe, 1994; Fisher, 1998; Liu and Jezek, 1999; Holmes et al., 2000; Talukdar, 2003a; Falorni et al., 2005; Carlisle, 2005; Maune, 2007; Florinsky, 2012). The general approach of evaluating elevation data is by using higher quality data as a reference. Several studies have been published on assessing the accuracy of SRTM data using...
higher accuracy reference data such as shuttle laser altimetry observations (Sun et al., 2003), National Elevation Dataset (NED), high-resolution airborne laser data (Smith and Sandwell, 2003; Hofton et al., 2006), elevations of ground control points (GCPs), U.S. Geological Survey DEM (Falorni et al., 2005), GPS (Hoffmann and Walter, 2006; Rodríguez et al., 2006) and globally-consistent data measured over airports runaways (Becek, 2008). Some researchers have used land cover as determinant in assessing SRTM elevation accuracy (Hodgson et al., 2003; Carabajal and Harding, 2006; Shortridge and Messina, 2011). Globally available high accuracy satellite laser altimetry data has provided a viable reference data to evaluate elevation models constructed from optical stereo-photogrammetry (Kääb, 2008), radar interferometry (Bamber and Gomez-Dans, 2005; Carabajal and Harding, 2005, 2006) and national elevation datasets (Beaulieu and Clavet, 2009).

Although substantial topographic modeling and elevation data quality work has been done over diverse landforms, research on wetland landscapes is inadequate, particularly in Africa. The Okavango Delta is a poorly researched region in topographic modeling and elevation data quality assessment; the present study addresses these issues. Assuming planimetric accuracy of the datasets (used in this study) is within reasonable limits at co-registration (< 1 m for micro- and < 30 m for mesotopographic models) and produces smaller vertical error (e.g. 1 to 5 m) because of relative flatness of the wetland topography (see Section 6.3), this study focuses on assessing vertical errors (as per Section 3.2.4, Chapter 3). Three sets of elevation data were assessed: 1) microtopographic models, 2) mesotopographic models, and 3) water surface elevation (Figure 6.1). Reference datasets used are: 1) GPS

![Figure 6.1 Outline for accuracy assessment of topographic (elevation) models. Elevation models are assessed against (higher accuracy) reference data to estimate the vertical error (root mean square error, RMSEz). Topographic datasets are defined as: Optical model 1 = airborne stereophotogrammetry Optical model 2 = IKONOS stereophotogrammetry Profiling radar model = AGS Imaging radar model = SRTM Optical stereo model = ASTER Profiling laser elevation = ICESat](image-url)
GCPs and postings, 2) analytical photogrammetric DEM, and 3) laser altimetry observations. This research addresses the science question (of Chapter I): To what extent does physiography and land cover acts as a determinant of vertical errors in elevation data (e.g. SRTM DSM)? The goal of this chapter is to assess the vertical error budgets of elevation datasets on the Okavango wetland region, where no comprehensive research is done on topographic modeling and elevation data quality assessment. Further, assessment helps selection of elevation data for integration to produce improved quality topographic models (see Chapter 7). Assessment comprises a three-step empirical methodology: 1) establishment of reference data, 2) partitioning the study area into physiographic regions and land cover types, and 3) assessment of elevation data/models (test sites, regional, and water level) with reference data, relative to step 2. Detailed statistical methods used for comparison and assessment of elevation data accuracy are given in Appendix XI.

6.2 Reference Datasets

This section describes reference datasets for assessing the elevation models measured and constructed in Chapter 4.

6.2.1 Preparing Datasets

Datasets: GPS GCPs and postings, ICESat profiling laser observations, and airborne stereophotogrammetric DEM (see details in Chapter 2, Section 2.4.2).

Approach: GPS measurements (GCPs and postings) form the main reference data (i.e. high vertical accuracy data). To establish an additional reference dataset, ICESat laser data were compared against GPS measurements. Airborne stereophotogrammetric DEM is the third set of reference data that is used in Chapter 7 (Section 7.2). GPS GCPs provides test site reference data, while GPS postings and ICESat laser measurements provides regional reference data. GPS postings provide sparse sampling (~7.5 km apart) and they are measured on selected features (surveyed in 1998-1999), while the ICESat provides larger and unbiased sampling (acquired between 2003-2009). Airborne analytical photogrammetric DEM provides detailed elevation information at a test site. Table 6.1 characterises the reference elevation datasets for the test sites and regional level.

<table>
<thead>
<tr>
<th>Elevation data</th>
<th>Coverage</th>
<th>Sample size</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS GCPs</td>
<td>Test sites (3)</td>
<td>47 control points</td>
</tr>
<tr>
<td>GPS postings</td>
<td>Regional</td>
<td>1002 postings (~7.5 km distance)</td>
</tr>
<tr>
<td>Laser altimetry observations (ICESat)</td>
<td>Regional</td>
<td>&gt;135000 footprints (70 m diameter, 170 m along-track, ~65 km across-track)</td>
</tr>
<tr>
<td>Analytical photogrammetric DEM</td>
<td>Test site</td>
<td>5 m grid-size model</td>
</tr>
</tbody>
</table>
6.2.2 Comparability of Laser Altimeter and GPS Measurements

Figure 6.2 presents the distribution of ICESat laser profiles and GPS postings on the Okavango Delta SRTM hydrologically conditioned elevation surface. Figure 6.2a shows the distribution of GPS postings and ICESat laser profiles, while Figure 6.2b shows the corresponding GPS postings on the laser shots.

![Image of Figure 6.2]

Figure 6.2 Distribution of GPS postings (yellow dots) and ICESat laser altimeter profiles (black) on the Okavango Delta region SRTM (U.S. Geological Survey) hydrologically conditioned elevation surface (90 m spatial resolution). The SRTM elevation ranges from 872 m to 1324 m with mean height of 957.37 m. a) GPS postings and ICESat profiles (2003-2009) on the delta, b) GPS postings on the corresponding ICESat footprints; these matching points are distributed across all landforms in the delta region.

Approach

The accuracy of topographic elevation measured by the laser altimeter on ICESat (Figure 6.2) was established by comparing against GPS measurements (~0.15 m vertical accuracy). The corresponding laser measurements (within a 300 m x 300 m cell, converted from laser points) to GPS measurements on the delta were extracted (Figure 6.2b). The cell size 300 m was selected to find well-distributed GPS samples over diverse landscapes for the assessment of ICESat data. These extracted ICESat points were then compared against GPS measurements:

\[
\Delta Z = ICESat_z - GPS_z
\]  

where \(\Delta Z\) is the elevation difference, \(ICESat_z\) is the elevation point in the ICESat observations, and \(GPS_z\) is the reference elevation posting. Three points with elevation difference (ICESat\(_z\) – GPS\(_z\)) of above 3 standard deviation are eliminated as laser outliers, out of 160 points (i.e. 99.73% of the data values lie within 3\(\sigma\) [3.6 m] of the mean). Further, to examine the effect of cell size in assessment of laser elevation, 200 m cell size was selected and following the principle used above corresponding laser points of GPS points on the delta were extracted (Figure 6.3).
Results and Discussion

Table 6.2 presents the comparative assessment between ICESat and GPS elevation (157 samples). The mean elevation of GPS is 967.78 m ($\sigma = 15.46$ m), while ICESat mean elevation is 967.76 m ($\sigma = 15.81$ m). The mean elevation deviation of ICESat is $-0.02$ m (median error $-0.068$ m) and standard deviation error of $1.208$ m. The RMSE of ICESat elevation is $1.205$ m, compared to GPS.

![Figure 6.3 Distribution of GPS postings (black) on the ICESat laser tracks (ICESat data cell 200 m x 200 m).](image)

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>$^7$GPSz</th>
<th>ICESatz</th>
<th>Difference ICESatz – GPSz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation</td>
<td>938.328</td>
<td>938.067</td>
<td>$-3.238$</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>1014.736</td>
<td>1018.196</td>
<td>$3.591$</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>967.777</td>
<td>967.758</td>
<td>$-0.019$</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>15.461</td>
<td>15.805</td>
<td>$1.208$</td>
</tr>
<tr>
<td>RMSE (ICESat)</td>
<td></td>
<td></td>
<td>$1.205$</td>
</tr>
</tbody>
</table>

$^7$GPS sample = 157 points.

Figure 6.4 shows that ICESat and GPS elevation corresponds well over the contrasting Kalahari landscapes that comprise wetlands, open water, grasslands and sand dunes. A high correlation exists between GPS and ICESat elevation ($R^2 = 0.99$, Figure 6.5a). Figure 6.5b shows the difference in elevation between two datasets, with a mean deviation of $-0.019$ m and range deviations between $-3.24$ m and $3.59$ m (Table 6.2).
Figure 6.4 ICESat and GPS elevation relation on the delta region. The profile reflect similarities between ICESat and GPS data (and not a transect along a line).

The assessment of ICESat against GPS elevation with 54 samples shows that mean GPS elevation is 955.6 m ($\sigma = 15.96$ m) and ICESat mean elevation is 955.79 m ($\sigma = 16.11$ m) (Table 6.3). The mean elevation error of ICESat is 0.19 m with a standard deviation error of 1.18 m. The RMSE of ICESat elevation is 1.19 m, compared to 1.21 m with 157 samples. As in the previous assessment, there is a high correlation between GPS and ICESat elevation ($R^2 = 0.99$, Figure 6.6a). Figure 6.6b shows the difference in elevation between two datasets, with a mean deviation of 0.19 m and range deviations between -2.79 m and 3.8 m (Table 6.3). The different cell size applied to ICESat (300 m and 200 m) had a negligible impact on the RMSE.
### Table 6.3 Comparison of GPS and corresponding elevation from ICESat measurements (200 m cell) (m) on the delta.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>'GPSz</th>
<th>ICESat</th>
<th>Difference ICESat - GPSz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation</td>
<td>923.294</td>
<td>923.330</td>
<td>-2.788</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>998.032</td>
<td>998.427</td>
<td>3.800</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>955.601</td>
<td>955.789</td>
<td>0.189</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>15.962</td>
<td>16.111</td>
<td>1.184</td>
</tr>
<tr>
<td>RMSE (ICESat)</td>
<td></td>
<td></td>
<td>1.188</td>
</tr>
</tbody>
</table>

*GPS sample = 54 points. Median elevation error = 0.128 m

### Figure 6.6 Comparison of ICESat and GPS elevation on the delta (54 samples). a) ICESat vs. GPS elevation relationship, with high positive correlation, b) elevation difference: ICESat - GPS.

### 6.2.3 Established Reference Datasets

The first set of reference data is the GPS GCPs and postings. The second set of reference data was established by comparing ICESat laser measurements against GPS elevation (Table 6.4). The RMSE of elevation datasets was used as a measure of accuracy for each dataset. Airborne stereo-photogrammetric DEM form the third set of reference data (used in Chapter 7). We assumed that the vertical accuracy of the photogrammetric DEM was ~1 m, as the model was generated using analytical photogrammetry using high accuracy GPS GCPs (~0.16 m vertical).

These reference datasets are used to assess accuracy of elevation models constructed as described in Chapter 4: 1) digital photogrammetric microtopographic model from IKONOS stereo-observations, 2) mesotopographic models: airborne radar model from airborne geophysical survey (AGS), C-radar model from SRTM, and optical stereo model from ASTER, and 3) water surface elevation from air- and spaceborne radar (AGS and SRTM), and laser (ICESat) observations. The microtopographic model was assessed with GPS measurements, while mesotopographic models and water surface elevation were assessed with GPS and ICESat laser measurements.
### Table 6.4 Accuracy of reference elevation datasets.

<table>
<thead>
<tr>
<th>Reference dataset</th>
<th>Method of establishment</th>
<th>Accuracy (RMSE, m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS GCPs (2002)</td>
<td>2002 vs. 1990s GCPs</td>
<td>*~0.16</td>
</tr>
<tr>
<td>GPS postings</td>
<td>As specified by Poseidon Geophysics</td>
<td>**~0.15</td>
</tr>
<tr>
<td>Laser altimetry observations (ICESat)</td>
<td>ICESat observations vs. GPS</td>
<td>***1.21</td>
</tr>
<tr>
<td>Analytical photogrammetric DEM</td>
<td>Analytical photogrammetric DEM vs. GPS GCPs</td>
<td>~1</td>
</tr>
</tbody>
</table>

Note: Vertical accuracy of *GPS GCPs and **GPS postings. For GPS postings, accuracy as specified by Poseidon Geophysics (a Geophysical survey company). ***RMSE of ICESat data was estimated using GPS controls/postings.

### 6.3 Geolocation Accuracy of Datasets

Both the reference datasets (described in the previous section) and the datasets evaluated in the following section are affected by positional errors. Although all datasets are georeferenced to same ellipsoid and datum, there are positional errors due to geolocation and georegistration of datasets. Here we have evaluated the impact of positional \((x,y)\) accuracy on the assessment of vertical accuracy of elevation datasets to understand the impact of the positional accuracy of datasets. For example, on the evaluation of elevation data from larger footprint datasets (CryoSat and ICESat), which were extracted at GPS measurements. The footprints of CryoSat and ICESat are 300 m and 70 m, respectively, while GPS provides point measurement \((x,y,z)\). Both CryoSat and ICESat data used in this study were point values \((x,y,z)\;\text{averaged over their footprints}\), they were converted to 300 m and 200 m cells, respectively, to extract their elevation at the location of GPS measurements.

To determine the impact of positional accuracy of elevation datasets, we analysed the variability in three subset DEMs (300 m x 300 m) of an analytical photogrammetry derived microtopographic model in the Maunachira test site (Okavango Delta) (see Chapter 4, Section 4.2.1). Figure 6.7 shows the location of subset DEMs, representing diverse topography in a seasonal to permanent swamp. The subset DEM 1 represent mixed landscape (islands and surroundings) with a local relief of 0.61 m (denoted by standard deviation). The subset DEM 2 represent a water body and surroundings with a relief of 0.21 m, while subset DEM 3 represent islands with a relief of 0.48 m (Table 6.5).

To complement results of relief variation (Table 6.5), semivariograms were plotted for the subset DEMs (Figure 6.8). The subset DEM 1 represents higher variability in elevations, followed by the subset DEM 3 with medium variability, while subset DEM 2 represents low elevation variability. These variabilities are denoted by semivariance \(\gamma\) over a distance. For example, \(\gamma = -0.45\) m on 200 m (subset DEM 1), followed by \(\gamma = -0.3\) m (subset DEM 3) and \(\gamma = -0.05\) m (subset DEM 2). Differences in elevation variability is because the scale of
Figure 6.7: Location of subset DEMs in the Maunachira test site DEM of the Okavango Delta (5 m spatial resolution). The subset DEMs (300 m x 300 m, red box) represent various wetland landscapes in local topographic settings. (See legend in Figure 4.5, Chapter 4).

Table 6.5: Characteristics of local topography in the Maunachira site based on airborne analytical photogrammetric DEM.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>SubDEM1</th>
<th>SubDEM2</th>
<th>SubDEM3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation (m)</td>
<td>952.445</td>
<td>949.147</td>
<td>953.406</td>
</tr>
<tr>
<td>Maximum elevation (m)</td>
<td>954.913</td>
<td>950.203</td>
<td>955.401</td>
</tr>
<tr>
<td>Mean elevation (m)</td>
<td>953.451</td>
<td>949.476</td>
<td>954.510</td>
</tr>
<tr>
<td>Standard deviation (m)</td>
<td>0.610</td>
<td>0.208</td>
<td>0.484</td>
</tr>
</tbody>
</table>

*Subset DEMs comprise 300 m x 300 m area.

Fluctuation is site-dependent. Figure 6.9 compares the semivariograms of the three subset DEM. If positional error is ~200 m (e.g. converted ICESat data), the local topographic variability (within a 200 m x 200 m cell) is between ~0.05 m to ~0.45 m (Figure 6.9), so the RMSE 1.2 m for ICESat (compared to GPS, see Section 6.2.2) is not due to local variability. Same applies to CryoSat data (300 m cell) with RMSE 2.5 m (compared to ICESat, see Chapter 7, Section 7.3.4) but the local topographic variability (within a 300 m x 300 m cell) is between ~0.1 m to 0.8 m. The topographic variability in these representative subset DEMs also confirms our earlier statement (see Chapter 2, Section 2.3.1) that the local topographic relief variation in the Okavango wetland is very low (1 m variation for every 4 km distance).
Figure 6.8 Spatial variability of local topography in the Maunachira site, Okavango wetland. a) Semivariogram of mixed landscape (SubDEM 1), b) semivariogram of water body areas (SubDEM 2), and c) semivariogram of islands (SubDEM 3). Semivariance is denoted by $\gamma$ (Y-axis).

Figure 6.9 Comparison of topographic variabilities in the Maunachira site of the Okavango wetland, represented by three SubDEM semivariograms. Within a 200 m x 200 m cell (e.g. ICESat), local topographic variability ranges from $-0.05$ m to $-0.45$ m. For a 300 m x 300 m cell (e.g. CryoSat), this variability ranges from $-0.1$ m to $-0.8$ m.
6.4 Microtopographic Models

This section assesses the vertical accuracy of two elevation datasets: 1) airborne optical stereo-based model, and 2) spaceborne optical stereo-based model (IKONOS).

Optical Model 1: Airborne optical stereo-model vs. GPS Reference Data: Assessment of the airborne stereo-model is presented in Section 6.2.3.

Optical Model 2: Spaceborne Optical Model vs. GPS Reference Data: The IKONOS stereo-image derived elevation model of the Jao test site (see Chapter 4, Section 4.2.2) was assessed using seven GPS points (that also include points used as control) (Figure 6.10). The GPS elevation is subtracted from the IKONOS elevation using a point-based approach:

$$\Delta Z = \text{IKONOS}_Z - \text{GPS}_Z$$

where $\Delta Z$ is the elevation difference, $\text{IKONOS}_Z$ is the elevation point in the IKONOS model, and $\text{GPS}_Z$ is the reference elevation posting.

Results

Table 6.6 presents for each location the GPS elevation and the corresponding elevation derived from the IKONOS stereo-images (1 m spatial resolution) using digital photogrammetry in the Jao test site. IKONOS stereo image-derived model resulted in 1.48 m RMSE, based on seven GPS check points (which also includes four points used as control in

Figure 6.10 Location of GPS control points (white dot inside black circles) on the digital photogrammetry derived IKONOS elevation model, Jao test site.
DEM generation with digital photogrammetry). Figure 6.11 shows the IKONOS digital stereo-photogrammetric and GPS elevation in the Jao test site. Data are normally distributed with a mean elevation difference of 0.15 m.

### Table 6.6 Comparison of GPS and IKONOS digital photogrammetry-derived elevation, Jao site.

<table>
<thead>
<tr>
<th>Point location (UTM zone 34 S) (m)</th>
<th>Datasets elevation (m)</th>
<th>Difference (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GPSz</td>
<td>IKONOSz</td>
</tr>
<tr>
<td>7898094.884 659401.030</td>
<td>974.252</td>
<td>973</td>
</tr>
<tr>
<td>7898100.595 659560.788</td>
<td>973.585</td>
<td>972</td>
</tr>
<tr>
<td>7896368.891 654698.086</td>
<td>974.160</td>
<td>972</td>
</tr>
<tr>
<td>7896549.465 654779.053</td>
<td>973.950</td>
<td>975</td>
</tr>
<tr>
<td>7890575.496 657516.747</td>
<td>971.524</td>
<td>973</td>
</tr>
<tr>
<td>7890469.290 657548.749</td>
<td>972.106</td>
<td>973</td>
</tr>
<tr>
<td>7892463.962 657357.487</td>
<td>973.607</td>
<td>972</td>
</tr>
</tbody>
</table>

RMSE (IKONOS) 1.480

*Includes all GPS points on the Jao site (including four used as control points).

![Comparison of IKONOS digital stereo-photogrammetric and GPS elevation, Jao test site.](image)

**Figure 6.11** Comparison of IKONOS digital stereo-photogrammetric and GPS elevation, Jao test site.

### 6.5 Mesotopographic Models

This section assesses vertical accuracy of four elevation models (Figure 6.1 & Table 6.7) of the Okavango Delta region: 1) GPS, 2) airborne radar (AGS), 3) spaceborne radar (SRTM), and 4) spaceborne optical-stereo (ASTER). These assessments were done using two sets of reference data: GPS GCPs and postings and ICESat laser observations.
Table 6.7 Mesotopographic datasets and their spatial levels of assessment.

<table>
<thead>
<tr>
<th>Elevation data</th>
<th>Reference data</th>
<th>Spatial level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positioning system model</td>
<td>GPS</td>
<td>Delta</td>
</tr>
<tr>
<td>Profiling radar model</td>
<td>GPS</td>
<td>Delta (swamp, non-swamp)</td>
</tr>
<tr>
<td>Imaging radar model</td>
<td>GPS, ICESat laser</td>
<td>Delta (swamp, non-swamp, land cover)</td>
</tr>
<tr>
<td>Optical stereo model</td>
<td>GPS, ICESat laser</td>
<td>Delta</td>
</tr>
</tbody>
</table>

The assessment of air and spaceborne radar elevation models of the delta was carried out on major physiographic regions (i.e. swamp/wetland and non-swamp/non-wetland), on major land cover types, and on water surface. The partitioning of the delta into physiographic regions, and wetlands into land cover types was necessary to describe and assess the quality of elevation models in detail, which provides regionalized estimates of elevation errors. Although physiographic regions are characterized by diverse topographic and biophysical features, each region has a certain degree of homogeneity. Similarly, each land cover type is characterized by homogeneity of topographic characteristics. To assess the quality of elevation datasets, a point-based approach was used. This study used large number of accurately measured GPS postings distributed across the delta. Figure 6.12 shows the distribution of GPS postings over the physiographic regions.

Figure 6.12 Distribution of GPS postings (black dots) in the Okavango Delta region. a) GPS postings on the wetland, b) GPS postings on non-wetland.
6.5.1 Global Positioning System Model vs. GPS Reference Data

The accuracy assessment of GPS elevation model was carried out using independent GPS GCPs for the delta. A point-based approach was used to assess the accuracy of IDW and Kriging-based interpolated GPS elevation models, which can be expressed by:

\[ \Delta Z = \text{GPSidwDEM}_z - \text{GPS}_z \]  
\[ \Delta Z = \text{GPSkrigDEM}_z - \text{GPS}_z \]

where \( \Delta Z \) is the elevation difference, \( \text{GPSidwDEM}_z/\text{GPSkrigDEM}_z \) are the elevation points in the respective models, and \( \text{GPS}_z \) is the independent reference elevation point.

Table 6.8 presents error characteristics of two GPS models, produced by interpolation using IDW and Kriging (Chapter 4, Section 4.31). The elevation error range (minimum and maximum) for IDW-based GPS model is from -2.56 m to 3.35 m (Figure 6.13b), while it is -1.73 m to 3.38 m (Figure 6.14b) for Kriging-based GPS model. Although Kriging-based GPS model resulted in higher RMSE (1.62 m) than the IDW-based model (1.45 m), Kriging produced slightly better topographic relief (\( \sigma = 13.68 \) m) than the IDW (\( \sigma = 13.62 \) m). The mean elevation deviation of IDW-based model was 0.75 m, while 0.94 m for Kriging-based model compared to 60 independent GPS measurements.

<table>
<thead>
<tr>
<th>Elevation data</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Standard deviation</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>IDW-based</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GPSz</td>
<td>935.016</td>
<td>986.312</td>
<td>956.055</td>
<td>14.080</td>
<td></td>
</tr>
<tr>
<td>GPSidwDEMz</td>
<td>937.010</td>
<td>986.259</td>
<td>956.805</td>
<td>13.621</td>
<td></td>
</tr>
<tr>
<td>GPSidwDEMz vs. GPSz</td>
<td>-2.563</td>
<td>3.347</td>
<td>0.750</td>
<td>1.256</td>
<td>1.454</td>
</tr>
<tr>
<td>Kriging-based</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GPSz</td>
<td>935.016</td>
<td>986.312</td>
<td>956.055</td>
<td>14.080</td>
<td></td>
</tr>
<tr>
<td>GPSkrigDEMz</td>
<td>938.252</td>
<td>986.347</td>
<td>956.994</td>
<td>13.682</td>
<td></td>
</tr>
<tr>
<td>GPSkrigDEMz vs. GPSz</td>
<td>-1.731</td>
<td>3.384</td>
<td>0.939</td>
<td>1.325</td>
<td>1.615</td>
</tr>
</tbody>
</table>

*GPS sample = 60 GCPs.*

Figure 6.13 shows that a strong correlation exists between GPS model elevation and independent GPS measurements (\( R^2 = 0.99 \), Figures 13a & 14a). The error distribution pattern of IDW and Kriging-based GPS models show positive error bias (Figures 6.13b & 14b). The positive bias (mean elevation deviation about 0.75 m, Table 6.8) is due to factors such as 1) inconsistent accuracy in GPS data (Geological Survey of Botswana [data used to create GPS models] vs. GPS GCPs measured by ETHZ and UCT [data used as a reference]), 2) clustered distribution of GPS GCPs (see Chapter 7, Figure 7.34), and 3) interpolated model from sparse GPS data.
6.5.2 Airborne Profiling Radar Model vs. GPS Reference Data

The accuracy assessment of airborne radar data (AGS) was carried out by comparing against GPS measurements at two levels: 1) the delta and 2) major physiographic regions, i.e. swamp and non-swamp areas. A point-based approach was used:

\[ \Delta Z = AGS_z - GPS_z \]  \hspace{1cm} (6.5)

where \( \Delta Z \) is the elevation difference, \( AGS_z \) is the elevation point in the model, and \( GPS_z \) is the reference elevation posting.

**Delta**

GPS postings (912) and their corresponding AGS measurements were compared. A strong correlation exists between two datasets (\( R^2 = 0.987 \), Figure 6.15a). Figure 6.15b shows the deviation of AGS measurements from the GPS elevation, with a mean elevation deviation.
1.48 m and standard deviation 2 m. The assessment of AGS data on the delta resulted in RMSE 2.48 m, compared to GPS elevation (Table 6.9). One extreme negative error point (~-19 m, Figure 6.15b) was due to GPS data error (either caused by survey or data processing). This point is located in the seasonal-occasional swamp in the south-east part of the delta with no high elevated ground (verified with Landsat ETM+ multispectral image-based land cover features). This was confirmed by elevation measurements from AGS and SRTM (in next Section 6.5.3), as these models do not show unusual height of this point. This GPS point was removed in further analysis.

![Figure 6.15](image-url) Comparison of AGS and GPS elevation. a) AGS vs. GPS elevation relationship, b) elevation difference: AGS - GPS.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>GPSz</th>
<th>AGSz</th>
<th>Difference AGSz - GPSz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation</td>
<td>957.543</td>
<td>959.02</td>
<td>-18.925</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>921.806</td>
<td>925</td>
<td>8.738</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>1019.359</td>
<td>1017</td>
<td>1.475</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>17.154</td>
<td>17.506</td>
<td>2</td>
</tr>
<tr>
<td>RMSE (AGS)</td>
<td></td>
<td></td>
<td>2.482</td>
</tr>
</tbody>
</table>

*GPS sample = 912 points.

**Swamp**

GPS postings (347) and their corresponding AGS measurements were compared on the swamp. Figure 6.16a shows strong association between the two datasets ($R^2 = 0.97$). Figure 6.16b shows the deviation of AGS measurements from the GPS, with a mean elevation deviation 2 m and standard deviation 1.9 m. The elevation deviation in AGS data (minimum and maximum) ranges between -4.35 m to 11 m. The assessment of AGS data on the swamp resulted in RMSE 2.63 m (Table 6.10). The high positive errors in the AGS data occurred due to swamp vegetation (island margin trees and channel margin papyrus), especially in the seasonal and occasional swamps (see Chapter 2, Figure 2.7).
Non-swamp

GPS postings (565) and their corresponding AGS elevation points were compared on the non-swamp. A strong correlation exists between the datasets on the non-swamp ($R^2 = 0.99$, Figure 6.17a), the correlation is higher compared to swamp ($R^2 = 0.97$). Figure 6.17b shows the deviation of AGS measurements from the GPS, with a mean elevation deviation about 1 m and standard deviation nearly 2 m (Table 6.10). The elevation deviation in AGS data (minimum and maximum) on the non-swamp ranges between $-7.5$ m to $7$ m. The assessment of AGS data on the non-swamp resulted in RMSE $2.25$ m (Table 6.10), which is lower than the RMSE on the swamp. Few high positive and negative errors in the AGS data were due to sand dunes and sand hills, as radar measurements were affected by slope of sand dunes and sand hills.

Figure 6.16 Comparison of AGS and GPS elevations on the swamp. a) AGS vs. GPS elevation relationship, b) elevation difference: AGS – GPS.

Figure 6.17 Comparison of AGS and GPS elevation on the non-swamp. a) AGS vs. GPS elevation relationship, b) elevation difference: AGS – GPS.
### Table 6.10 Comparison of GPS elevation and corresponding elevation from AGS (m), on swamp and non-swamp.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>Swamp</th>
<th>Non-swamp</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation</td>
<td>933.318</td>
<td>936</td>
<td>921.806</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>990.398</td>
<td>997</td>
<td>1019.36</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>960.087</td>
<td>962.154</td>
<td>955.98</td>
</tr>
<tr>
<td>RMSE (AGS)</td>
<td>2.633</td>
<td>2.250</td>
<td></td>
</tr>
</tbody>
</table>

\(^*\)Swamp GPS sample = 347 points; \(^*\)Non-swamp GPS sample = 565 points.

### 6.5.3 Spaceborne Imaging Radar Model vs. GPS & Laser Reference Data

Several authors assessed the accuracy and quality of SRTM elevation data over diverse landscape topographic regions of the world (Rabus *et al.*, 2003; Rodriguez *et al.*, 2005; Falorni *et al.*, 2005; Brown *et al.*, 2005; Farr *et al.*, 2007). However, no detailed assessments of its quality and accuracy on the African topography has been done, except general assessments (at continental scale) and observations (Rodriguez *et al.*, 2006). This section assesses the vertical accuracy of the SRTM elevation data on the Okavango Delta region (see Chapter 4, Section 4.3.3) by two sets of reference data: 1) sparse but high accuracy GPS measurements, and 2) large ICESat laser measurements.

#### Radar vs. GPS Elevation

The accuracy assessment of SRTM data (original and filtered) was carried out by comparing against GPS measurements at three levels: 1) the delta, 2) major physiographic regions, i.e. swamps and non-swamps, and 3) land cover. A point-based approach was used:

\[ \Delta Z = \text{SRTM}_z - \text{GPS}_z \]  

where \( \Delta Z \) is the elevation difference, \( \text{SRTM}_z \) is the elevation point in the SRTM model, and \( \text{GPS}_z \) is the reference elevation posting.

#### Delta

GPS postings (1099) and their corresponding SRTM measurements (original and filtered) were compared on the delta. A strong correlation exists between SRTM and GPS measurements on the delta (\( R^2 = 0.99 \), Figures 6.18a and 19a). Figure 6.18b shows the deviation of SRTM measurements from the GPS, with a mean elevation deviation 0.58 m and standard deviation 2.13 m. Most error values lie between \( \pm 5 \) m elevations. The elevation deviation in SRTM original data (minimum and maximum) on the delta ranges between \( -20 \) m to \(-16 \) m. Filtering in the frequency domain significantly reduced the negative elevation error (from \( -20 \) m to \(-5.5 \) m), but it increased the positive error (Table 6.11). The assessment of SRTM data on the delta resulted in RMSE 2.21 m, for the filtered SRTM model RMSE is 2.36 m. This slightly higher RMSE for filtered model is due to few erroneous edge pixels resulted during filtering, which produced high positive errors. But filtering did improve
the SRTM model by producing more realistic landscape topography than the original model (see Chapter 4, Section 4.3.3).

There were two extreme error values (Figure 6.18b), which are related to GPS measurement/processing errors (verified with Landsat 7 ETM+ image-based land cover features, explained in Section 6.5.2). No unusual depressions or peaks exist at these locations. One GPS posting that had nearly -20 m error deviation compared to SRTM measurements was removed.

**Figure 6.18** Comparison of SRTM original elevation and GPS measurements on the delta. a) SRTM original vs. GPS elevation relationship, b) elevation difference: SRTM original – GPS.

**Figure 6.19** Comparison of SRTM filtered elevation and GPS measurements on the delta. a) SRTM filtered vs. GPS elevation relationship, b) elevation difference: SRTM filtered – GPS.

**Table 6.11** Comparison of GPS elevation and corresponding elevation from SRTM original and filtered models (m) on the delta.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>GPSz</th>
<th>SRTMz</th>
<th>Differencez</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation</td>
<td>921.806</td>
<td>923.6</td>
<td>922</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>1042.596</td>
<td>1042.37</td>
<td>1040</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>959.498</td>
<td>960.076</td>
<td>960.416</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>19.04</td>
<td>19.201</td>
<td>19.201</td>
</tr>
</tbody>
</table>

RMSE (SRTM)          | 2.21  | 2.363

GPS sample = 1099 points.
Swamp

On the wetland/swamp, there were 351 GPS postings (Figure 6.12a) sampling diverse landscape topography. Their corresponding elevation measurements were extracted from SRTM original model (90 m) and filtered model (30 m), and compared against GPS postings (Figure 6.20). Though 351 GPS postings may not adequately represent all types of topography, they are sufficient for a stable estimation of the error budgets of elevation models on the wetland. The assessment of SRTM original data on the swamp resulted in RMSE 2.42 m, with a mean elevation deviation 1 m and standard deviation 2.2 m. For the filtered SRTM data, RMSE resulted in 2.1 m with a mean elevation deviation of 1.2 m and standard deviation of 1.7 m (Table 6.12). Filtering in the frequency domain has slightly improved the quality of the swamp SRTM model by removing speckles. It has significantly reduced the elevation errors (minimum elevation from ~ -4.3 m to -2.6 m, and maximum elevation error from about 11 m to 6 m). Similar to AGS data (Section 6.5.2), there are high positive errors in the SRTM data (Figures 6.20b & d) occurred due to swamp vegetation, especially in the seasonal and occasional swamps (see Chapter 2, Figure 2.7). Note, radar instrumental errors are not considered here.

Figure 6.20 Comparison of SRTM original and filtered elevation with GPS measurements on the swamp, a) SRTM original vs. GPS elevation relationship, b) elevation difference: SRTM original - GPS, c) SRTM filtered vs. GPS elevation relationship, d) elevation difference: SRTM filtered - GPS.
Table 6.12 Comparison of GPS elevation and corresponding elevation from SRTM original and filtered models (m) on the wetland.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>'GPSz</th>
<th>SRTMz</th>
<th>Difference^</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original</td>
<td>Filtered</td>
<td>GPS – SRTM</td>
</tr>
<tr>
<td>Minimum elevation</td>
<td>933.318</td>
<td>935</td>
<td>938</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>995.973</td>
<td>996.381</td>
<td>999.403</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>960.45</td>
<td>961.482</td>
<td>961.668</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>13.003</td>
<td>12.881</td>
<td>12.582</td>
</tr>
<tr>
<td>RMSE (SRTM)</td>
<td></td>
<td></td>
<td>2.423</td>
</tr>
</tbody>
</table>

^GPS sample = 351 points.

Non-swamp

Over the non-swamp area, there are 748 GPS postings representing diverse land covers such as grassland, woody vegetation and sand dunes (Figure 6.12b). Their corresponding SRTM original (90 m) and filtered (30 m) elevation measurements were extracted, and compared against GPS measurements (Figure 6.21). The strong correlation exists between SRTM (original and filtered) and GPS elevation on the non-swamp ($R^2 = 0.99$, Figure 6.21a&c), and the correlation was higher compared to swamp ($R^2 = 0.97$ to 0.98).
The RMSE resulted in 1.97 m, with a mean elevation deviation 0.4 m and standard deviation 1.94 m for the SRTM original model. For the filtered SRTM model, RMSE is 2.48 m with a mean elevation deviation 0.8 m and standard deviation 2.35 m (Table 6.13). A few higher positive error in non-swamp SRTM model is due to effects on radar measurements by slope and shadow of sand hills, sand dunes and their shadow, tree cover, and man-made structures. This higher RMSE for non-swamp filtered SRTM model (Table 6.13) is due to few erroneous edge pixels resulted during filtering, which produced high positive errors. However, in general filtering has improved the SRTM model by producing more realistic landscape topography (see Chapter 4, Section 4.3.3).

Table 6.13 Comparison of GPS elevation and corresponding elevation from SRTM original and filtered models (m) on the non-swamp.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>GPSz</th>
<th>SRTMz</th>
<th>Differencez</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original</td>
<td>Filtered</td>
<td>GPS − SRTM</td>
</tr>
<tr>
<td>Minimum elevation</td>
<td>921.806</td>
<td>923.6</td>
<td>922</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>1042.595</td>
<td>1042.37</td>
<td>1040</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>959.043</td>
<td>959.435</td>
<td>959.83</td>
</tr>
<tr>
<td>RMSE (SRTM)</td>
<td></td>
<td></td>
<td>1.974</td>
</tr>
</tbody>
</table>

*GPS sample = 748 points.

Land Cover

The SRTM elevation model provides a consistent dataset, however, its vertical accuracy is affected by biophysical factors (e.g. land cover). To assess land cover-dependent bias in SRTM data, models (original and filtered) were compared against GPS measurements as per land cover type. Figure 6.22 shows the spatial distribution of 350 GPS postings on the Okavango wetland land cover, derived from Landsat 7 ETM+ MIR channel (band-7) (see Chapter 5, Section 5.5.1). The MIR channel provided better distinction between wetland and non-wetland than multispectral channels (Chapter 5). Out of the 350 GPS postings, 164 points (47%) located in the swamp, 86 points (24%) in the open water, 59 points (17%) in the land-vegetation, and 41 points (12%) in the bare soil (Table 6.14). Out of total wetland area (Figure 6.18), swamp comprises 48%, followed by open water (20%), land-vegetation (21%) and bare soil (11%). Thus, the distribution of GPS postings is nearly proportional to the land cover type area.

In the swamp, the deviation in SRTM elevation occurred due to land cover heterogeneity. Table 6.14 presents the range of error in SRTM models (original and filtered) compared to GPS, as per land cover types (as derived in Figure 6.22). The range of differences is larger for original SRTM data (−4.3 m to 11 m) than the filtered SRTM (−2.6 m to 7 m). Mostly, the SRTM overestimates elevation, on the open water surface it was up to 11 m (compared to GPS), followed by swamp (7.5 m) and lowest on the land-vegetation (5.7 m). Filtering in the frequency domain considerably reduced errors in the SRTM data by removing speckles, particularly on the open water (Table 6.14).
Figure 6.22 Distribution of GPS postings (red dots) on the Okavango wetland land cover type. The land cover map is derived from Landsat 7 ETM+ MIR channel (band-7) images. GPS measurements were used to assess elevation accuracy.

### Table 6.14 Range deviation in SRTM original and filtered (SRTMF) elevation compared to GPS measurements, as per land cover type.

<table>
<thead>
<tr>
<th>Land cover</th>
<th>Number of points(^{a})</th>
<th>Range of error (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(% of total sample)</td>
<td>SRTM(_z) – GPS(_z)</td>
</tr>
<tr>
<td>Open water</td>
<td>86 (24)</td>
<td>-2.752 - 11.088</td>
</tr>
<tr>
<td>Swamp</td>
<td>164 (47)</td>
<td>-4.308 - 7.484</td>
</tr>
<tr>
<td>Land-vegetation</td>
<td>59 (17)</td>
<td>-3.109 - 5.712</td>
</tr>
<tr>
<td>Bare soil</td>
<td>41 (12)</td>
<td>-3.164 - 6.849</td>
</tr>
<tr>
<td>All</td>
<td>350 (100)</td>
<td>-4.308 - 11.088</td>
</tr>
</tbody>
</table>

\(^{a}\)GPS sample = 350 points.

Table 6.15 shows the errors in SRTM models (original and filtered) as per land cover types, estimated using GPS measurements. The RMSE of SRTM original model over all land cover type was 2.4 m, while it was 2 m for the filtered model. Land cover type-wise error measures were derived to provide a better representation of error distribution and show the performance of the filtering. It is recognized that a single global measure (RMSE) does not represent the spatial distribution of elevation errors across a study area (Fisher, 1998; Fisher and Tate, 2006; Kyriakidis et al., 1999). Land cover-wise RMSEs of elevation models give a better representation of error structure than a single measure, although there are spatial variations in elevation error within a particular land cover type. As per land cover types, the SRTM data (original) gave the highest elevation error on the open water surface (RMSE 2.6
m), while it is 2.4 m on the swamp, 2.3 m on the bare soil and 2 m on the land-vegetation (Table 6.15). Filtering has reduced errors from 2.6 m to 2 m (RMSE) on the open water surface and swamps, and from 2.3 m to 1.9 m on the bare soil in SRTM original data. However, on the land-vegetation that is composed of dense forests and trees (e.g. Chief’s island), built-up areas (i.e. man-made structures), hills and sand dunes, the filtered SRTM data resulted marginally higher error (RMSE = 2.3 m) than the SRTM original (2 m). On the open water and swamps, the filtering has improved representation of local relief by removing erroneous values and smoothing the surface (a of 1.55 m and 1.69 m, from original 2.37 m and 2.13 m, respectively).

Table 6.15 Errors in SRTM models (original and filtered) as estimated using GPS measurements, as per land cover type.

<table>
<thead>
<tr>
<th>Land cover class</th>
<th>SRTMz – GPSz (m)</th>
<th>SRTMFz – GPSz (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean error</td>
<td>Standard dev.</td>
</tr>
<tr>
<td>Open water</td>
<td>1.184</td>
<td>2.366</td>
</tr>
<tr>
<td>Swamp</td>
<td>1.224</td>
<td>2.131</td>
</tr>
<tr>
<td>Land-vegetation</td>
<td>0.941</td>
<td>1.874</td>
</tr>
<tr>
<td>Bare soil</td>
<td>0.078</td>
<td>2.324</td>
</tr>
<tr>
<td>All</td>
<td>1.032</td>
<td>2.195</td>
</tr>
</tbody>
</table>

*GPS sample = 350 points.

Figure 6.23 shows the errors in SRTM models (original and filtered) as per land cover type, as estimated using 350 GPS measurements. Except for the land-vegetation class, filtering has improved the SRTM vertical accuracy. Overall, filtering has reduced errors in the SRTM model by about 17%. On the open water surface and swamps, filtering has reduced error by about 24% and 18%, respectively.

![Figure 6.23 Errors in SRTM elevation models (original and filtered) on the Okavango wetland as per land cover type, estimated using GPS measurements.](image-url)
Radar vs. Laser Elevation

Approach

This section assesses vertical accuracy of SRTM elevation data on the Okavango Delta using 133526 ICESat laser shots:

\[
\Delta Z = SRTM_z - ICESat_z
\]

(6.7)

where \( \Delta Z \) is the elevation difference, \( SRTM_z \) is the elevation point in the model, and \( ICESat_z \) is the reference elevation point.

Figure 6.24 shows the distribution of ICESat laser profiles (133539 footprints, include points with extreme values) on the Okavango Delta SRTM elevation surface. Extreme laser shots were identified and removed using following criteria: 1) ICESat laser points above 1400 m height (as no elevation point exists in the Okavango region above 1400 m), and 2) three sigma rule (laser shots above ±3\( \sigma \) in elevation difference data). ICESat measurements provided larger samples compared to GPS (with reasonably high vertical accuracy, RMSE 1.2 m compared to GPS).

Results and Discussion

The SRTM model of the delta resulted in RMSE 1.9 m compared to ICESat measurements (about 133500 samples), with a mean elevation deviation 0.7 m (median deviation 0.66 m) and standard deviation error 1.7 m (Table 6.16). The elevation deviation in SRTM model
ranges between −13.73 m to 12.75 m. On an average, the SRTM elevation is higher than the ICESat by 0.70 m (also see Chapter 7, Figure 7.26).

Table 6.16 Comparison of ICESat points and corresponding elevation from SRTM model (m) on the delta.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>SRTMz</th>
<th>ICESat</th>
<th>Difference SRTMz − ICESat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation</td>
<td>921</td>
<td>921.477</td>
<td>−13.729</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>1036</td>
<td>1034.813</td>
<td>12.746</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>957.125</td>
<td>956.422</td>
<td>0.703</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>17.917</td>
<td>18.303</td>
<td>1.711</td>
</tr>
<tr>
<td>RMSE (SRTM)</td>
<td></td>
<td></td>
<td>1.905</td>
</tr>
</tbody>
</table>

*ICESat sample = 133526 points.

Figure 6.25 shows a strong correlation between SRTM and ICESat elevation ($R^2 = 0.99$, Figure 6.25a). Figure 6.25b shows the deviation of SRTM measurements from the ICESat, most points lie between −5 and 8 m, with a positive error bias in SRTM data. These errors are mainly resulted from radar instrumental problems (not investigated here) and topographic-biophysical characteristics of the land surface, and not influenced by geolocation accuracy of datasets.

![Figure 6.25](image_url)
6.5.4 Spaceborne Optical Model vs. GPS and Laser Reference Data

This section assesses the vertical accuracy of ASTER model on the Okavango Delta region using sparse GPS postings and large ICESat laser observations. While GPS provided biased samples (measurement on regularly-spaced locations), ICESat measurements provided unbiased samples (Figure 6.26).

Optical vs. GPS Elevation

The accuracy assessment of ASTER elevation model (original and filtered) on the delta was carried out by comparing against 983 GPS postings (Figure 6.26a). A point-based approach was used:

\[ \Delta Z = \text{ASTER}_z - \text{GPS}_z \]  \hspace{1cm} (6.8)

where \( \Delta Z \) is the elevation difference, \( \text{ASTER}_z \) is the elevation point in the model, and \( \text{GPS}_z \) is the reference elevation posting.

Figure 6.26 GPS postings and ICESat laser altimeter profiles on the Okavango Delta Terraster elevation surface (Version 2, 30 m spatial resolution). The ASTER elevation ranges from 894 m to 1383 m with an average height of 961 m. a) GPS postings on the delta surface (red dots), and b) ICESat laser profiles (2003-2009) on the delta surface (black). GPS and ICESat points are distributed across all landscapes in the delta.

Results and Discussion

Assessment of ASTER model resulted in RMSE 4.32 m compared to GPS elevation, with a mean elevation deviation 0.95 m and standard deviation error 4.22 m (Table 6.17). Elevation error in ASTER model ranges between -12.75 m to 16.02 m. Filtering ASTER model in the frequency domain significantly reduced the RMSE from 4.32 m to 3.48 m.
Table 6.17 Comparison of GPS elevation and corresponding elevation from ASTER original and filtered models (m) on the delta.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>GPSz</th>
<th>ASTERz</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original</td>
<td>Filtered</td>
<td>GPS - ASTER</td>
</tr>
<tr>
<td>Minimum elevation</td>
<td>923.051</td>
<td>916</td>
<td>-12.75</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>1042.065</td>
<td>1040</td>
<td>16.021</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>959.274</td>
<td>960</td>
<td>0.945</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>19.276</td>
<td>19</td>
<td>4.221</td>
</tr>
<tr>
<td>RMSE (ASTER)</td>
<td></td>
<td></td>
<td>4.323</td>
</tr>
</tbody>
</table>

*GPS sample = 983 points.

A relatively strong correlation exists between ASTER and GPS elevation ($R^2 = 0.95$, Figure 6.27a). Figure 6.27b shows the deviation of ASTER measurements from the GPS, most points lie between -5 m and 10 m, with a clear positive error bias in ASTER data. These errors are caused by factors such as production method (i.e. digital photogrammetry, which generates DSMs), time difference of stereo-image acquisition and image qualities, mosaicking errors of individual ASTER elevation models (each ASTER scene covers 60 km x 60 km area), and topographic-biophysical characteristics of the land surface.

![Figure 6.27 Comparison of ASTER and GPS elevation](image)

Figure 6.28 presents the frequency domain filtered ASTER data in relation to GPS elevation. After filtering, the correlation between filtered ASTER and GPS measurements has increased from $R^2 = 0.97$ (unfiltered ASTER model, Figure 6.28a) to $R^2 = 0.95$ (filtered model, Figure 6.27a). The magnitude of vertical errors has reduced, but the error distribution pattern remained similar as the unfiltered model with high positive error bias. The periodic deviations in filtered ASTER data (Figure 6.28b) is due to periodicity problem in ASTER dataset, which were created by mosaicking stereo models (see Figure 6.26).
Figure 6.28 Comparison of ASTER filtered and GPS elevation. a) ASTER filtered vs. GPS elevation relationship, with high positive correlation, b) elevation difference: ASTER filtered – GPS, with positive error bias in ASTER data but lower than the unfiltered ASTER model.

Optical vs. Laser Elevation

Approach

The accuracy assessment of ASTER elevation model on the delta was carried out comparing against 133501 ICESat measurements (Figure 6.26b). A point-based approach was used:

$$\Delta Z = \text{ASTER}_z - \text{ICESat}_z$$

(6.9)

where $\Delta Z$ is the elevation difference, ASTER$_z$ is the elevation point in the model, and ICESat$_z$ is the reference elevation point. Figure 6.24 shows the distribution of ICESat laser profiles (with 133539 footprints) on the Okavango Delta. The laser shots with extreme values were identified and removed using the following criteria mentioned in Section 6.5.3.

Results and Discussion

ASTER model of the delta resulted in RMSE 4.43 m compared to ICESat elevation, with a mean elevation error of 1.52 m (median error of 1.47 m), and standard deviation error of 4.16 m (Table 6.18). The elevation error in ASTER model ranges between −28.13 m to 25.77 m.

Table 6.18 Comparison of ICESat elevation and corresponding elevation from ASTER model (m) on the delta.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>ICESat</th>
<th>ASTER</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation</td>
<td>921.477</td>
<td>912</td>
<td>−28.131</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>1034.813</td>
<td>1038</td>
<td>25.766</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>956.417</td>
<td>957.932</td>
<td>1.515</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>18.299</td>
<td>18.252</td>
<td>4.158</td>
</tr>
<tr>
<td>RMSE (ASTER)</td>
<td></td>
<td></td>
<td>4.425</td>
</tr>
</tbody>
</table>

${}^1$ICESat sample = 133501 points.
Figure 6.29 shows that a strong correlation exists between ASTER and ICESat elevation ($R^2 = 0.95$, Figure 6.29a). Figure 6.29b shows the error distribution pattern, most points lie between -10 and 15 m elevation difference, with a positive error bias in ASTER elevation (reasons are explained in earlier section).

6.6 Water Surface Elevation

This section assesses accuracy of water surface elevations measured from air- and spaceborne radar, and spaceborne laser observations on the Okavango Delta using GPS measurements (Figure 6.1 & Table 6.19).

<table>
<thead>
<tr>
<th>Elevation data</th>
<th>Reference data</th>
<th>Spatial level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Profiling radar (AGS)</td>
<td>GPS</td>
<td>Delta main channel</td>
</tr>
<tr>
<td>Imaging radar (SRTM)</td>
<td>GPS</td>
<td>Delta main channel</td>
</tr>
<tr>
<td></td>
<td>GPS</td>
<td>Delta water surface</td>
</tr>
<tr>
<td></td>
<td>GPS</td>
<td>Delta open water surface</td>
</tr>
<tr>
<td>Profiling laser (ICESat)</td>
<td>GPS</td>
<td>Delta water surface</td>
</tr>
</tbody>
</table>

6.6.1 Imaging & Profiling Radar Water Elevation vs. GPS Reference Data

The potentials of SRTM and airborne radar (AGS) water surface measurement for mapping water surface topography were evaluated using 214 GPS postings distributed on the delta. Assessments were carried out: 1) on the main channel, 2) on the water surface (including aquatic vegetated areas), and 3) on the open water surface. The main purpose was to assess the quality of SRTM and AGS elevation data in measuring water surface elevation.
Main Channel

Data and Approach

Data used to measure water level elevation along the main channel are: GPS postings, SRTM (original and filtered, 30 m spatial resolution), and AGS (50 m). There are 23 GPS postings (19 measured by the UCT and 4 by the ETHZ) along the main channel (about 250 km) (Figure 6.30). The corresponding SRTM and AGS elevation measurements were extracted at GPS postings and compared against GPS by subtracting GPS elevation from their elevation, as expressed by:

\[
\Delta Z = SRTM_z - GPS_z \\
\Delta Z = \text{SRTM filtered}_z - GPS_z \\
\Delta Z = AGS_z - GPS_z
\]

where \(\Delta Z\) is the elevation difference, \(SRTM_z\), \(\text{SRTM filtered}_z\), and \(AGS_z\) are points in the elevation models, and \(GPS_z\) is the referenced elevation posting.

Figure 6.30 GPS measurements (yellow dots) on water surface along the main channel in the Okavango Delta (on Landsat 7 ETM+ multispectral image).

Results and Discussion

Figure 6.31 presents the differences in water surface elevation along the main channel between GPS and elevation measurements of SRTM (90 m and 30 m), and AGS (50 m). Comparison of SRTM data (points from 30 m cell) against 23 GPS measurements resulted in a mean elevation deviation 5.1 m and RMSE 5.5 m. The frequency domain filtering of SRTM data improved the mean deviation to 4.3 m and RMSE to 4.7 m (Figure 6.31b, Table 6.20). The mean water elevation of 23 GPS postings is 964.91 m, while the mean water elevation of corresponding SRTM measurements is 970.02 m. AGS data (points from 50 m cell) were
compared against 22 GPS postings that resulted in a mean elevation deviation 5.63 m and RMSE 5.84 m (Table 6.21). The mean water elevation for 22 GPS postings is 963.69 m, while the mean elevation of corresponding AGS measurements is 969.32 m. Results show that SRTM provided better water surface elevation measurement than the AGS, compared to GPS (Figure 6.31c).

![Figure 6.31](image)

**Figure 6.31** Differences in water surface elevation along the main channel between GPS elevation and elevation from SRTM and AGS data. a) SRTM elevation vs. GPS elevation, b) SRTM original and filtered elevation vs. GPS elevation, c) SRTM original and AGS elevation vs. GPS elevation, d) SRTM (90 m) vs. SRTM (30 m) elevation.

The SRTM heights are, however, higher than the GPS, because SRTM measures surface heights of objects. Further, SRTM surface water elevation measurements were affected by factors such as the number of data takes, look angles, and the velocity of water flow (Kiel et al., 2006). GPS elevations are water level heights, measured in the field. IDW interpolated SRTM data (30 m) maintains the integrity of the original SRTM data (mean elevation 960.076 m and 960.093 m, respectively, for 90 m and 30 m). SRTM data was interpolated to a higher spatial resolution dataset to make it compatible with AGS data (50 m) and examine the effects of spatial resolution.
Table 6.20 Comparison of GPS elevation and corresponding elevation from SRTM original and filtered elevation (m) on the main channel water level.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>'GPSz</th>
<th>SRTMz</th>
<th>SRTMFz</th>
<th>SRTM - GPS</th>
<th>SRTMF - GPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation</td>
<td>930.407</td>
<td>937.407</td>
<td>939</td>
<td>0.817</td>
<td>0.009</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>991.66</td>
<td>1000.764</td>
<td>1000</td>
<td>9.104</td>
<td>8.34</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>964.905</td>
<td>970.019</td>
<td>969.17</td>
<td>5.093</td>
<td>4.269</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>17.482</td>
<td>17.1</td>
<td>16.778</td>
<td>2.173</td>
<td>1.961</td>
</tr>
<tr>
<td>RMSE (SRTM/SRTMF)</td>
<td>5.52</td>
<td>4.68</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*GPS sample = 23 points.

Table 6.21 Comparison of GPS elevation and corresponding elevation from AGS model (m) on the main channel water level.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>'GPSz</th>
<th>AGSz</th>
<th>Difference (AGSz - GPSz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation</td>
<td>930.896</td>
<td>936</td>
<td>2.01</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>987.76</td>
<td>997</td>
<td>9.24</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>963.689</td>
<td>969.319</td>
<td>5.63</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>16.869</td>
<td>17.106</td>
<td>1.581</td>
</tr>
<tr>
<td>RMSE (AGS)</td>
<td>5.838</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*GPS sample = 22 points.

Water Surface

Data and Approach

To assess SRTM data quality on the water surface (including aquatic vegetated areas) of the Okavango Delta, 214 GPS measurements were used (191 measured by the regional gravity survey of Botswana, 19 by UCT and 4 by the ETHZ). Note, the GPS postings were measured on land surface, however, many points measured at the water surface level (as generally the land-water elevation difference is negligible in the delta). The assumption is that these GPS postings represent water surface or near-water surface elevation measurements.

Figure 6.32 shows the spatial distribution of 214 GPS postings on the Okavango Delta water surface and on the SRTM elevation model. The water surface mask (Figure 6.32a) was extracted from Landsat 7 ETM+ multispectral image of early April 2000, which is about a month later than the SRTM data acquisition date (February 2000). The assumption is there was not much change on the topographic and biophysical characteristics during that period.
Figure 6.32 GPS postings (red dots) on the Okavango Delta water surface. a) GPS postings on the water surface mask derived from Landsat 7 multispectral image, b) water surface GPS postings on the SRTM model. These GPS measurements were used to assess accuracy of SRTM water level elevation.

The corresponding elevation points of SRTM original and filtered models are compared against GPS measurements:

\[
\Delta Z = \text{SRTM}_Z - \text{GPS}_Z \tag{6.13}
\]
\[
\Delta Z = \text{SRTM filter}ed_Z - \text{GPS}_Z \tag{6.14}
\]

where \(\Delta Z\) is the elevation difference, \(\text{SRTM}_Z\) and \(\text{SRTM filter}ed_Z\) are points in the elevation model, and \(\text{GPS}_Z\) is the reference elevation posting.

Results and Discussion

Table 6.22 presents statistical assessment of SRTM data in measuring water surface elevation on the Okavango Delta. The SRTM original data resulted in RMSE 2.41 m, while filtered SRTM data produced RMSE 2.1 m. Standard deviations between SRTM original and GPS measurements is 2 m, while it is 1.65 m between filtered SRTM data and GPS measurements. Results demonstrate that the water surface elevation can be estimated from SRTM data at a vertical accuracy of about 2 m. The filtering the SRTM data in the frequency domain has substantially improved its quality. After filtering, the range of elevation deviation (minimum and maximum) decreased from 14.5 m to 9.3 m (compared to GPS elevation), considering both positive and negative deviations.
Table 6.22 Comparison of GPS elevation and corresponding elevation from SRTM original and filtered data (m) on the delta water surface.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>( ^{\prime} \text{GPSz} )</th>
<th>SRTMz</th>
<th>SRTMFz</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SRTM - GPS</td>
</tr>
<tr>
<td>Minimum elevation</td>
<td>939.134</td>
<td>941.033</td>
<td>942</td>
<td>-3.998</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>993.408</td>
<td>993.852</td>
<td>999.403</td>
<td>10.477</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>963.539</td>
<td>964.768</td>
<td>964.843</td>
<td>1.229</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>12.511</td>
<td>12.195</td>
<td>12.132</td>
<td>2.078</td>
</tr>
<tr>
<td>RMSE (SRTM/SRTMF)</td>
<td></td>
<td></td>
<td></td>
<td>2.41</td>
</tr>
</tbody>
</table>

\(^{\prime}\)GPS sample = 213 points.

Figure 6.33 presents the water surface elevation difference on the Okavango Delta between GPS and corresponding SRTM (original and filtered) measurements. The SRTM heights are higher than the GPS (Figures 6.33a & b), however, filtering has marginally reduced the deviation on the SRTM data from 6–8 m to 4–6 m (Figures 6.33c vs. d). These results confirm the potential of SRTM data in measuring water surface elevation at a regional scale, as previously demonstrated on the Amazon by LeFavour and Alsdorf (2005). There are high positive errors in the SRTM water elevation (Figures 6.33b & d) that occurred over the

![Figure 6.33](image_url)

**Figure 6.33** Differences in water surface elevation between GPS elevation and elevation of SRTM original and filtered model on the Okavango Delta. a) SRTM original vs. GPS, b) elevation difference: SRTM original - GPS, c) SRTM original and filtered elevation vs. GPS, and d) elevation difference: SRTM filtered - GPS. Note, these profiles (figures a and b) reflect differences between GPS and SRTM data on the delta (and not transect along lines).
seasonal and occasional swamp water surface, which are mostly covered by aquatic and non-aquatic vegetation (see Chapter 2, Figure 2.7). Further, SRTM measurements are averages over 90 m grid, which in most cases are mixed, while GPS measurements are selected points.

Open Water Surface

The SRTM open water surface topographic model is shown in Chapter 4 (Section 4.4.1). The assessment of SRTM open water surface elevation in the delta was carried out comparing against sparse GPS measurements (Chapter 7, Table 7.15) and large ICESat laser samples. The assessment against 57 GPS measurements resulted in RMSE 1.44 m, with a mean elevation deviation ~0.5 m. After open water-dependent bias calibration in SRTM data with 6706 ICESat measurements (Chapter 7, Section 7.3.2), the RMSE decreased to 1.35 m with a mean deviation 0.009 m (Chapter 7, Table 7.15).

Further, the assessment of SRTM open water data against ICESat measurements (6706 laser shots) resulted in RMSE ~2 m with a mean elevation deviation of 0.48 m (see Chapter 7, Table 7.12). Note, ICESat laser water elevation is higher than the GPS measurements with a mean deviation of 0.15 m (see Section 6.6.2).

6.6.2 Profiling Laser Water Elevation vs. GPS Reference Data

Approach

The accuracy assessment of ICESat laser water elevation on the Okavango Delta was carried out by comparing against GPS measurements:

\[ \Delta Z = \text{ICESat}_z - \text{GPS}_z \]  

(6.15)

where \( \Delta Z \) is the elevation difference, ICESat\(_z\) is the water elevation point, and GPS\(_z\) is the reference water elevation posting. The location of GPS postings and ICESat laser profiles on the Okavango Delta is shown in Figure 6.2. A delta water surface mask (Figure 6.32a) was used to extract corresponding GPS and ICESat measurements.

Results and Discussion

The accuracy assessment of ICESat water laser measurements in the delta resulted in RMSE 0.76 m compared to GPS elevation (10 samples), with a mean elevation deviation 0.15 m (median error 0.001 m), and standard deviation error 0.79 m (Table 6.23). The elevation error in ICESat water laser data ranges between −0.9 m to 1.86 m. For completeness, we also assessed the ICESat measurement accuracy over non-water areas in the delta. The assessment of ICESat against 147 non-water GPS samples resulted in RMSE 1.23 m with a mean elevation error −0.03 m (median error −0.07 m) and standard deviation error 1.23 m. The elevation error in ICESat non-water laser data ranges between −3.24 to 3.59 m. For all areas (water and non-water), the assessment of ICESat against 157 GPS samples resulted in RMSE 1.21 m, with a mean error 0.02 m (and median error −0.07 m) (see detail in Section 6.2.2).
Table 6.23 Comparison of GPS elevation and corresponding elevation from ICESat on the Okavango Delta.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Standard dev.</th>
<th>RMSEz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water(^1)</td>
<td>0.9</td>
<td>1.858</td>
<td>0.15</td>
<td>0.788</td>
<td>0.762</td>
</tr>
<tr>
<td>Non-water(^2)</td>
<td>-3.238</td>
<td>3.591</td>
<td>-0.03</td>
<td>1.233</td>
<td>1.229</td>
</tr>
<tr>
<td>Overall(^3)</td>
<td>0.019</td>
<td>1.21</td>
<td></td>
<td></td>
<td>1.21</td>
</tr>
</tbody>
</table>

\(^1\)Water GPS sample = 10; \(^2\)Non-water GPS sample = 147; \(^3\)Overall GPS sample = 157 points.

A strong correlation exists between ICESat and GPS water elevations (R\(^2\) = 0.99, Figure 6.34a). Figure 6.34b shows that most points lie within ±1 m of elevation deviation, with no distinct bias.

![Figure 6.34](image)

(a) ICESat vs. GPS elevation relationship, with high positive correlation. (b) Elevation difference: ICESat - GPS.

6.7 Characterisation of Errors in Multi-technology Elevation Data

This section summarizes error characteristics of topographic data and models described in the preceding sections: reference data, microtopographic, mesotopographic, and water surface elevation.

Reference Data

Three sets of reference data were used: GPS GCPs and postings, ICESat laser observations, and airborne stereophotogrammetric DEM. The accuracy of GPS GCPs over is 0.11 m, while accuracy of GPS postings is ±0.15 m. ICESat laser measurements produced 1.2 m accuracy, compared to GPS elevation. The accuracy of airborne stereophotogrammetric DEM is ±1 m.

Microtopographic Models

Both airborne and spaceborne stereophotogrammetric elevation models of test sites (with different physiographic settings) provided detailed microtopographic information, with vertical accuracies (RMSE) between ±1 m to 1.5 m.
Mesotopographic Models

The mesotopographic models: GPS-based, AGS, SRTM, and ASTER, produced distinct error patterns. GPS-based model with highest vertical accuracy (RMSE = 1.6 m), AGS and SRTM models medium accuracy (RMSE = 2.2 m to 2.4 m), and ASTER model the lowest accuracy (RMSE = about 4.3 m) (Table 6.24 and Figure 6.35). The range of errors are high for AGS, SRTM and ASTER (between -20 to 16 m), while GPS-based model have low range deviation (-1.7 m to 6.8 m). Although the number of GPS samples used to assess these models vary, however, these assessments here show the trends of error in mesotopographic models (see result of evaluation of these models with consistent GPS samples in Chapter 8). Assessment of SRTM and ASTER data using large ICESat samples produced similar trends in error.

Table 6.24 Multiplatform technology-based mesotopographic models and their error characteristics on the delta.

<table>
<thead>
<tr>
<th>Elevation model</th>
<th>Minimum error</th>
<th>Maximum error</th>
<th>Mean error</th>
<th>Standard deviation</th>
<th>RMSEz</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS-based</td>
<td>-1.731</td>
<td>6.845</td>
<td>1.044</td>
<td>1.633</td>
<td>1.615</td>
</tr>
<tr>
<td>Profiling radar (AGS)</td>
<td>-18.925</td>
<td>8.738</td>
<td>1.475</td>
<td>2</td>
<td>2.482</td>
</tr>
<tr>
<td>Imaging radar (SRTM)</td>
<td>-19.894</td>
<td>15.567</td>
<td>0.578</td>
<td>2.130</td>
<td>2.210</td>
</tr>
<tr>
<td>Optical stereo imaging (ASTER)</td>
<td>-12.750</td>
<td>16.021</td>
<td>0.945</td>
<td>4.221</td>
<td>4.323</td>
</tr>
</tbody>
</table>

*Models were evaluated by GPS measurements, distributed over diverse landscapes in the delta. Positioning system model was assessed by 60 GPS GCPs, profiling radar by 912 GPS postings, imaging radar by 1099 GPS postings, and optical stereo imaging model by 983 GPS postings.

Figure 6.35 Vertical error budgets of multiplatform technology-based mesotopographic models of the Okavango Delta.
SRTM vs. ASTER

To understand the error structure of SRTM and ASTER models is important, as they provide consistent coverage over the study region. Table 6.25 compares the elevation errors in SRTM and ASTER models, as estimated using large ICESat laser samples distributed over diverse landscapes in the delta. The vertical error in ASTER elevation data is more than twice the SRTM data (RMSE: ASTER = 4.43 m, SRTM = 1.9 m). In the ASTER model, the elevation error ranges between -28 m to 26 m, while for the SRTM it is between -14 m to 13 m. However, ASTER data provided about twice the topographic relief than the SRTM (σ: ASTER = 4.16 m, SRTM = 1.77 m), because of its higher spatial resolution.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>SRTMz</th>
<th>&quot;ASTERz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation error</td>
<td>-13.729</td>
<td>-28.131</td>
</tr>
<tr>
<td>Maximum elevation error</td>
<td>12.775</td>
<td>25.766</td>
</tr>
<tr>
<td>Mean elevation error</td>
<td>0.703</td>
<td>1.515</td>
</tr>
<tr>
<td>Median elevation error</td>
<td>0.664</td>
<td>1.465</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.771</td>
<td>4.158</td>
</tr>
<tr>
<td>RMSE</td>
<td>1.905</td>
<td>4.425</td>
</tr>
</tbody>
</table>

* ICESat reference sample = 133526 points; "ICESat reference sample = 133501 points.

Water Surface Elevation

In measuring water elevation on the main channel of the delta, SRTM provided better measurements than AGS data. However, both produced about 5.5 m elevation deviation compared to GPS measurements. Note, there are time differences among these datasets. But on the delta water surface, SRTM measurement resulted in RMSE 2.4 m, compared to 213 GPS measurements. Filtered SRTM enhanced the accuracy to RMSE 2.1 m.

The SRTM measurement of open water surface level of the delta resulted in RMSE 1.44 m, compared to 57 GPS samples, filtered SRTM improved the accuracy to RMSE 1.35 m. With large samples, ICESat assessment of SRTM open water level resulted in -2 m RMSE, which was expected as ICESat heights are higher than the GPS height by 0.2 m (see Chapter 7, Figure 7.26). ICESat laser measurements provided improved water elevation estimation than the SRTM. The RMSE resulted in 0.76 m when compared against GPS elevation, with a mean deviation of 0.15 m.

6.8 Conclusion

Assessing elevation data and models statistically revealed the varying quality of data products, in terms of accuracy and reliability. We assessed the accuracy (RMSE) of elevation models generated in Chapter 4, and other datasets for establishing reference and measuring water level elevation. As a reference, GPS provided the main dataset with high vertical accuracy (~0.15 m). Two additional reference datasets – ICESat laser data and an airborne photogrammetric DEM – were established by benchmarking against GPS. GPS provided higher accuracy regional reference data but sparse samples, while ICESat provided regional
reference data with large samples (1.2 m accuracy, compared to GPS). The photogrammetric
DEM provided detailed test site reference data, used in Chapter 7 (~1 m accuracy). The
evaluation of the geolocation accuracy of elevation datasets shows that the positional
accuracy did not have much influence on estimated local topographic variability.

Airborne and spaceborne (IKONOS) stereophotogrammetric models of test sites (by
analytical and digital methods, respectively) produced high vertical accuracy
microtopographic datasets (~1 m and 1.5 m, respectively). The Okavango Delta regional
mesotopographic models from GPS, profiling and imaging radar (AGS and SRTM), and
optical stereo imaging (ASTER) observations produced variable accuracy datasets. The GPS-
based model produced high accuracy dataset (1.6 m), AGS and SRTM produced medium
accuracy datasets (2.2 m to 2.4 m, compared to GPS), while ASTER produced the lowest
accuracy dataset (4.3 m, compared to GPS) (see Table 6.24). Filtering in the frequency
domain slightly improved the SRTM and ASTER elevation accuracy. Although the GPS
sample size was not uniform in these assessments, results show the error trends in the
datasets. Assessment of these datasets using large ICESat samples confirmed this trend. The
vertical accuracy of ASTER data is about two times worse than SRTM's. Errors were higher
over the wetland than the non-wetland areas (2.4 m and ~2 m, respectively, for SRTM
compared to GPS). In the wetland, errors were within the range of 1.9 m to 2.2 m (bare soil to
vegetated areas).

Water surface topography (including aquatic vegetated areas) from SRTM produced 2.4
m accuracy (compared to GPS) and filtering the model improved accuracy to 2.1 m. Over the
open water surface, SRTM produced 1.4 m accuracy (compared to GPS), whereas filtering
marginally improved the accuracy of the model. Assessment with large ICESat samples gave
~2 m accuracy for the open water SRTM model. Note that time difference among datasets
were not considered here. ICESat provided better water elevation measurements than SRTM,
with 0.76 m accuracy compared to GPS (with a mean deviation of 0.15 m).

These findings contributed significantly to the understanding of the error budgets in the
data products and nature of the errors (this chapter), and of the ways to reduce them (Chapter
7). We found that physiography and land cover influenced marginally vertical errors in the
SRTM data in the Okavango Delta region. We provided for the first time a comprehensive
evaluation of multiplatform-based elevation data accuracy over the Okavango Delta. Further
assessment of multiplatform observation-based elevation data products will be done in
Chapter 7.
Chapter 7

Integrating Multiplatform Elevation Observations

It is not a simple matter to differentiate unsuccessful from successful experiments. [...] Work that is finally successful is the result of a series of unsuccessful tests in which difficulties are gradually eliminated.

— Robert H. Goddard (1882–1945)

In Chapter 4, we presented elevation models measured and constructed from diverse platform observations at various levels of spatial detail, whereas in Chapter 6 we assessed the accuracy of these models. This chapter focuses on creating improved elevation models from constructed and other datasets through innovative integration approaches and methods. The resultant integrated elevation models are then evaluated.

**Keywords:** Multiplatform; remote observations; elevation data; error assessment; spectral filtering; data fusion; bias calibration; data merging; integrated models; model evaluation.

### 7.1 Fusion and Merging of Elevation Observations

Effective integration of multiplatform elevation observations lead to the development of improved topographic models of the earth and other planets. This is particularly important to topographic modeling of the earth’s complex and remote wetland landscapes. The construction of such topographic models require development of approaches for integrating disparate but complementary elevation datasets. The main goal of integration is to construct improved quality elevation models by synergistic fusion and merging of elevation data, measured from multiple platforms at diverse spatial resolution and accuracy. In principle, integration of data from multiple sources provide significant advantages over single source data (Hall and Llinas, 1997). However, several aspects need to be considered in elevation data integration such as data selection, integration techniques and evaluation procedures. The data issues are related to the techniques of their generation, resolution, and accuracy. The availability of appropriate elevation datasets is one the key aspects in integration. Accurate co-registration of datasets is vital for data integration, as misregistration produce erroneous results (Townshend et al., 1992; Dai and Khorram, 1998; Van Niel et al., 2008). Finally, the optimal integration of multiplatform elevation data relies on the consideration of uncertainties that come with the measurements and the model estimates.

Elevation data integration is a complex research issue and represents a fundamental problem due to conflicting attributes (elevation and gradients) and varying degrees of accuracy (Weibel and Heller, 1994). This chapter addresses the science question (Chapter 1): how far does integration of multiplatform elevation data increases accuracy and reliability of topographic models? Some researchers have used the Fourier transforms in remote sensing
and topographic science to study land surface phenology (Moody and Johnson, 2001), analyse time series NDVI data (Menenti et al., 1993; Azzali and Menenti, 2000), fuse satellite images (Ling et al., 2007), do gravimetric terrain corrections (Kirby and Featherstone, 1999), investigate DEM error patterns (Liu and Jezek, 1999), and analyse topographic data (Ricard et al., 1987; Mulla, 1988; Pan, 1989; Ansoult, 1989; Harrison and Lo, 1996; Perron et al., 2008). A few authors have used data from one elevation model to fill the gaps in another model (Slatton et al., 2002; Kaab, 2005). The research on Fourier analyses of topographic data, however, did not address the fusion of elevation data. Similarly, no work deals with merging physiographic region and land cover-wise calibrated elevation data, particularly on wetland environments. Thus, it is essential to develop approaches and methods for integrating data to produce hybrid elevation datasets. Here, we propose fusion and merging approaches for integrating elevation data from diverse platforms (as per Section 3.2.4, Chapter 3). Figure 7.1 presents an outline of these integration approaches. The first approach applies a Fourier transform in the frequency domain with grid elevation data, followed by filtering and frequency fusion. The second approach combines elevation data through physiographic region and land cover-wise bias calibration, and integrates elevation observations after bias calibration to produce DEMs. In both approaches, the assumption is that integration of elevation data from diverse platforms results in improved elevation datasets/DEMs, and thereby presents more realistic topography than individual elevation dataset alone can provide.

**Figure 7.1** Outline for integrating multiplatform elevation observations (test site and regional level) for improved wetland topographic modeling. Photogrammetric DEM and GPS measurement provides the reference data for evaluating vertical accuracy (implies by RMSE2) of fused and merged datasets, respectively. Datasets are defined as:

- Airborne profiling radar = AGS
- Spaceborne imaging radar = SRTM
- Spaceborne profiling laser = ICESat
- Spaceborne optical stereo = ASTER
- Spaceborne profiling radar = CryoSat

![Diagram](image-url)
Fusion of elevation data is done at a test site for which a photogrammetrically-derived detailed DEM (Chapter 4, Section 4.2.1) is available for microtopographic evaluation. This investigation examines the level of improvement we can achieve through fusion of multisource elevation data in the frequency domain. Since fusion is confined to a test site and no detailed DEM is available for the whole study area for evaluation, a merging approach is developed. Merging elevation data for the whole study area is done by two strategies: 1) bias calibration of lower accuracy elevation models by sparse higher accuracy data (Section 7.2), and 2) bias calibration of lower accuracy elevation measurements (point data) by sparse higher accuracy data, followed by integration of corrected datasets to produce elevation models through interpolation (Section 7.3). These strategies are called merging approach since calibration of lower accuracy elevation data with higher accuracy data incorporates information from higher accuracy data (for the first strategy) and incorporates information from higher accuracy data, followed by integration of corrected datasets (for the second strategy). Independent higher accuracy reference data is used to evaluate the merged data products (Section 7.4).

7.2 Fusion of Elevation Observations

This section describes methods to fuse elevation data acquired from diverse platforms, and then evaluates their quality. Table 7.1 presents datasets for fusion in the frequency domain.

<table>
<thead>
<tr>
<th>Fusion elevation dataset</th>
<th>Spatial level</th>
<th>Reference data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spaceborne imaging* and airborne profiling radar</td>
<td>Test site</td>
<td>Airborne photogrammetric DEM</td>
</tr>
<tr>
<td>Spaceborne imaging radar* and GPS-based model</td>
<td>Test site</td>
<td>Airborne photogrammetric DEM</td>
</tr>
</tbody>
</table>

*SRTM C-band.

7.2.1 Fusion Methods and Approaches

Remotely sensed digital image fusion is a well-established field, and there are numerous methods to do it (Pohl, 1996; Wald et al., 1997; van Der Meer, 1997; Pohl and Van Genderen, 1998). The goal is to improve the image quality by combining data from various spectral bands and sensors, especially fusion of higher spatial resolution panchromatic and lower/medium resolution multispectral images. These methods, however, cannot be applied to the fusion of elevation data, as the third dimension (z) in elevation models is not the spectral signature of Earth's surface cover (e.g. land cover) but terrain. Elevation data of earth surface provide terrain heights above mean sea level with reference to an ellipsoid (e.g. WGS84), and these heights remained the same irrespective of measurement techniques (ground, air or space-based). A simple method of fusion is the merging and averaging of two or more elevation datasets of the same area without considering their error budgets. In this approach, all datasets get equal treatment in fusion. In the Okavango Delta, simply merging and averaging SRTM and airborne geophysical survey's (hereafter AGS) profiling radar-based elevation model can improve their accuracy. The reason being AGS elevation model is a smoothed surface, while SRTM model represents a rough surface. Generally, merging one dataset with another adds to the other additional information in constructing a more realistic topographic model than an individual dataset can present.
Here, we devised a frequency domain method for fusion of multiplatform elevation data. We propose two approaches to fuse elevation data: 1) frequency domain filtering, and fusion by merging and averaging (FMA), and 2) frequency domain filtering, and fusion by merging using weights and averaging (FWA). In the FMA approach, the cut-off frequency for each dataset was determined by trial and error. Based on the cut-off frequency, we extracted information from each dataset. In the next step, we merged and averaged the information, and finally transformed back to the spatial domain as a fused DEM. The FMA approach, however, does not take into account error budgets in the dataset. To overcome the limitation of FMA approach, we proposed a FWA approach. The FWA approach establishes the cut-off frequency for each dataset based on the error budget defined by the mean square error (MSE). Based on the error budgets, the cut-off frequency was decided to extract information from each dataset and then added together, and finally transformed back to the spatial domain as a fused DEM. The MSE of datasets is a criterion to assign the cut-off frequency to each dataset, which was derived with reference to better quality data (i.e. airborne photogrammetric DEM). This method allows fusion of several elevation datasets, however, accurate co-registration of datasets is essential.

This chapter describes the fusion of the elevation data measured by SRTM with two other datasets: airborne radar (AGS) model and GPS-based elevation model (i.e. MDEM, Gumbricht et al. 2005). The SRTM elevation data were measured by a single-pass InSAR imaging technology, AGS data measured by a radar altimeter profiling technology, and MDEM was generated based on sparse GPS postings on the delta using land-vegetation cover information (from Landsat images) as a determinant. The fusion of elevation datasets was carried out in the frequency domain.

### 7.2.2 Evaluation of Fusion Datasets

The vertical accuracy of the three elevation datasets (AGS, SRTM and MDEM) on a test site in Maunachira (Okavango Delta) was evaluated against the higher accuracy airborne photogrammetric DEM. These elevation datasets were used for fusion. The test site in Maunachira is located (upper-left X,Y: 732584 N, 7888831 E and lower-right X,Y: 738864 N, 7878231 E) in the permanent and seasonal swamps. The site covers an area of 6.3 km x 10.6 km (66.8 km²); the details about the site are given in Chapter 4 (Section 4.3.1). Multiplatform elevation data requires assessment of their characteristics and error structures for devising methods for fusion. The photogrammetric DEM has a 10 m spatial resolution and it was used as a reference data. To match with the photogrammetric DEM to assess the accuracy of fused data, SRTM, AGS and MDEM datasets were scaled down to 10 m spatial resolution using IDW interpolation method. Table 7.2 presents characteristics of the datasets, SRTM model shows the highest mean elevation (~957 m) while photogrammetric DEM the lowest (~952 m). The photogrammetric DEM represent the highest relief features (σ=1.9 m), while AGS the lowest (σ= 0.73 m).

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>Photogrammetric</th>
<th>SRTM</th>
<th>AGS</th>
<th>MDEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation</td>
<td>946</td>
<td>949</td>
<td>954</td>
<td>952</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>958</td>
<td>967</td>
<td>958</td>
<td>957</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>951,619</td>
<td>956,723</td>
<td>956,282</td>
<td>953,904</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>1.902</td>
<td>1.35</td>
<td>0.727</td>
<td>0.826</td>
</tr>
</tbody>
</table>
Table 7.3 presents the error characteristics of the four elevation datasets in relation to photogrammetric DEM. SRTM model gave the highest vertical RMSE (5.53 m), followed by the SRTM filtered model (5.37 m) and AGS elevation model (4.95 m), while MDEM resulted in lowest RMSE (2.72 m).

Table 7.3 Error characteristics of elevation datasets: SRTM, SRTMF, AGS and MDEM.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum error</td>
<td>-2</td>
<td>-2</td>
<td>-1</td>
<td>-3</td>
</tr>
<tr>
<td>Maximum error</td>
<td>16</td>
<td>10</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Mean error</td>
<td>5.104</td>
<td>4.555</td>
<td>4.664</td>
<td>2.286</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>2.115</td>
<td>1.79</td>
<td>1.666</td>
<td>1.48</td>
</tr>
<tr>
<td>RMSE</td>
<td>5.525</td>
<td>5.37</td>
<td>4.95</td>
<td>2.723</td>
</tr>
</tbody>
</table>

Table 7.4 presents an evaluation of the similarity (p) of elevation models with the photogrammetric DEM. A moderate correlation exists between photogrammetric DEM and MDEM (p= 0.67), while photogrammetric DEM and AGS elevation model show lower correlation (p= 0.5). SRTM original and filtered models are poorly correlated with the photogrammetric DEM (p= 0.19).

Table 7.4 Similarities (p) between photogrammetric DEM and other elevation models.

<table>
<thead>
<tr>
<th>Datasets</th>
<th>Correlation coefficient (p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photogrammetric DEM vs. SRTM</td>
<td>0.189</td>
</tr>
<tr>
<td>Photogrammetric DEM vs. SRTMF</td>
<td>0.19</td>
</tr>
<tr>
<td>Photogrammetric DEM vs. AGS</td>
<td>0.495</td>
</tr>
<tr>
<td>Photogrammetric DEM vs. MDEM</td>
<td>0.672</td>
</tr>
</tbody>
</table>

The correlation between SRTM and AGS models is low (p= 0.295), as also between SRTM model and MDEM (p= 0.248), while it is relatively high between AGS model and MDEM (p= 0.655). The low correlation represents difference in elevation structure of the models. The low frequency surface of AGS model and the high frequency surface of SRTM model (with low p value) when fused result in each adding to the other value-added information, and thereby have potential to produce an improved DEM.

Figure 7.2 presents the elevation models (10 m spatial resolution) of the Maunachira test site: photogrammetric DEM, SRTM model, AGS elevation model and MDEM. The photogrammetric DEM provides detailed micro-topographic structure and information with a relief (a) of ~2 m (Table 7.2). The SRTM model presents poor topographic structure, with a standard deviation of 1.35 m. AGS model represent a smooth surface with elevation ranges between 954 m and 958 m, and with low relief variation (σ = 0.73 m); however, it provides relatively good topographic structure, though less detailed in comparison with the photogrammetric DEM. MDEM presents poor topographic structure (σ = 0.83 m); in fact, it presents erroneous elevation structures (Figure 7.2d). The MDEM resulted in a low RMSE (2.72 m) and good correlation (p= 0.67 m) compared to photogrammetric DEM because it was created from GPS elevation postings (the vertical accuracy of which is similar to the accuracy of elevation of photogrammetric DEM at point location).
Figure 7.2 Elevation models (10 m spatial resolution) of the Maunachira test site. a) photogrammetric DEM, b) SRTM model, c) AGS elevation model and d) MDEM (a GPS-based model). Airborne photogrammetric DEM (reference data) represent elevation range (minimum and maximum) of 12 m. Among other datasets, SRTM model have 18 m elevation range, while AGS and MDEM have 4 m and 5 m ranges, respectively.
7.2.3 Profiling and Imaging Radar Models

Fused Model 1: This section fused the AGS and SRTM models by two methods. The resultant fused models are then evaluated against the photogrammetric DEM.

Fusion Methods

Method 1
This method used a strategy of frequency domain filtering, and fusion by merging and averaging (FMA), i.e. the fusion of elevation data by spectral filtering and merging. The filtering and fusion strategy is presented in Figure 7.3, which requires several processing steps. First, two sample elevation datasets — AGS and SRTM elevation models were co-registered to the photogrammetric DEM. Then, error characteristics of these datasets were assessed comparing with the reference photogrammetric DEM through difference images (AGS vs. photogrammetric DEM; SRTM vs. photogrammetric DEM). AGS and SRTM elevation models were then separately transformed into frequency domain by applying fast Fourier transform (FFT). A circular highpass filter (IHPF) was applied to the Fourier spectrums of two elevation models with cut-off frequencies decided by trial-and-error to extract noise spectrums (i.e. high frequency spectrums). High spatial frequency content is associated with frequent changes of brightness with position (Richards and Jia, 2006). IHPF-filtered noise spectrums (AGS spectrum and SRTM spectrum) are then subtracted from original AGS and SRTM frequency spectrums, respectively, to derive AGS and SRTM denoised spectrums. These denoised spectrums (of AGS and SRTM) were merged and then averaged to derive the fused spectrum. This fused spectrum was transformed back to the spatial domain as a fused DEM by applying inverse FFT (IFFT). Finally, the vertical accuracy of fused DEM was assessed by photogrammetric DEM.

Method 2
This method used a strategy of frequency domain fusion by filtering and merging with a weight factor (FWF), i.e. the fusion of filtered elevation datasets as per error budgets. The MSE was used to derive weights for each dataset based on their error budgets. The MSE (Appendix XI) was used as a criterion for estimation; smaller the MSE closer the estimation is to the actual data. The filtering and fusion strategy is presented in Figure 7.3, and detailed processes are described in Method 1. For SRTM and AGS elevation models, MSEs were calculated with reference to the photogrammetric DEM. The ratio of error (i.e. MSE) between SRTM and AGS elevation models determined the cut-off frequency of each model in spectral filtering.
Figure 7.3 Approach for spectral filtering and frequency domain fusion of elevation data.

Results and Quality Assessment

Figure 7.4 presents fused SRTM filtered & AGS, and fused SRTM filtered & AGS based on MSE weight models. On both fused models, fusion has brought smoothness to the rough SRTM elevation, while improved the smooth structure of the AGS elevation. The first approach has produced better topographic structure (pattern and shape of features) (Figure
7.4a) than the second approach (Figure 7.4b), when compared against photogrammetric DEM (Figure 7.2a).

The RMSE of the fused models (Table 7.5) show that both fusion methods (FU1 and FU2) has improved the SRTM model. The mean difference between the SRTM model and photogrammetric DEM was 5.1 m and RMSE 5.53 m (SRTM), while mean difference between AGS elevation model and photogrammetric DEM was 4.7 m and RMSE 4.95 m (AGS) (Table 7.3). After filtering and fusion, the mean difference has reduced to 4.6 m and RMSE to 4.2 m (with Method 1), and mean difference to 3.8 m and RMSE to 4.2 m (with Method 2).

Table 7.5 Comparison of the fused elevation models, obtained with Method 1 (FU1) and Method 2 (FU2).

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>Fused DEM (m)</th>
<th>Elevation difference, (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FU1 $^\dagger$</td>
<td>FU2 $^\ddagger$</td>
</tr>
<tr>
<td>Minimum elevation</td>
<td>952</td>
<td>952</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>960</td>
<td>959</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>956.17</td>
<td>955.438</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.856</td>
<td>0.854</td>
</tr>
<tr>
<td>RMSE (Fused DEMs)</td>
<td>4.894</td>
<td>4.242</td>
</tr>
</tbody>
</table>

$^\dagger$FU1 (method 1) = Fusion between SRTM filtered & AGS, $^\ddagger$FU2 (method 2) = Fusion between SRTM filtered & AGS, based on MSE weight.

Figure 7.4 Fused DEMs of the Maunachira test site. a) Fused SRTM filtered & AGS model, b) fused SRTM filtered & AGS model, based on MSE weights.
Figure 7.5 shows the elevation difference images of fused SRTM filtered & AGS model (FU1) vs. photogrammetric DEM, and fused SRTM filtered & AGS model based on MSE weight (FU2) vs. photogrammetric DEM. The MSE weight-based fusion approach has improved the quality of the model, which is visible when comparing error structures of elevation difference images (Figures 7.5a vs. b) and RMSEs (Table 7.6).

![Elevation difference images](image)

**Figure 7.5** Elevation difference images, a) SRTM filtered & AGS fused DEM vs. photogrammetric DEM, b) SRTM filtered & AGS fused DEM, based on MSE weight vs. photogrammetric DEM. The second approach has produced improved error structure than the first approach.

The progressive improvement in vertical accuracy has occurred in the SRTM elevation model, first by spectral filtering, then by fusion with the AGS elevation dataset (Table 7.6). A purposeful improvement is achieved by fusing SRTM and AGS elevation data, particularly by fusion based on the MSE weight. This is a gain to SRTM model by adding values from AGS elevation dataset. Figure 7.6 presents the errors in elevation models: SRTM original, SRTM filtered, fused SRTMF & AGS model, and fused SRTMF & AGS model based on MSE weight, all evaluated against the photogrammetric DEM.

<table>
<thead>
<tr>
<th>Elevation models</th>
<th>Mean error (m)</th>
<th>RMSE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRTM</td>
<td>5.1</td>
<td>5.52</td>
</tr>
<tr>
<td>SRTM (filtered)</td>
<td>4.56</td>
<td>5.37</td>
</tr>
<tr>
<td>SRTMF &amp; AGS fused</td>
<td>4.56</td>
<td>4.894</td>
</tr>
<tr>
<td>SRTMF &amp; AGS fused, based on MSE weight</td>
<td>3.82</td>
<td>4.242</td>
</tr>
</tbody>
</table>

Table 7.6 Error statistics of original, filtered, and fused elevation models.
7.2.4 Imaging Radar and GPS-based Models

Fused Model 2: In this section, we describe how SRTM and GPS-based (MDEM) fused model of the Maunachira test site was obtained, using the approach described in Section 7.2.3. Then, these fused models were evaluated using photogrammetric DEM.

Methods

First, two sample elevation datasets: SRTM and GPS-based (MDEM) models were co-registered to the photogrammetric DEM, and then error characteristics of sample datasets were evaluated against the photogrammetric DEM (SRTM vs. photogrammetric DEM; MDEM vs. photogrammetric DEM). Using the same procedure (Section 7.2.3, Figure 7.3), filtering and fusion of the SRTM elevation and the MDEM model was carried out. In the second method, MSE for SRTM model and MDEM was calculated with reference to photogrammetric DEM. The ratio of the error (i.e. MSE values) between SRTM model and MDEM provided the basis for deciding cut-off frequencies for spectral filtering of each model.

Results and Quality Assessment

Figure 7.7 presents the fused SRTM filtered & MDEM, and fused SRTM filtered & MDEM based on MSE weight. The first fusion approach has brought smoothness to the SRTM elevation model, while improved the structure of the MDEM elevation model. The second approach has improved the quality of the fused DEM statistically, however, structurally (topographic pattern, shape) it performed poorly compared to the result of the first approach. This is because of difference in MSE on datasets; SRTM contributed less in the fusion due to high MSE, while MDEM contributed more because of low MSE.
Table 7.7 characterizes the topographic structure of fused elevation models. Both fusion approaches have improved the SRTM elevation model (3.8 m and 2.7 m RMSEs, respectively for FU1 and FU2).

Table 7.7 Comparison of the fused elevation models, obtained with Method 1 (FU1) and Method 2 (FU2).

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>Fused DEM (m)</th>
<th>Elevation difference, (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FU1</td>
<td>FU2</td>
</tr>
<tr>
<td>Minimum elevation</td>
<td>951</td>
<td>951</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>959</td>
<td>957</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>955.02</td>
<td>953.89</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.888</td>
<td>0.858</td>
</tr>
<tr>
<td>RMSE (Fused DEMs)</td>
<td>3.795</td>
<td>2.712</td>
</tr>
</tbody>
</table>

FU1 = Fusion between SRTM filtered model & MDEM, FU2 = Fusion between SRTM filtered model & MDEM, based on MSE weight.

Figure 7.8 presents the elevation difference images of 1) fused SRTM filtered & MDEM vs. photogrammetric DEM, and 2) fused SRTM filtered & MDEM based on MSE weight vs. photogrammetric DEM. MSE weight-based fusion approach improves the quality of the model as evident from visual comparison of the difference images (Figure 7.8a vs. b), and error statistics (Table 7.7).
As with fusion with the AGS model, the elevation accuracy of the SRTM model improves steadily, first by spectral filtering, then by fusion with the MDEM dataset (Table 7.8, Figure 7.9). The mean error is reduced from 5.1 m to 2.27 m, while RMSE is reduced from 5.5 m to 2.7 m. A substantial improvement has occurred by fusing SRTM filtered elevation data and MDEM. The overall error of MDEM, and fused SRTMF-MDEM based on MSE weight is nearly the same (RMSE= 2.7 m) as the fused model got more information from the MDEM dataset. Figure 7.9 presents the trends of errors in elevation models: SRTM original, SRTM filtered, fused SRTMF & MDEM, and fused SRTMF & MDEM based on MSE weight.

Table 7.8 Error statistics of original, filtered, and fused elevation models.

<table>
<thead>
<tr>
<th>Elevation models</th>
<th>ME (m)</th>
<th>RMSE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRTM</td>
<td>5.1</td>
<td>5.52</td>
</tr>
<tr>
<td>SRTMF (filtered)</td>
<td>4.56</td>
<td>5.37</td>
</tr>
<tr>
<td>SRTMF &amp; MDEM fusion</td>
<td>3.4</td>
<td>3.8</td>
</tr>
<tr>
<td>SRTMF &amp; MDEM fusion based on MSE weight</td>
<td>2.27</td>
<td>2.712</td>
</tr>
</tbody>
</table>
7.3 Merging Elevation Observations

This section describes two approaches to merge elevation data from varied platforms, and then evaluates their vertical accuracy. The main purpose of merging elevation observations is to improve the quality in terms of vertical accuracy and topographic structure (physical features of the terrain). Table 7.9 presents elevation datasets, which were bias calibrated and combined at various spatial resolution and coverage, along with datasets for evaluation.

Table 7.9 Elevation datasets used in this section for merging, bias calibration and validation.

<table>
<thead>
<tr>
<th>Elevation data</th>
<th>Calibration data</th>
<th>Determinant data</th>
<th>Spatial level</th>
<th>Reference data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imaging radar(^1)</td>
<td>Profiling laser</td>
<td>Land cover(^2)</td>
<td>Delta, wetland</td>
<td>GPS posting(^6)</td>
</tr>
<tr>
<td>Optical stereo imaging(^2)</td>
<td>Profiling laser</td>
<td>-</td>
<td>Delta</td>
<td>GPS posting</td>
</tr>
<tr>
<td>Profiling radar(^3)</td>
<td>Profiling laser/</td>
<td>-</td>
<td>Delta</td>
<td>GPS posting</td>
</tr>
<tr>
<td></td>
<td>GPS</td>
<td></td>
<td></td>
<td>GPS posting</td>
</tr>
<tr>
<td>GPS</td>
<td>-</td>
<td>-</td>
<td>Delta</td>
<td>GPS GCP(^7)</td>
</tr>
</tbody>
</table>

\(^1\)SRTM C-band, \(^2\)ASTER GDEM, \(^3\)CryoSat SIRAL, \(^4\)ICESat GLAS, \(^5\)from Landsat 7, \(^6\)Geological Survey of Botswana, \(^7\)ETHZ survey.
7.3.1 Merging Methods

Combining heterogeneous elevation data is challenging because of diversity in attributes such as elevation and gradients, and varying accuracy. New approaches and methods are required for optimal use of disparate elevation data from various platforms and instruments to produce improved quality datasets.

Several authors assessed the elevation accuracy of the SRTM (Sun et al., 2003; Carabajal and Harding, 2005; Rodríguez et al., 2006) and of the ASTER (Hayakawa et al., 2008) elevation data, while some authors examined the land cover-dependent errors in SRTM elevation data (Carabajal and Harding, 2006; Hofton et al., 2006; Bhang et al., 2007). However, limited attention was given to correct elevation bias of these datasets. Further, integration of data from varied platforms to produce elevation models received little attention, especially for modeling wetland topography. This study focuses on merging elevation data through bias calibration of lower accuracy data (e.g. SRTM, ASTER and CryoSat) with higher accuracy data (GPS and ICESat) over the Kalahari landscape (low-relief Okavango wetland, and surrounding land-vegetation and sand dunes). The vertical error difference between the lower and higher accuracy data was used as an offset (i.e. Mean Elevation Difference, MED) and this offset was used as a correction factor for lower accuracy data. This study also assesses land cover-dependent elevation bias in the SRTM data on the Okavango wetland. The main purpose of merging elevation data (Table 7.9) was to improve the vertical accuracy. We devised two approaches to achieve this:

**Merging Approach 1**
Bias calibration of lower accuracy elevation models (continuous surface) by higher accuracy data, i.e. incorporating higher accuracy information into lower accuracy data.

**Merging Approach 2**
Bias calibration of lower accuracy point elevation data by higher accuracy data, and then combining bias-corrected datasets to construct integrated models through interpolation.

In the merging approach 1, the biases in SRTM and ASTER data were calibrated using ICESat laser data. As the SRTM provides consistent data at 90 m spatial resolution, and better vertical accuracy than the ASTER model (see Chapter 6, Section 6.7), elevation bias in the SRTM data was calibrated for the delta, wetland and for each land cover. This enables 1) the examination of error distribution patterns on the data, and 2) examine to what extent physiographic region and land cover-dependent elevation bias in SRTM data could be corrected using ICESat data over the Okavango wetland. Both original and bias-calibrated SRTM and ASTER datasets were evaluated by GPS measurements.

In the merging approach 2, first the bias in the ICESat data was calibrated to GPS elevation, followed by bias calibration of CryoSat data to calibrated-ICESat data (as ICESat-CryoSat provides large pair data). These corrected datasets for the delta region were merged and then interpolated to construct integrated elevation models at a SRTM spatial resolution (to keep consistency of datasets for evaluation). The constructed elevation models: 1) integrated profiling radar and laser (CryoSat + ICESat), and 2) integrated profiling radar and laser, and positioning system (CryoSat + ICESat + GPS), were then evaluated by independent GPS measurements. The procedures for bias calibration of dataset and their integration are described in respective sections.

Table 7.10 presents an outline of the elevation datasets used for merging: 1) datasets calibrated: SRTM, ASTER, ICESat and CryoSat; 2) datasets used for bias calibration: GPS and ICESat; 3) datasets integrated: (bias-calibrated ICESat + bias-calibrated CryoSat) and (bias-calibrated ICESat + bias-calibrated CryoSat + GPS); and 4) independent GPS measurements: for evaluation of all merged products. Biases in SRTM, ASTER and CryoSat
data were calibrated to ICESat elevation and GPS-calibrated ICESat data (with large samples), while the bias in the ICESat data was calibrated to GPS elevation (high accuracy but small sample size).

Table 7.10 Outline of elevation datasets used for merging.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>SRTM</th>
<th>ASTER</th>
<th>ICESat</th>
<th>CryoSat</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRTM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASTER</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ICESat</td>
<td>7.3.2</td>
<td>7.3.3</td>
<td>7.3.4 &amp; 7.3.5</td>
<td></td>
</tr>
<tr>
<td>CryoSat</td>
<td></td>
<td></td>
<td>E</td>
<td></td>
</tr>
<tr>
<td>GPS</td>
<td>7.3.2</td>
<td>7.3.3</td>
<td>C</td>
<td>E</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7.3.5</td>
<td></td>
</tr>
</tbody>
</table>

Note: = datasets calibrated (C), = merging, = evaluation (E). Numbers denote sections in the chapter.

**7.3.2 Imaging Radar and Profiling Laser Data**

*Merged Data 1 (Figure 7.1):* We describe a merging approach through bias calibration of the SRTM data using ICESat laser measurements over the Okavango Delta region. Bias calibration incorporates higher accuracy laser information into the lower accuracy SRTM data (for the delta, wetland, and land cover type) (Table 7.9). The main purpose of bias calibration was to improve the vertical accuracy of SRTM data by correcting vertical offset. This section first evaluates the datasets, and then uses a merging approach.

**Data**

Datasets used to construct a merged elevation model are: SRTM model, ICESat observations (2003–2009), and Landsat 7 ETM+ multispectral image-based land cover map (derived in Chapter 5). The GPS measurements were used to evaluate the merged model. The characteristics of these datasets are described in Chapters 2 & 4. Figure 7.10 shows the distribution of ICESat profiles over the Okavango Delta SRTM elevation model.
Figure 7.10 ICESat altimeter profiles (black) on the Okavango Delta SRTM elevation model. These laser shots (133526) were acquired during 19 laser campaigns, February 2003 to October 2009.

Figure 7.11 shows the distribution of ICESat laser shots on the Okavango wetland land cover (open water, swamp, land-vegetation and bare soil). The number of laser shots is roughly proportional to each land cover type area (Table 7.11). The largest number of laser shots are available over swamps, followed by open water and land-vegetation, and the smallest number on bare soil.
Evaluation of Datasets

The deviation of the SRTM elevation from ICESat measurements ranges between −13.73 m to 12.75 m on the delta, as estimated with 133526 laser shots. The mean elevation error was 0.7 m (median error 0.66 m) and RMSE was 1.91 m (standard deviation error 1.71 m) (Chapter 6, Table 6.16). Over the wetland, the SRTM error ranges between −9.71 m to 11.35 m, estimated by 24219 laser shots (Table 7.11). The mean elevation error was 0.67 m and RMSE was about 2 m (standard deviation error 1.93 m) (Table 7.12).

The land cover-wise range in elevation error between SRTM and ICESat data (Table 7.11) shows that the highest error were over the swamp and the lowest over the bare soil. Open water and land-vegetation areas gave similar range of vertical errors in the SRTM data.
Table 7.11 Range of errors in the Okavango wetland SRTM model relative to land cover types, estimated using ICESat laser measurements.

<table>
<thead>
<tr>
<th>Land cover class</th>
<th>Number of points (% of total sample)</th>
<th>Range of elevation error (m) SRTMz - ICESatz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open water</td>
<td>6706 (28)</td>
<td>-9.456 - 9.017</td>
</tr>
<tr>
<td>Swamp</td>
<td>10410 (43)</td>
<td>-9.710 - 11.348</td>
</tr>
<tr>
<td>Land-vegetation</td>
<td>6132 (25)</td>
<td>-8.409 - 9.838</td>
</tr>
<tr>
<td>Bare soil</td>
<td>971 (4)</td>
<td>-6.173 - 7.726</td>
</tr>
<tr>
<td>All</td>
<td>24219</td>
<td>-9.71 - 11.348</td>
</tr>
</tbody>
</table>

*ICESat sample = 24219 points.*

Table 7.12 presents the error statistics of the Okavango wetland SRTM data assessed against ICESat observations, for each major land cover type. The mean error in the SRTM elevation data ranges between 0.38 m (bare soil) and 0.83 m (land-vegetation), with a mean overall error of 0.67 m over the wetland. The SRTM data open water and bare soil elevation have lower mean error than over swamp and land-vegetation. The SRTM wetland relief (σ) varies between 1.7 m over the bare soil to ~2 m on the swamp.

Table 7.12 Errors in the Okavango wetland SRTM elevation model for different land cover types, estimated using ICESat laser measurements.

<table>
<thead>
<tr>
<th>Land cover class</th>
<th>Error characteristics in SRTM model (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean error</td>
</tr>
<tr>
<td>Open water</td>
<td>0.477</td>
</tr>
<tr>
<td>Swamp</td>
<td>0.734</td>
</tr>
<tr>
<td>Land-vegetation</td>
<td>0.827</td>
</tr>
<tr>
<td>Bare soil</td>
<td>0.380</td>
</tr>
<tr>
<td>All</td>
<td>0.672</td>
</tr>
</tbody>
</table>

*ICESat sample = 24219 points.*

Merging Approach

Figure 7.12 presents the approach for merging the SRTM model and ICESat data over the Okavango Delta region. First, all datasets were georeferenced to the Clarke 1880 ellipsoid and Cape datum (with orthometric height). Then, outliers in ICESat laser data were removed using criteria explained in Chapter 6 (Section 6.2.2), data voids in the SRTM model were corrected, and a land cover map of the Okavango wetland was derived from Landsat 7 images (see Chapter 5).

Laser measurements were collected for the delta, wetland and land cover type and the corresponding SRTM points were extracted. These pairs of SRTM and laser points were compared to estimate bias in the SRTM data (mean elevation difference, MED), and these offsets were used as bias calibration parameters. The SRTM model was calibrated for the delta, wetland and land cover type using MED. For the delta, the SRTM mean elevation is characterized by 0.703 m positive bias compared to ICESat elevation (133526 laser shots, see Table 6.16, Chapter 6). For the wetland, SRTM mean elevation is characterized by 0.67 m positive bias compared to ICESat elevation (24219 laser shots), while for the land cover type
the SRTM mean elevation bias ranges from 0.38 m over the bare soil to 0.83 m on the land-vegetation compared to ICESat elevation (Table 7.12). Finally, bias calibrated SRTM (delta, wetland and land cover type) models were evaluated by GPS measurements. Note, the elevation bias (offset) in the ICESat data (0.19 m compared to GPS heights, estimated using 54 GPS measurements in Chapter 6), is not considered here.

![Diagram](image)

**Figure 7.12** Approach for merging spaceborne imaging radar and profiling laser elevation data. Land cover data was used as a determinant to extract ICESat and SRTM elevation by land cover type, and then calibrate elevation data and assess merged elevation datasets.

**Results and Discussion**

**Delta Level**

Figure 7.13 shows the error statistics of SRTM model on the Okavango Delta region. The ICESat-based calibration removed positive bias, but it have produced negative bias of ~0.32 m (as estimated by GPS assessment, Table 7.13). Bias correction marginally improved the vertical accuracy of SRTM model from 1.71 m to 1.70 m. The corrected SRTM model had an accuracy very similar to the uncorrected model (Table 7.13), so is not visualised here (for SRTM, see Figure 4.16 in Chapter 4).
Figure 7.13 Error characteristics of SRTM model on the Okavango Delta. a) elevation difference: SRTM – GPS, b) elevation difference: ICESat-calibrated SRTM – GPS. The delta comprises wetland and surrounding non-wetland areas.

Table 7.13 Comparison of GPS elevation and corresponding SRTM original and ICESat-calibrated measurements (m) on the delta.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>GPSz</th>
<th>SRTMz</th>
<th>SRTM_calib</th>
<th>Elevation difference</th>
<th>SRTM – GPS</th>
<th>SRTM_calib – GPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation</td>
<td>921.276</td>
<td>922</td>
<td>921.297</td>
<td>-6.252</td>
<td>-6.955</td>
<td></td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>1042.065</td>
<td>1038</td>
<td>1037.297</td>
<td>5.898</td>
<td>5.195</td>
<td></td>
</tr>
<tr>
<td>Mean elevation</td>
<td>958.858</td>
<td>959.239</td>
<td>958.536</td>
<td>0.381</td>
<td>-0.322</td>
<td></td>
</tr>
<tr>
<td>Standard deviation</td>
<td>19.357</td>
<td>19.239</td>
<td>19.239</td>
<td>1.672</td>
<td>1.672</td>
<td></td>
</tr>
<tr>
<td>RMSE</td>
<td></td>
<td></td>
<td></td>
<td>1.714</td>
<td>1.702</td>
<td></td>
</tr>
</tbody>
</table>

*GPS sample = 1000 points. SRTM median error = 0.382 m, SRTM calibrated median error = -0.321 m.

Wetland

The SRTM elevation over the Okavango wetland was characterized by a positive bias of 0.67 m, compared to ICESat laser elevation. The error statistics of the SRTM model (original and calibrated) on the Okavango wetland (Figure 7.14) show that laser-based calibration has reduced the elevation error from 1.79 m to 1.71 m, as estimated by GPS measurements (Table 7.14). The mean elevation error in the SRTM wetland model reduced from 0.54 m to -0.15 m. ICESat-based calibration of SRTM wetland model slightly improved its vertical accuracy.
Figure 7.14 Error characteristics of SRTM model on the Okavango wetland. a) elevation difference: SRTM – GPS, b) elevation difference: ICESat-calibrated SRTM – GPS. Wetland covers four land cover classes: open water, swamp, land-vegetation, and bare soil.

Table 7.14 Comparison of GPS elevation and corresponding SRTM original and ICESat-calibrated measurements (m) on the wetland.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>GPSz</th>
<th>SRTMz</th>
<th>SRTM calibz</th>
<th>Elevation differencez</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation</td>
<td>936.322</td>
<td>936</td>
<td>935.173</td>
<td>-3.977</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>995.443</td>
<td>996</td>
<td>995.266</td>
<td>6.052</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>958.974</td>
<td>959.514</td>
<td>958.826</td>
<td>0.540</td>
</tr>
<tr>
<td>RMSE</td>
<td></td>
<td></td>
<td>1.791</td>
<td></td>
</tr>
</tbody>
</table>

*GPS sample = 247 points. SRTM wetland median error = 0.401 m, SRTM calibrated wetland median error = -0.249 m.

Land Cover

Figure 7.15 presents the error characteristics of SRTM elevation data (original and calibrated) by land cover type over the Okavango wetland, using GPS measurements as a reference. Land cover-wise calibration of SRTM data reduced the vertical error in the model over open water and swamp areas, but only marginally over the land-vegetation area (Table 7.15). However, bare soil elevation shows slight increase in error after calibration because small number of GPS samples used for evaluation. In general, the vertical error did not improve much with this wetland cover dependent bias correction.
Figure 7.15 Error characteristics of SRTM elevation data by land cover type in the Okavango wetland. Original SRTM (left) and bias-corrected SRTM (right).
Table 7.15 Error statistics of SRTM and ICESat-calibrated SRTM by land cover type in the Okavango wetland, estimated by GPS measurements (247 postings).

<table>
<thead>
<tr>
<th>Land cover class</th>
<th>Error SRTMz (m)</th>
<th>Error SRTM calibratedz (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Median</td>
</tr>
<tr>
<td>Open water</td>
<td>0.486</td>
<td>0.552</td>
</tr>
<tr>
<td>Swamp</td>
<td>0.774</td>
<td>0.660</td>
</tr>
<tr>
<td>Land-veg</td>
<td>0.439</td>
<td>-0.062</td>
</tr>
<tr>
<td>Bare soil</td>
<td>-0.616</td>
<td>-0.884</td>
</tr>
</tbody>
</table>

1Evaluation GPS sample: open water = 57; swamp = 101; land-vegetation = 78; bare soil = 11.

7.3.3 Optical Stereo Imaging and Profiling Laser Data

*Merged Data 2 (Figure 7.1)*: This section describes the bias correction of ASTER global elevation data (GDEM) by ICESat laser observations over the Okavango Delta region.

Data Characteristics

ASTER-GDEM and ICESat elevation data (133505 shots, 2003–2009) were merged to construct an improved elevation model. ICESat altimeter profiles on the Okavango Delta ASTER model was shown in Chapter 6 (Figure 6.26b). GPS measurements (1000 postings) were used for evaluation of the merged model. The ASTER elevation difference was between -28.13 m and 25.77 m at the delta level, as estimated by 133501 ICESat laser shots. The MED was 1.515 m (median difference 1.47 m) and RMSE was 4.425 m, with a standard deviation of error 4.158 m (Table 6.18, Chapter 6).

Merging Approach

Figure 7.16 presents the approach for merging spaceborne optical stereo imaging and profiling laser elevation data over the Okavango Delta region. First, all datasets were georeferenced to Clarke 1880 ellipsoid and Cape datum (with orthometric height). Then, outliers in ICESat laser data were removed using criteria mentioned in Chapter 6 (Section 6.2.2), extreme elevation values in the ASTER GDEM were detected and corrected manually through visualization.

From ICESat laser observations on the delta, the corresponding ASTER elevation points were extracted at the location of laser points. These pair ASTER and laser points were compared to estimate the bias (MED) in the ASTER model, and this MED was used as a calibration parameter. Corrected ASTER mean elevation is characterized by 1.515 m positive bias, compared to ICESat measurements (133501 laser shots, see Table 6.18, Chapter 6). The Okavango Delta ASTER elevation model was evaluated by GPS measurements. Note, the bias in ICESat data (0.19 m compared to GPS heights, estimated using 54 GPS measurements in Chapter 6), is not considered here.
Results and Discussion

Figure 7.17 shows error characteristics of the ASTER GDEM on the Okavango Delta region. The ICESat-based calibration removed positive bias, but it introduced negative bias of $-0.4$ m (as estimated using the GPS reference, Table 7.16). In general, bias correction only marginally improved the vertical accuracy of ASTER model from 4.52 m to 4.4 m. ASTER GDEM data is discarded for further analysis as its vertical accuracy is much lower than the SRTM.
Figure 7.17 Error characteristics of ASTER elevation model on the Okavango Delta. a) elevation difference: ASTER - GPS, b) elevation difference: ICESat-calibrated ASTER - GPS.

Table 7.16 Comparison of GPS elevation and corresponding ASTER original and ICESat-calibrated measurements (m) on the delta.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>GPSz</th>
<th>ASTERz</th>
<th>ASTER calibz</th>
<th>Elevation difference ASTER - GPS</th>
<th>Elevation difference ASTER calib - GPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation</td>
<td>921.276</td>
<td>917</td>
<td>915.485</td>
<td>-11.763</td>
<td>-13.278</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>1042.065</td>
<td>1040</td>
<td>1038.485</td>
<td>17.375</td>
<td>15.860</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>958.858</td>
<td>959.961</td>
<td>958.446</td>
<td>1.103</td>
<td>-0.412</td>
</tr>
</tbody>
</table>

*GPS sample = 1000 points. ASTER median elevation error = 0.957 m, ASTER calibrated median elevation error = -0.559 m

7.3.4 Profiling Radar and Laser Data

*Merged Data 3 (Figure 7.1):* This section first describes the bias correction of CryoSat-2 SIRAL and ICESat GLAS observations over the Okavango Delta region. Next, it deals with the construction of an integrated elevation model combining radar and laser observations after bias correction using GPS measurements. Bias correction incorporates GPS elevation information into the CryoSat and ICESat elevation to improve their vertical accuracy. Independent GPS measurements were used to evaluate the model.

Data

The following datasets were used to construct an integrated elevation model: ICESat (133526 shots) acquired during 2003-2009, and CryoSat (52252 shots) acquired during February 2012 to January 2013 (Figure 7.18). GPS GCPs (60 points) were used to evaluate the model.
Merging Approach

To construct an integrated elevation model of the Okavango Delta region from spaceborne profiling laser and radar observations, a calibration and integration approach was developed (Figure 7.19). First, all datasets were georeferenced to Clarke 1880 ellipsoid and Cape datum (with orthometric height). Then, outliers in the ICESat data were removed using the criteria mentioned in Chapter 6 (Section 6.2.2). Outliers in the CryoSat data were corrected using the following criteria: 1) elevation values >1400 m were removed as outliers (no elevation points >1400 m in the Okavango Delta region), 2) points with elevation difference (CryoSat - ICESat) > ±3 standard deviations are eliminated as CryoSat outliers (i.e. 99.73% of the data values lie within ±3σ of the mean), and 3) further extreme values in ICESat-calibrated CryoSat data were removed using SRTM as a reference (data points with ±20 m MED).

The ICESat laser points were converted to 200 m cell, and their elevation at the GPS points was extracted over the delta. These pair GPS and laser elevation points were compared to estimate vertical offset (MED) in the laser data, and this offset was used to correct the bias in ICESat data. The offset in the ICESat data is 0.19 m compared to GPS heights (estimated using 54 GPS points, in Chapter 6). The CryoSat radar points were converted to 300 m cell (same as original footprints), and their elevation at the GPS-calibrated ICESat points were extracted over the delta. These pair laser and radar points were compared to estimate vertical
Corrected ICESat data

Comparison (ICESat-GPS)  
Calibration parameter

ICESat data calibration

Bias calibration

Data integration & interpolation

Integrated elevation model

Evaluation

GPS observations

Corrected CryoSat-2 data

Correction to 300 m grid

Extraction of CryoSat points

Comparison (CryoSat-ICESat) calibration parameter

Bias calibration

Figure 7.19 Approach for merging spaceborne profiling radar and laser data for constructing an integrated elevation model of the Okavango Delta. GPS measurements were used to bias correct ICESat data, and corrected-ICESat data were used to bias correct CryoSat data. Independent GPS measurements were used to evaluate the integrated elevation model.

offset (MED) in the radar data, and this offset was used to correct the bias in CryoSat data. The calibrated radar and laser data were merged, and then interpolated by kriging to construct an integrated elevation model of the Okavango Delta region. Finally, this integrated model was evaluated by GPS measurements.
Evaluation of Datasets

The vertical error characteristics of ICESat data over the Okavango Delta is described in Chapter 6 (Section 6.2.2). ICESat mean elevation error is 0.19 m and RMSE is 1.19 m, as estimated by 54 independent GPS measurements. Here, we evaluate the vertical error characteristics of CryoSat data. ICESat measurements (10359 points) and the corresponding CryoSat elevations were compared at the delta level. A high correlation exists between ICESat and CryoSat elevation ($R^2 = 0.99$, Figure 7.20a). Figure 7.20b shows the difference in elevation between two datasets with a MED of $-1.88$ m after removal of extreme values, and vertical error range of about 36 m in the CryoSat compared to ICESat (Table 7.17). This MED was used as an offset to bias correct the CryoSat deviations. The RMSE was 2.54 m and standard deviation 1.71 m (Table 7.17).

![Figure 7.20](image)

**Figure 7.20** Comparison of CryoSat-2 (spatial resolution 300 m) and ICESat elevation on the Okavango Delta. a) CryoSat vs. ICESat elevation, b) elevation difference: CryoSat – ICESat. CryoSat mean elevation error is $-1.88$ m, and RMSE is 2.543 m (as estimated by GPS-calibrated ICESat laser measurements). Note, ICESat data was bias corrected to GPS elevation, with MED 0.189 m as offset.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>ICESat</th>
<th>CryoSat</th>
<th>Elevation difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation</td>
<td>921.689</td>
<td>918.643</td>
<td>-18.588</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>1024.922</td>
<td>1018.519</td>
<td>18.638</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>955.509</td>
<td>953.628</td>
<td>-1.881</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>17.094</td>
<td>17.046</td>
<td>1.711</td>
</tr>
<tr>
<td>RMSE (CryoSat)</td>
<td></td>
<td></td>
<td>2.543</td>
</tr>
</tbody>
</table>

*GPS-calibrated ICESat sample = 10359 points. CryoSat median elevation error = $-1.529$ m.

Table 7.17 Comparison of ICESat elevation and corresponding measurements from CryoSat (300 m cell) (m) on the delta.

Figure 7.21 presents error characteristics of ICESat-calibrated CryoSat-2 elevation on the Okavango Delta, after removal of extreme values. This removed the systematic negative bias in the CryoSat elevation. A high correlation exists between ICESat and ICESat-calibrated
CryoSat elevation with 10359 samples ($R^2 = 0.99$) (Figure 7.21a). Figure 7.21b shows the difference in elevation between two datasets with a MED of 0.0 m and the range of errors between -16.7 m and 20.5 m in the calibrated-Cryosat data compared to ICESat (Table 7.18). The RMSE and standard deviation resulted in 1.71 m (Table 7.18).

**Table 7.18** Comparison of ICESat elevation and corresponding measurements (m) from ICESat-calibrated CryoSat (300 m cell) on the delta.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>ICESat</th>
<th>CryoSat calibrated</th>
<th>Elevation difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation</td>
<td>921.689</td>
<td>920.524</td>
<td>-16.707</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>1024.922</td>
<td>1020.400</td>
<td>20.519</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>955.509</td>
<td>955.509</td>
<td>0.000</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>17.094</td>
<td>17.046</td>
<td>1.711</td>
</tr>
<tr>
<td>RMSE (CryoSat)</td>
<td></td>
<td></td>
<td>1.711</td>
</tr>
</tbody>
</table>

*GPS-calibrated ICESat sample = 10359 points. Calibrated-Cryosat median elevation error = 0.352 m.

**Results and Discussion**

Figure 7.22 presents the integrated IceCryo Elevation Model (ICEM) constructed by interpolation of bias corrected ICESat and CryoSat observations (185778 shots) using kriging. The ICEM covers ~59125 km² area, with elevation ranges from 919.57 m to 1040.77 m with a mean elevation of 958.96 m and standard deviation 20 m.

Figure 7.23 presents the integrated ICEM with 5 m interval contours. Integrated ICEM contains outliers because of profile-wise laser/radar elevation shots (Figure 7.23a). The model was filtered in the frequency domain to reduce extreme values, and thereby enhancing the visual representation of the topography (Figure 7.23b). To visualise detailed topographic structure, 2.5 m interval contours were derived from the filtered ICEM model (Figure 7.24).
Figure 7.22 Integrated IceCryo elevation model (ICEM), constructed from ICESat and CryoSat observations by kriging interpolation (90 m spatial resolution). The model covers ~59125 km² (2563 x 2848 pixel). The ratio of predictors and predicted grids is ~1:39 (i.e. total ICESat and CryoSat observations : total grids produced in the ICEM model by interpolation).

Figure 7.23 a) Integrated ICEM with contours (5 m interval), b) filtered integrated ICEM with contours (5 m interval). Contours reveal the outliers in the model because of profile-wise laser/radar elevation shots, and not well-distributed points. The model was filtered in the frequency domain to reduce extreme values.
Contour plots (with elevation values) show clear delineation of the panhandle (north-west) and other landscape features in the delta. The finding demonstrated the value of merging dual-altimetry (laser and radar) observations to construct mesotopographic models. Note, CryoSat data (product used by this author) can only be used in combination with other elevation data (e.g., ICESat) to make them useful by removing extreme values and correcting bias with higher accuracy elevation data. CryoSat both overestimates and underestimates some elevation points, particularly off-track observations that contain extreme values.

**Figure 7.24** Filtered integrated ICEM with contours (2.5 m interval). The model clearly delineated topographic features, as revealed by contour patterns and shapes.

### 7.3.5 Profiling Laser, Profiling Radar and GPS Data

**Merged Data 4 (Figure 7.1):** This section combines CryoSat-2 and ICESat altimetry observations with the GPS measurements over the Okavango Delta region. The main purpose is to further improve the integrated elevation model produced as described in the preceding section (Section 7.3.4) by combining profiling radar and laser observations (after the bias correction based on GPS elevation) and GPS postings. Bias calibration incorporates GPS information into the CryoSat and ICESat elevation to correct their vertical offsets.
Data
The following datasets were used to construct an integrated elevation model: ICESat (133526 shots), CryoSat (52252 shots), GPS (1051 postings), and GPS-calibrated SRTM (114 points) (Figure 7.25). Independent 60 GPS GCPs were used for evaluation of the model. Few SRTM elevation points (green dots) were used, after bias-calibration with GPS elevation, to fill the gaps in the GPS postings dataset.

Figure 7.25 Multiplatform elevation observations on the Okavango Delta. ICESat laser (blue, 133526 shots) from 2003-2009, CryoSat-2 radar (red, 52252 shots) from February 2012 to January 2013, GPS (black, 1051 postings), and GPS-calibrated SRTM (green, 114 points). Total observation = 186,898 points.

Evaluation of Datasets
The vertical error characteristics of ICESat data is described in Chapter 6 (Section 6.2.2), while the error characteristics of CryoSat data is described in the preceding section (Section 7.3.4). Figure 7.26 presents the vertical error characteristics ICESat, CryoSat and SRTM elevation data and their relation to GPS height (which represent actual topography). The mean elevation of CryoSat radar altimetry observations is lower than the ICESat laser height by about 2 m, and -1.9 m lower than the GPS height. ICESat mean elevation is -0.2 m higher than the GPS terrain height. The SRTM mean elevation is higher than both GPS and ICESat elevation, 0.70 m from the ICESat elevation and -1 m from the GPS elevation.
Figure 7.26 Spaceborne laser and radar mean elevation difference, relative to actual terrain (GPS height) over the Okavango Delta region. CryoSat radar altimetry mean elevation is about 2 m lower than the ICESat laser altimetry elevation (estimated by 10359 ICESat observations), while ICESat mean elevation is ~0.2 m higher than the GPS height (estimated by 54 GPS measurements). The SRTM mean elevation is higher than both GPS and ICESat elevation; 0.70 m from the ICESat elevation, as estimated by 133526 laser observations.

Merging Approach

To further improve the integrated elevation model constructed from ICESat and CryoSat observations in the preceding section, GPS postings over the delta and some GPS-calibrated SRTM elevation points were incorporated. A bias calibration and integration approach was developed (Figure 7.27). First, all datasets were georeferenced to Clarke 1880 ellipsoid and Cape datum (with orthometric height). Then, outliers in the ICESat laser data were removed using criteria mentioned in Chapter 6 (Section 6.2.2). Outliers in the CryoSat data were corrected using the criteria as mentioned in Section 7.3.4. Removal of extreme CryoSat elevation (off-track) points was further aided by visual inspection of the interpolated combined model.

The ICESat laser points were converted to 200 m grid (along-track), and their corresponding elevations at the location of GPS points were extracted over the delta. Point to grid conversion was required to find corresponding GPS points, as GPS points were measured independently of laser shots. These corresponding GPS and laser points were compared to estimate the offset in the laser data (mean vertical error), and this offset was used for bias correction. The offset in the ICESat laser data is 0.19 m compared to GPS heights (estimated using 54 GPS points, see Chapter 6). The CryoSat points were converted to 300 m grid (along-track, same as original footprints), and their corresponding elevation at the GPS-calibrated ICESat elevation points were extracted over the delta. These ICESat and CryoSat points were compared to estimate the offset in the CryoSat data (mean vertical error), and this offset was used for bias correction. The corrected ICESat and CryoSat data, GPS postings, and GPS-calibrated SRTM points were combined. This combined dataset was interpolated by kriging to construct an improved integrated elevation model (comparable to SRTM spatial resolution) of the Okavango Delta region. Finally, this integrated model was evaluated by independent GPS measurements.
Integrating Multiplatform Elevation Observations

Figure 7.27 Approach for merging spaceborne profiling laser, profiling radar and GPS elevation data for constructing an integrated elevation model of the Okavango Delta. GPS measurements were used to calibrate ICESat laser data, and GPS-calibrated laser data were used to calibrate CryoSat radar data. Independent GPS check points were used to validate the integrated elevation model.

Results and Discussion

Figure 7.28 presents the integrated ICG elevation model (90 m spatial resolution), constructed from ICESat, CryoSat, and GPS observations by kriging. Integrated ICG model elevation ranges from 919.57 m to 1042.51 m with a mean elevation of 958.98 m and standard deviation of 19.98 m. Figure 7.29 presents the integrated ICG model with 5 m interval contours. Integrated ICG contains outliers because of profile-wise laser/radar elevation shots (Figure 7.29a). The model was filtered in the frequency domain to reduce extreme values, and thereby enhancing the visual representation of the model (Figure 7.29b).
Figure 7.28 Integrated ICG elevation model of the Okavango Delta (90 m spatial resolution). The model was constructed by kriging interpolation, from combined spaceborne profiling laser and radar, and GPS observations. The ratio of predictor and predicted grids is 1:39 (i.e. total ICESat, CryoSat, GPS and GPS-calibrated SRTM observations : total grids produced in the integrated ICG model by interpolation).

Figure 7.29 a) Integrated ICG elevation model with contours (5 m interval), b) filtered integrated ICG model with contours (5 m interval). Outliers in the model, as revealed by contours, were filtered in the frequency domain.
Figure 7.30 presents the filtered ICG model with 2.5 m interval contours, which shows the detailed topographic structure. Contour (with elevation values) patterns and shapes clearly depicts diverse landscape topographic features such as the panhandle (north-west) (Figure 7.30b), Lake Ngami (Figure 7.30c), and other features of the delta region. This result demonstrated the value of merging spaceborne dual-altimetry (laser and radar) and GPS measurements to construct improved quality mesotopographic model.
For further clarity on the landscape topographic structure of the Okavango Delta region, contours were derived at 2.5 m and 1 m intervals (Figures 7.31 and 7.32, respectively) from the filtered integrated ICG model. Contour structures of the model (with elevation values) visually improved understanding of the delta topography and its complex landscape features. Many smaller elevated grounds, especially islands in the wetland are delineated.

Figure 7.31 Contours of the filtered integrated ICG model (2.5 m interval). These contours delineated diverse landscape topographic features of the delta.
Figure 7.32 Contours of the filtered integrated ICG model (1 m interval). Contours delineated detailed landscape topographic structure of the delta.
7.4 Evaluation of Integrated Elevation Data and Models

This section evaluates fused and merged elevation datasets, constructed in previous sections. Fused elevation models are compared to each other to understand the implications of fusion method and selecting datasets for fusion. The vertical accuracy of merged elevation datasets are assessed by comparing with GPS elevation, at various spatial levels.

7.4.1 Comparison of Fused Models

Here, the fused models constructed by two methods in the frequency domain by combining: 1) imaging and profiling radar, and 2) imaging radar and GPS-based datasets are compared.

Table 7.19 shows that both fused models had a produced moderate vertical accuracy, i.e. 2 m to 5 m, as defined in Chapter 2 (Table 2.3). The fused SRTM&AGS (imaging and profiling radar) model produced better landscape topographic structure, although RMS errors are higher compared to fused SRTM&MDEM (imaging radar and GPS) model. Landscape topographic structure is defined based on pattern and shape of topographic features (Chapter 2, Table 2.3).

Table 7.19 Comparison of statistical and visual characteristics of fusion.

<table>
<thead>
<tr>
<th>Fusion method</th>
<th>RMSEz (m)</th>
<th>Topographic structure*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fused SRTMF &amp; AGS</td>
<td>Fused SRTMF &amp; MDEM</td>
</tr>
<tr>
<td>Method 1</td>
<td>4.894</td>
<td>3.8</td>
</tr>
<tr>
<td>Method 2</td>
<td>4.243</td>
<td>2.712</td>
</tr>
</tbody>
</table>

*Based on visual assessment of topographic features in the elevation model (see Table 2.3, Chapter 2).

Figure 7.33 compares the fused elevation models constructed with different methods and datasets. Method 1 (fusion of datasets in the frequency domain) produced better topographic structure (Figures 7.33a & c) than the method 2 (fusion of datasets in the frequency domain, based on MSE weight) (Figures 7.33b & d).
Figure 7.33 Comparison of fused elevation models. a&b) Fused imaging and profiling radar with method 1 (fusion of datasets in the frequency domain) and 2 (fusion of datasets in the frequency domain, based on MSE weight), c&d) Fused imaging radar and MDEM with method 1 and 2. The first approach represents better topographic structure in the fused model than the second approach (compared to photogrammetric DEM, Figure 7.2a).
7.4.2 Assessment of Merged Datasets

In this section, we assess the vertical accuracy of merged elevation datasets against higher accuracy GPS reference data. The merged datasets are 1) ICESat-calibrated SRTM model, 2) ICESat-calibrated ASTER model, 3) GPS-calibrated ICESat and CryoSat integrated model, and 4) GPS-calibrated ICESat and CryoSat and GPS integrated model. Table 7.20 presents the merged datasets, constructed by combining disparate but complementary datasets at various spatial scales over the Okavango Delta region.

Table 7.20 Merged elevation datasets and reference data for validation at various spatial levels.

<table>
<thead>
<tr>
<th>Merged dataset</th>
<th>Spatial level</th>
<th>Reference data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imaging radar &amp; profiling laser (SRTM &amp; ICESat)</td>
<td>Delta, wetland, land cover type</td>
<td>GPS GCP</td>
</tr>
<tr>
<td>Optical stereo imaging &amp; profiling laser (ASTER &amp; ICESat)</td>
<td>Delta</td>
<td>GPS GCP</td>
</tr>
<tr>
<td>Profiling radar &amp; laser (CryoSat &amp; ICESat)</td>
<td>Delta</td>
<td>GPS GCP</td>
</tr>
<tr>
<td>Profiling laser &amp; radar and GPS (ICESat &amp; CryoSat and GPS)</td>
<td>Delta</td>
<td>GPS GCP</td>
</tr>
</tbody>
</table>

Calibrated Models

Comparison of SRTM and ASTER Models

Bias correction of SRTM and ASTER elevation models with ICESat on the Okavango Delta has marginally improved their overall vertical accuracy (RMSE), from 1.71 m to 1.7 m for SRTM and from 4.52 m to 4.4 m for ASTER (Table 7.21). The vertical accuracy of ASTER data is much lower than the SRTM, so it was discarded for further analysis.

Table 7.21 Comparison of SRTM and ASTER elevation models (original and ICESat-calibrated) on the Okavango Delta, as estimated by GPS measurements (1000 posting).

<table>
<thead>
<tr>
<th>Elevation model</th>
<th>Errors in elevation models (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ME</td>
</tr>
<tr>
<td>SRTMz</td>
<td>0.381</td>
</tr>
<tr>
<td>SRTMCz*</td>
<td>-0.322</td>
</tr>
<tr>
<td>ASTERz</td>
<td>1.103</td>
</tr>
<tr>
<td>ASTERCz**</td>
<td>-0.412</td>
</tr>
</tbody>
</table>

*Bias calibrated using ICESat observations (133526 shots), with elevation offset 0.703 m; **bias calibrated using ICESat observations (133502 shots), with elevation offset 1.515 m.

Imaging Radar and Profiling Laser Data

Wetland Level: Incorporation of ICESat measurements to calibrate bias in the SRTM model of the Okavango wetland has significantly reduced its MED (from 0.54 m to −0.15 m). But
the calibrated model (SRTMC) only marginally improved the vertical accuracy (RMSE), from 1.79 m to 1.71 m (Table 7.22).

**Table 7.22** Comparison of SRTM original and ICESat-calibrated SRTM models on the Okavango wetland, as estimated by GPS measurements (247 posting).

<table>
<thead>
<tr>
<th>Elevation model</th>
<th>Errors in elevation models (m)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean error</td>
<td>Median error</td>
<td>Standard dev.</td>
<td>RMSE</td>
</tr>
<tr>
<td>SRTMz</td>
<td>0.540</td>
<td>0.401</td>
<td>1.712</td>
<td>1.791</td>
</tr>
<tr>
<td>SRTMCz*</td>
<td>-0.148</td>
<td>0.249</td>
<td>1.707</td>
<td>1.710</td>
</tr>
</tbody>
</table>

*Calibrated using ICESat observations (24219 shots), with elevation offset 0.672 m.

**Land Cover:** Incorporation of ICESat measurements to bias correct the SRTM model of the wetland has marginally improved the vertical accuracy over the open water and swamps, from 1.44 m to 1.35 m (open water) and from 1.82 m to 1.65 m (swamp) (see Table 7.15). Over the land-vegetation and bare soil areas, the improvement by bias correction was negligible. In general, land cover did not influence much the SRTM elevation data of this region.

**Integrated Models**

Here, we assessed the vertical errors of the integrated IceCryo and ICG models. Figure 7.34 shows the distribution of GPS control points on the integrated IceCryo elevation model of the Okavango Delta.

**Figure 7.34** Distribution of GPS GCPs (red dots) on the Okavango Delta integrated IceCryo elevation model. GPS points inside black circles are ETHZ surveyed GCPs, other points are from Geological Survey of Botswana. These points were used to assess the vertical accuracy of merged elevation models.
Table 7.23 presents the vertical errors in the integrated IceCryo model, evaluated against GPS measurements. The error ranges between -2 m and 3.54 m, with a mean error of 1.18 m and standard deviation of 1.26 m. The vertical accuracy (RMSE) of integrated ICG model is 1.72 m, as estimated with 60 GPS control points.

**Table 7.23** Comparison of GPS and corresponding elevation (m) from integrated IceCryo elevation model on the delta.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>GPS</th>
<th>IceCryo</th>
<th>Elevation difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation</td>
<td>933.867</td>
<td>936.805</td>
<td>-2.013</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>986.312</td>
<td>984.299</td>
<td>3.537</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>955.934</td>
<td>957.118</td>
<td>1.184</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>14.256</td>
<td>14.078</td>
<td>1.264</td>
</tr>
<tr>
<td>RMSE (CryoSat)</td>
<td></td>
<td></td>
<td>1.724</td>
</tr>
</tbody>
</table>

*GPS sample = 60 points. Calibrated-IceCryo median elevation error = 1.180 m.

Figure 7.35 shows high correlation between GPS and IceCryo model elevation ($R^2 = 0.99$). The difference in elevation between the two datasets shows a positive bias in the integrated IceCryo model, which is due to the inherent bias in ICESat and CryoSat data compared to GPS elevation (Figure 7.26). Bias correction of ICESat to GPS elevation, and subsequent bias correction of CryoSat with bias-corrected ICESat elevation did not eliminate positive biases completely.

**Figure 7.35** Comparison of integrated IceCryo model and GPS elevation on the delta. a) IceCryo vs. GPS elevation relationship, with high positive correlation, b) elevation difference: IceCryo - GPS elevation.

Table 7.24 presents the vertical errors in the integrated ICG model, compared to GPS elevation. The error ranges between -2 m and 3 m, with a mean error of ~1 m and standard
deviation of 1.15 m. The vertical accuracy of the integrated ICG model is 1.53 m, as estimated by 60 GPS control points.

Table 7.24 Comparison of GPS elevation and corresponding measurements (m) from integrated ICG elevation model on the delta.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>GPSz</th>
<th>Integrated ICGz</th>
<th>Elevation difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation</td>
<td>933.867</td>
<td>933.904</td>
<td>-2.013</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>986.312</td>
<td>984.299</td>
<td>3.037</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>955.934</td>
<td>956.948</td>
<td>1.014</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>14.256</td>
<td>14.152</td>
<td>1.152</td>
</tr>
<tr>
<td>RMSE (IntCG)</td>
<td></td>
<td></td>
<td>1.527</td>
</tr>
</tbody>
</table>

*GPS sample = 60 points. Integrated ICG median elevation error = 0.965 m.

Figure 7.36 shows high correlation between GPS and ICG model elevation ($R^2 = 0.99$). The difference in elevation between the two datasets shows a positive bias in the integrated ICG model, although less than the integrated IceCryo model. This is due to the inherent bias in ICESat and CryoSat data compared to GPS elevation. Bias correction of ICESat and CryoSat data with GPS elevation did not totally eliminate positive biases in the datasets.

![Figure 7.36 Comparison of integrated ICG model and GPS elevation on the delta, a) ICG vs. GPS elevation relationship, with high positive correlation, b) elevation difference: ICG - GPS elevation.](image)

Global Evaluation of Mesotopographic Models

Table 7.25 presents the topographic characteristics of the merged mesotopographic models of the Okavango Delta region. The mean elevation deviation of merged imaging radar and profiling laser (IR&PL) and merged optical stereo imaging and profiling laser (OSI&PL) models was ~1 m higher than the integrated IceCryo (PL&R) and integrated ICG (PL&R and PS) models. This is because of few high elevation points of the Tsodilo Hills in the IR and
OSI models and inherent positive bias in these elevation datasets (compared to GPS and ICESat heights).

Table 7.25 Characteristics of merged mesotopographic models of the Okavango Delta.

<table>
<thead>
<tr>
<th>Descriptor</th>
<th>IR &amp; PL</th>
<th>OSI &amp; PL</th>
<th>PL &amp; R</th>
<th>PL&amp;R and PS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation</td>
<td>917.297</td>
<td>899.485</td>
<td>919.573</td>
<td>919.573</td>
</tr>
<tr>
<td>Maximum elevation</td>
<td>1340.297</td>
<td>1346.485</td>
<td>1040.765</td>
<td>1042.513</td>
</tr>
<tr>
<td>Mean elevation</td>
<td>960.085</td>
<td>960.274</td>
<td>958.957</td>
<td>958.982</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>20.004</td>
<td>20.334</td>
<td>20.003</td>
<td>19.976</td>
</tr>
</tbody>
</table>

*Merged IR&PL and OSI&PL models comprise few high elevation points of the Tsodillo Hills (north-western part of the study area), while integrated IceCryo (PL&R), and integrated ICG (PL&R and PS) models do not have laser and radar altimetry observations and GPS measurements over the Tsodillo Hills.

Figure 7.37 shows the elevation characteristics of IR and OSI, and four merged elevation models. The IR, OSI, merged IR&PL, and merged OSI&PL models have high elevation deviations (minimum and maximum) because of Tsodillo Hills (with few high elevation points). Integrated IceCryo and ICG models have low elevation deviation.

Figure 7.37 Elevation characteristics of merged mesotopographic models. The high maximum in the first four models is due to the Tsodillo Hills in the north-west part of the study area. The profiling laser (ICESat) and radar (CryoSat), and GPS do not include measurements over this small hill.
Evaluation by GPS Controls

The merged mesotopographic models were evaluated against 60 GPS control points, distributed across the delta. Table 7.26 presents the vertical error statistics of merged mesotopographic models, constructed from diverse spaceborne observations.

Table 7.26 Error statistics (m) of the multiplatform technology-based merged elevation models.

<table>
<thead>
<tr>
<th>Elevation model\textsuperscript{1}</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Median</th>
<th>Standard deviation</th>
<th>RMSEz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Merged OSI &amp; PL</td>
<td>-11.689</td>
<td>12.869</td>
<td>0.509</td>
<td>0.567</td>
<td>4.451</td>
<td>4.443</td>
</tr>
<tr>
<td>Integrated PL &amp; R</td>
<td>-2.013</td>
<td>3.537</td>
<td>1.184</td>
<td>1.180</td>
<td>1.264</td>
<td>1.724</td>
</tr>
<tr>
<td>Integrated PL&amp;R and PS</td>
<td>-2.013</td>
<td>3.037</td>
<td>1.014</td>
<td>0.965</td>
<td>1.152</td>
<td>1.527</td>
</tr>
</tbody>
</table>

\textsuperscript{1}Models were evaluated by 60 GPS GCPs, distributed across all landscapes in the delta. [IR = imaging radar, PL = profiling laser, OSI = optical stereo imaging, PL&R = profiling laser and radar, PS = positioning system]. All models are at 90 m spatial resolution, except OSI (30 m).

Figure 7.38 shows the vertical error characteristics of merged mesotopographic elevation models of the Okavango Delta. The ICESat-calibrated ASTER model (merged OSI&PL) has the largest range of vertical errors (~ ±12 m), followed by ICESat-calibrated SRTM model (merged IR&PL, ~ -9 m to 5 m), while integrated IceCryo and ICG models have the lowest range of vertical errors (~ -2 m to 3 m). The vertical error budgets of merged elevation models (Figure 7.39) shows that integrated IceCryo and ICG models provided the highest vertical accuracy (1.72 m and 1.53 m, respectively), while merged OSI&PL the lowest (4.44 m) (Table 7.26).
Figure 7.38 Vertical error characteristics of multiplatform technology-based merged elevation models of the Okavango Delta.

Figure 7.39 Vertical error budgets of multiplatform technology-based merged elevation models of the Okavango Delta.

Figure 7.40 presents the integrated mesotopographic models of the Okavango Delta (90 m spatial resolution). The smoothed GPS-based elevation model is used as a basis to evaluate other models, as this model has provided a realistic topographic structure in terms of pattern and shape. The laser/radar profile-wise errors in the integrated IceCryo elevation model (red ellipse, Figure 7.40b) was significantly reduced by adding GPS elevation postings in the IceCryo dataset (Figure 7.40c). The integrated ICG model was created by kriging combining
GPS-calibrated ICESat and CryoSat, and GPS measurements (Figure 7.25). Integrated models provided a detailed topographic structure of the delta.

Figure 7.40 Integrated mesotopographic models of the Okavango Delta (90 m spatial resolution). a) GPS-based model, b) integrated IceCryo elevation model with strips, because of laser and radar track-wise data, c) integrated ICG model, and d) filtered integrated ICG model. GPS-based model provides a smoothed elevation surface, while integrated IceCryo and ICG models provide improved topographic structure. GPS-based model is used here to compare the other two models.

Figure 7.41 presents the contours of the Okavango Delta topography (5 m interval), derived from mesotopographic models (90 m spatial resolution). The GPS-based model
provides the general structure of the topography (pattern and shape), while integrated IceCryo and ICG models provided detailed topographic structure. The integrated IceCryo and ICG models were filtered to remove laser/radar profile-wise smaller outliers.

Figure 7.41 Contours of the Okavango Delta topography, derived from mesotopographic models (90 m spatial resolution, 5 m contour interval). a) GPS-based model, b) integrated IceCryo elevation model, c) filtered integrated IceCryo model, and d) filtered integrated ICG model. GPS-based model provides the geometry of the delta topography, and the reference for the other datasets. Integrated models were filtered in the frequency domain to remove profile-wise smaller outliers.

Figure 7.42 presents the detailed geometric structure of the Okavango Delta topography (2.5 m contour interval), derived from mesotopographic models (90 m spatial resolution).
These four models provide the improved representation of the Okavango Delta region in terms of accurate topographic structure and high vertical accuracy. The GPS-based model provides a clear topographic structure because of well-distributed samples across the study area. Finer contour level (2.5 m) revealed the profile-wise smaller outliers in the integrated IceCryo elevation model, which were removed by filtering in the frequency domain (Figure 7.23b). Integrated ICG model (Figure 7.28) was also filtered (in the frequency domain) to remove smaller profile-wise outliers, although fewer outliers than in the integrated IceCryo model. Among the four merged models and the GPS-based model, integrated IceCryo and

**Figure 7.42** Contours of the Okavango Delta topography, derived from mesotopographic models (90 m spatial resolution, 2.5 m contour interval), a) GPS-based model, b) integrated IceCryo elevation model, c) filtered integrated IceCryo model, and d) filtered integrated ICG model.
ICG models provide the most improved representation of topography in terms of topographic structure and vertical accuracy.

7.5 Conclusion

Diverse platforms provide disparate datasets (in resolution and accuracy), but have complementary information which can be combined to produce vertically accurate data products and thus an improved representation of topographic structure. Therefore, we integrated air, space and ground-based observations.

Data integration was done by fusion in the frequency domain (test site) and merging by bias calibration and data integration (delta region). The frequency domain fusion of 1) profiling and imaging radar (AGS and SRTM: FU1) and 2) imaging radar and GPS-based (SRTM and MDEM: FU2) data improved the vertical accuracy in the SRTM data (from 5.5 m to 4.2 m [FU1] and from 5.5 m to 2.7 m [FU2], compared to high resolution airborne photogrammetric DEM). Data merging was done by two strategies: 1) merging elevation data by bias correction (i.e. incorporation of higher accuracy information), and 2) merging bias corrected data to produce elevation models through interpolation. Merging imaging radar and profiling laser (SRTM and ICESat) by the first strategy, i.e. incorporating higher accuracy ICESat information (from large samples) into lower accuracy SRTM data through bias calibration, marginally improved the delta SRTM model (from 1.71 m to 1.7 m, compared to GPS measurements [large samples]). With a similar approach, merging optical stereo imaging and profiling laser (ASTER and ICESat) marginally improved the delta ASTER model (from 4.5 m to 4.4 m, compared to GPS measurements [large samples]). In both cases, bias in ICESat data were first calibrated to GPS elevation. Physiographic region and land cover dependent bias calibration of SRTM data revealed minimal influence of physiography and land cover on vertical errors over this region.

An integrated 'IceCryo' elevation model, constructed by interpolating merged profiling laser and radar (GPS-based bias calibrated ICESat and CryoSat) data (second strategy), produced an improved model of the Okavango Delta (1.7 m accuracy, compared to 60 GPS GCPs). This model was further improved by adding sparse GPS data (to GPS-based bias calibrated ICESat and CryoSat) to produce the integrated 'ICG' model (1.5 m accuracy, compared to 60 GPS GCPs). Evaluation of the two models from the first strategy (merged SRTM and ICESat, and merged ASTER and ICESat) using same 60 GPS GCPs produced 2.7 m and 4.4 m accuracy, respectively. These results shown that integrated models (IceCryo and ICG) provided much higher accuracy than the models improved by bias calibration only (using the first strategy). For integrated modeling, ICESat provides most observations along profiles, but with a wide across-track spacing, while CryoSat provides fewer but closer across-track observations over the delta (see Figure 7.25). GPS provide sparse but well-distributed samples. Thus, they complement to have larger elevation measurements over the delta. ICESat provides stable measurements (mean elevation -0.2 m higher than the GPS), but CryoSat data have extreme values and a negative bias (1.88 m lower than the GPS, see Figure 7.26). Note, CryoSat data (product used in this study) can only be used along with complimentary measurements (e.g. ICESat).

Both frequency domain fusion and data merging proved to be powerful approaches for integration of multiplatform elevation data. We established that integration of multiplatform elevation observations significantly increase accuracy and reliability of topographic models. This study contributed to the advancement of multiplatform-based data integration technology with novel approaches, and further advancement of the landscape topographic modeling.
PART III.

Conclusions
Chapter 8

Summary and Conclusions

I have had my results for a long time; but I do not yet know how I am to arrive at them.

– Carl Friedrich Gauss (1777–1855)

This chapter highlights the main contributions of the thesis in measuring and modeling landscape topography from diverse platform observations. Science questions are recalled, maps the error budgets of data products, and the research implications for topographic modeling and improved understanding of the Okavango Delta topography are presented. The chapter is concluded with recommendations for future research.

**Keywords:** Multiplatform; remote observation; remote measurement; landscape topography; wetland; elevation modeling; microtopography; mesotopography; water surface topography; land cover; accuracy assessment; data integration; error budget; research implication; recommendation.

### 8.1 Science Contributions

Remote observation and measurement technology has revolutionized the mapping of the earth surface and other planetary bodies with observations by a suite of instruments on diverse platforms (aerial, spaceborne, and ground-based). A multiplatform observation approach offers an effective way to construct topographic models where we face challenges from inconsistent data and coverage, resolution, and accuracy. This thesis addressed the general science issue formulated in Chapter 1: measuring and constructing variable resolution topographic models of wetlands from observations acquired by devices on board diverse platforms, and integrating these multisource elevation observations to produce improved elevation models. The science goal was to develop novel approaches and methods to measure wetland landscape topography. The study provided a comprehensive approach to measure and model topography of wetland environments from diverse platform observations. The study documented the advantages of a multiplatform approach to measure and model landscape topography in general, and Okavango Delta wetland topography in particular. The results are variable resolution and accuracy elevation models over the delta from diverse platform observations. This chapter first provides overall conclusion on the requirements of multiplatform observations, and a multiplatform approach to wetland topographic modeling. Then, it addresses the science questions, followed by research implications and directions for future research. The major findings, about the problem statement and science questions (Chapter 1), are presented in the following sections.
8.1.1 Wetland Topography from Multiplatform Observations

Wetlands, especially in semi-arid desert environments, provide important hydro-environmental services and require conservation of their fragile ecosystem. In modeling wetland hydrological and environmental processes, topographic information is crucial. The Okavango Delta, a remote inland wetland in the Kalahari basin (Africa), lacks accurate and reliable topographic information, particularly DEMs. This deficiency has limited the progress in modeling the Okavango hydro-environmental processes (Bauer, 2004). Despite technological advancements, in many parts of the earth measurements of landscape topography and processes are limited by inconsistent data, coverage, resolution and accuracy. To overcome these limitations, this study used observations from diverse platforms to construct topographic models of the Okavango Delta and to evaluate their quality and availability. A multiplatform observation approach was adopted to complement disparate elevation observations over the delta.

This study described the landscape characteristics of the delta, highlighted the data acquisition techniques from diverse platforms, explored the availability of data, outlined the requirements of terrain elevation and land cover, and finally described the available technologies to measure elevation over a course of spatial scales. The study was oriented to measure and model Okavango wetland and its environs landscape topography.

8.1.2 Multiplatform Approach

The approach developed in this study provided step-by-step procedures, and implemented them over contrasting Kalahari landscapes (Okavango wetland, and surrounding land-vegetation and sand dunes) (Chapters 4-7). A multiplatform approach was required (as single platform-based observations were inadequate) to measure and construct variable spatial resolution and vertically accurate elevation models of the entire Okavango Delta (see Chapter 3, Section 3.2). To realize this, the study used observations from a suite of instruments on aerial, space and ground-based platforms.

This approach was implemented through the following stages:
1) Measuring and modeling micro- and mesotopography (Chapter 4)
2) Mapping land cover as a determinant of elevation data accuracy and bias calibration (Chapter 5)
3) Establishing reference elevation datasets (Chapter 6)
4) Assessing elevation data accuracy (Chapter 6 & 7)
5) Integrating elevation data to improve quality of topographic modeling (Chapter 7)
6) Mapping error budgets of elevation (Chapter 8).

The approach addressed the general science statement/question of the thesis formulated in the Chapter I: how can we measure and construct variable resolution topographic models of wetlands from observations acquired by devices on board diverse platforms, and integrate these multisource elevation observations to produce vertically improved models?

8.1.3 Measuring and Modeling Landscape Topography

Landscape topography is a representation of the earth surface by elevation models, with land cover as a determinant of elevation data accuracy and bias calibration. DEMs provide the fundamental datasets from which several topographic parameters (e.g. elevation, slope and aspect) can be derived.
Here we address the science question 1: What is the advantage of a multiplatform observation approach to measure and construct landscape topographic models of a wetland environment?

This study has measured and modeled 1) microtopography from aerial and spaceborne optical stereo-observations using stereophotogrammetric techniques, 2) regional mesotopography from global positioning system, airborne profiling and spaceborne imaging radar observations, spaceborne optical stereo-observations, and integrated spaceborne imaging radar and profiling laser observations, and 3) water surface topography from spaceborne imaging radar and profiling laser observations. It has mapped wetland land cover from spaceborne optical observations by an unsupervised clustering approach and demonstrated the potential of single-band spectral information content over multi-band information. The multiple technologies used to measure and construct DEMs of the Okavango Delta were complementary. The result is a multiple technology demonstration over a remote area that lacked accurate and reliable topographic data for hydrological and environmental modeling.

Elevation

Microtopography

The optical stereo-observations from an airborne platform and from the IKONOS satellite were the source of detailed micro-topographic models using analytical and digital photogrammetry, respectively. Although models are limited to test sites, they demonstrated the potential in modeling wetland topography at high spatial resolution. DEM derived from airborne stereo-images by analytical photogrammetry produced the most accurate and reliable topographic information. The elevation model derived by digital photogrammetry from IKONOS stereo-images contained erroneous elevation values, which required filtering (in the frequency domain). Both models differed significantly in vertical accuracy: analytical photogrammetric model provided terrain level elevation, while digital photogrammetric model gave the surface height of objects. Although a direct comparison is not possible (due to different locations), both models provided the detailed topographic structure of landscapes.

Mesotopography

The sparse GPS-based elevation measurements produced a coarse resolution topographic model of the delta, but it has provided the most accurate reference for creating regional elevation models of the Okavango Delta as well as to evaluate the quality of models derived by other technologies. The elevation measurements by airborne radar altimetry (AGS) produced a generalized topographic model of the delta. DEM derived from SRTM data produced a homogeneous, consistent, medium spatial resolution topographic model of the whole delta, including water surface elevation. The vertical accuracy of spectral filtered SRTM data was better than 2.5 m, when compared against GPS elevation (~0.15 m). Although ASTER GDEM provided higher spatial resolution elevation data than the SRTM, its vertical accuracy (> 4 m) was much lower than the SRTM data. The main conclusion is that SRTM elevation data provided the best medium spatial resolution DEM for the whole Okavango Delta; however this dataset requires filtering of erroneous elevation values. Spectral analysis and filtering in the frequency domain proved to be a powerful technique in removing erroneous values from SRTM and ASTER elevation datasets.

This study revealed the negative elevation bias in the GPS data measured by the Geological Survey of Botswana using the provisional EGM96 model with WGS84 datum.
The adjustment of this bias requires subtraction of $\sim 0.53$ m as a vertical correction factor, as specified in the final EGM96 model (Lemoine et al., 1998). This discrepancy in the GPS measurements was discovered when these data were compared with the ICESat laser altimetry elevation data (which are referenced to final EGM96 and WGS84 datum).

**Water Surface Topography**

Remote observations of the water surface elevation provided an alternative to ground-based gauging. In this study, we measured the Okavango Delta water surface topography from SRTM data, and estimated the water level changes from ICESat laser observations. A combined radar-optical approach was developed to water surface topographic modeling, using a water surface mask derived from optical observations (Landsat 7 MIR-band), while a laser-optical approach was developed to estimate changes in water level. Both approaches produced promising results, SRTM provided the Okavango Delta water surface topography while ICESat gave water level changes.

**Characterisation of Multi-technology Elevation Data and Models**

Air- and spaceborne optical stereo-photogrammetric models produced detailed microtopographic structure of landscapes. Although a direct comparison of two microtopographic models is not possible because of different locations, both model gave 1 m to 1.5 m vertical accuracy. The general feature of all mesotopographic models (GPS-based, AGS, SRTM and ASTER) is minimum elevation $\sim 920$ m over the delta. The various technologies gave complementary measurements of the minimum elevation. The maximum elevation of SRTM and ASTER models was about 1340 m, while the maximum elevation in interpolated GPS-based and AGS models was $\sim 1040$ m as they contain no measurements over the Tsodillo Hills (highest elevated site in the study area). The slight differences in minimum elevation range and maximum elevation range among the models are due to differences in data acquisition technologies, biophysical aspects (e.g. land/vegetation cover), sand dunes and sand hills. Water surface elevation from SRTM and ICESat produced promising results over the Okavango Delta, while SRTM produced a water surface topographic model, ICESat estimated the changes in water level elevation.

The multiplatform-based diversity of observations provided a powerful tool to construct variable resolution topographic models over this complex wetland landscape. The study reveals the advantage of a multiplatform approach to construct landscape topographic models over wetland environments, especially over a remote region of the world.

**Land cover**

Space-based optical observation provides major dataset for mapping land cover that is consistent, repeatable and reliable. Land cover products are important for various applications in engineering, hydrology, and resource management. It is important information for assessing the quality of DEMs, and correcting elevation bias.

Here we address the science question 2: How significant is single-channel spectral information (e.g. Landsat 7 mid-infrared) content compared to multispectral observations for mapping wetland land cover?

A single-band observation approach, as devised in this study, to classify wetland land cover from multispectral images, proved to be as accurate as multispectral classification. This study assessed the multispectral bands of Landsat 7 and IKONOS using spectral
characteristics of wetland land cover in the Okavango Delta, then an appropriate band was selected. Landsat 7 MIR (band-7) and IKONOS NIR wavelengths provided suitable spectral information for wetland land cover classification and delineation of the nonwetland-wetland boundary, because wetlands have very low reflectance in these regions of the electromagnetic spectrum. IKONOS NIR channel alone provided valuable spectral features of wetland land cover compared to multispectral observations. Landsat 7 MIR channel gave as similar result. For Landsat and IKONOS, multispectral image classification only marginally increased the land cover delineation accuracy over the single-band image classification. The spectral clustering and classification of an appropriate single band image (e.g. NIR or MIR) is an efficient technique to extract land cover information. Mid-infrared observations alone (e.g. Landsat 7 band-6) provide equally useful spectral information compared to multispectral (six bands) observations for mapping wetland land cover. The partitioning of single-band image into wetland land cover classes proved to be a promising approach. These land cover products served as useful determinants of elevation accuracy and elevation bias calibration (Chapters 6 and 7, respectively).

8.1.4 Assessment of Elevation Data and Models

Assessment of accuracy and reliability of digital elevation data/models is a fundamental component of topographic modeling. This study assessed the vertical error budgets of elevation datasets to review alternate topographic data. Further, the assessment helped to select appropriate elevation data to produce integrated improved topographic models. The positional accuracy of datasets had negligible impact on the assessment of vertical accuracy, because the relief variation over larger footprint datasets (e.g. CryoSat with 300 m cell) is in the range of ~0.1 m to ~0.8 m (see Chapter 6, Section 6.3).

This section addresses the science question 3: To what extent does physiography and land cover act as a determinant of vertical errors in elevation data (e.g. SRTM DSM)?

In this study, the assessment was done by: 1) establishing reference data, 2) partitioning the study area into physiographic regions and land cover, and 3) assessing the elevation data/models against the reference data. The study assessed the vertical errors of microtopographic and mesotopographic models and water surface elevation using three sets of reference data (GPS GCPs and postings, ICESat laser altimetry observations, and analytical photogrammetric DEM).

Reference data

GPS measurements formed the main reference data. Two additional reference datasets were established by comparing against GPS measurements: 1) ICESat laser altimetry observations, and 2) airborne analytical stereo-photogrammetric DEM. ICESat data comparison against GPS measurements (~0.15 m accuracy) resulted in RMSE 1.2 m. Photogrammetric DEM had a RMSE of ~1 m compared to GPS. GPS and ICESat measurements provided regional reference data with sparse and large samples, respectively, while photogrammetric DEM provided detailed elevation information at a test site.

Assessments

Microtopographic Models

The vertical accuracy of two elevation datasets was assessed using a point-based approach: 1) airborne optical stereo-based model, and 2) spaceborne optical (IKONOS) stereo-based
model. The analytical photogrammetric DEM provided denser sampling as a continuous elevation surface, which is a reliable reference data for detailed assessment of low accuracy elevation models. We assumed the vertical accuracy of photogrammetric DEM was ~1 m, as the model was generated using analytical photogrammetry with high precision GPS GCPs (0.11 m vertical). IKONOS stereo image-derived digital photogrammetric model resulted in RMSE 1.48 m, compared to GPS measurements.

Mesotopographic Models

The vertical accuracy of four mesotopographic models was assessed: 1) GPS-based, 2) airborne profiling radar (AGS), 3) spaceborne imaging radar (SRTM), and 4) spaceborne optical-stereo imaging (ASTER). Two sets of reference data: GPS GCPs/postings and ICESat laser observations were used (Chapter 6). The physiography and land cover-based assessment of AGS and SRTM models established that elevation errors are larger over the water and wetlands than non-water/wetland areas (i.e. dry land, grassland and other vegetated areas, and sand dunes). The GPS-based assessment of all mesotopographic models (Table 8.1) showed that the GPS-based model produced highest vertical accuracy (RMSE), followed by SRTM, airborne profiling radar, while ASTER had the lowest vertical accuracy. Note, the GPS-based model produced the highest vertical accuracy as it was constructed by interpolation of GPS measurements.

Table 8.1 Multitechnology-based mesotopographic models and their error characteristics on the delta.

<table>
<thead>
<tr>
<th>Elevation model</th>
<th>Mean error</th>
<th>Standard deviation</th>
<th>RMSE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS-based</td>
<td>1.044</td>
<td>1.633</td>
<td>1.615</td>
</tr>
<tr>
<td>Profiling radar (AGS)</td>
<td>1.475</td>
<td>2</td>
<td>2.482</td>
</tr>
<tr>
<td>Imaging radar (SRTM)</td>
<td>0.578</td>
<td>2.130</td>
<td>2.210</td>
</tr>
<tr>
<td>Optical stereo imaging (ASTER)</td>
<td>0.945</td>
<td>4.221</td>
<td>4.323</td>
</tr>
</tbody>
</table>

*Models were evaluated against GPS measurements distributed over diverse landscapes in the delta. Positioning system model was assessed by 60 GPS GCPs, profiling radar by 912 GPS postings, imaging radar by 1099 GPS postings, and optical stereo imaging model by 983 GPS postings.

Water Surface Elevation

Water surface topography from SRTM data was assessed against GPS measurements, which resulted in 2.4 m elevation error (RMSE); filtering of SRTM data in the frequency domain lowered the error to about 2 m. This showed that water surface elevation can be measured from SRTM data at an accuracy of about 2 m. The AGS elevation model resulted in about 2.6 m elevation error (RMSE) compared to GPS measurements. The ICESat laser measurements of delta water level resulted in RMSE 0.76 m with a mean deviation of 0.15 m, compared to GPS elevations. ICESat measurements also revealed the changes in water level elevation over the Okavango Delta, from 2003 to 2009. During this period, which covered both flooding and dry seasons, ~1.5 m water level fluctuations occurred. The ICESat recorded the historical flooding (biggest since 1960s) over the delta on 1 April 2009 and estimated the water level rise of 0.8 m over the 2007 flooding season (on 4 April).
8.1.5 Integration of Elevation Observations

To optimize topographic modeling from disparate but complementary observations requires effective integration of multiplatform elevation observations. The goal of integration was to construct improved quality elevation models by fusion and merging of elevation data. Combining heterogeneous elevation data is challenging, however, because of diversity in attributes such as elevation and gradients, and varying accuracy. We devised two approaches for data integration. The first approach applied a Fourier transform in the frequency domain with grid elevation data, followed by filtering and frequency domain fusion. The second approach combined elevation data after physiographic region and land cover-wise elevation bias calibration, and integrated elevation observations to produce DEMs. The fusion was carried out in the frequency domain, while merging was done by bias calibration and data integration.

The next section addresses the science questions 4 & 5:
How far does integration (fusion and merging) of multiplatform elevation data increases accuracy and reliability of elevation models?
To what extent does bias calibration in elevation data (e.g. SRTM and ASTER DSMs) improve vertical accuracy?

The study integrated elevation observations from multiple platforms and sources to construct improved quality topographic models over the Okavango Delta, and thereby enhanced their usability. Data integration was achieved by two approaches: 1) fusion of elevation models, and 2) merging elevation data.

**Fusion of Elevation Data**

The goal of data fusion was to construct improved quality elevation models using data from multiple sources, generated by different technologies at different spatial resolutions and accuracy. A fusion approach in the frequency domain was used to construct models from SRTM, AGS and GPS-based elevation data. The spectral analysis and filtering with this approach were valuable to remove erroneous elevation values from SRTM elevation data. The results confirmed that fused DEMs are superior to individual elevation datasets, as fusion reduces elevation error and improves the topographic structure. Progressive reductions in error occurred in the SRTM data by frequency domain filtering, and fusion with other two elevation datasets (from RMSE 5.5 m to 2.7 m), compared to airborne photogrammetric DEM (~1 m accuracy). The fused SRTM & AGS model has produced better landscape topographic structure, although RMSE was higher (4.2 m) compared to fused SRTM & MDEM model (2.7 m). The fusion of SRTM & MDEM elevation models produced better statistical results than the fused SRTM & AGS model. However, MDEM added less to the spatial structure of the SRTM data than the AGS model does.

The conclusion of elevation data fusion is that with carefully chosen approaches (e.g. spectral filtering and fusion domain frequency), the quality of DEMs can significantly be improved. The fusion proved to be a promising approach in improving wetland topographic models.

**Merging Elevation Data**

The goal of data merging was to construct improved quality elevation models by calibrating elevation bias and merging data from multiple technologies at different spatial resolutions and accuracy. We devised two approaches: 1) calibration of lower accuracy elevation data by
higher accuracy data (using land cover as a determinant), and 2) calibration of lower accuracy elevation data by higher accuracy data, and followed by combining calibrated datasets to construct integrated models. The first approach merged elevation data by bias calibration (incorporating higher accuracy information to the lower accuracy data), and this approach was applied on the SRTM and ASTER data by calibrating to ICESat data. The second approach merged bias calibrated elevation data to produce elevation models. CryoSat data were calibrated with ICESat, and then both ICESat and ICESat-calibrated CryoSat data were calibrated with GPS measurements. These bias-corrected datasets were merged and interpolated to produce DEMs. All data products were validated against independent GPS measurements.

Incorporation of ICESat laser measurements for bias calibration of SRTM and ASTER elevation models over the Okavango Delta has only marginally improved their overall vertical accuracy (from RMSE 1.71 m to 1.7 m for SRTM and from RMSE 4.52 m to 4.4 m for ASTER), when compared against GPS measurements. Wetland-dependent bias calibration of SRTM data to ICESat measurements slightly improved the model (from RMSE 1.8 m to 1.7 m). Similar results achieved with wetland land cover dependent bias calibration of SRTM data to ICESat measurements. Land cover did not influence much on the SRTM data over this region. The second merging approach, however, produced improved quality elevation models, first by combining ICESat and CryoSat data, and then by combining ICESat, CryoSat and GPS data. This approach produced the most structurally correct and accurate mesotopographic DEMs of the Okavango Delta region (RMSE: 1.5 m to 1.7 m), compared to other models (RMSE: 2.7 m to 4.7 m, see Table 8.2). Although GPS-based model produced RMSE 1.6 m (that served as a reference), models from the second merged approach created detailed topographic structure (along with accuracy). Also, this approach for the first time used ICESat and CryoSat data over the Okavango Delta, and thereby demonstrated capabilities of these new technologies in constructing topographic models. In short, this study revealed the potential of multiplatform observation approach in constructing wetland landscape topographic models.

8.1.6 Mapping Error Budgets of Elevation Datasets

Micro and Mesotopography

Error budgets of elevation data products provide the overall quality of datasets. Here we mapped the error budgets in the elevation datasets, measured and constructed over the Okavango Delta. The vertical error of two microtopographic models, derived from air- and spaceborne optical stereophotogrammetry, showed that airborne model with analytical photogrammetry resulted in better topographic structure and accuracy than the spaceborne model with digital photogrammetry. Table 8.2 presents the error characteristics of mesotopographic models, measured and constructed from observations acquired by imaging radar (SRTM), optical stereo imaging (ASTER), profiling laser (ICESat), profiling radar (CryoSat) and positioning system (GPS). ICESat laser-calibrated SRTM and ASTER models gave a marginal improvement of vertical accuracy, compared to original models. The integrated ICESat, CryoSat and GPS (PL & R and PS) model gave the highest vertical accuracy, compared to all other mesotopographic models. This is followed by GPS-based model, while ASTER model had the lowest vertical accuracy.
Table 8.2 Multiplatform technology-based mesotopographic models and their error characteristics as assessed by GPS measurements.

<table>
<thead>
<tr>
<th>Elevation model</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Median</th>
<th>Standard deviation</th>
<th>RMSEz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imaging radar (IR)</td>
<td>-9.028</td>
<td>5.247</td>
<td>1.778</td>
<td>1.887</td>
<td>2.307</td>
<td>2.898</td>
</tr>
<tr>
<td>Merged OSI &amp; PL</td>
<td>-11.689</td>
<td>12.869</td>
<td>0.509</td>
<td>0.567</td>
<td>4.451</td>
<td>4.443</td>
</tr>
<tr>
<td>Positioning system (PS)</td>
<td>-1.731</td>
<td>6.845</td>
<td>1.044</td>
<td>0.604</td>
<td>1.633</td>
<td>1.615</td>
</tr>
<tr>
<td>Integrated PL &amp; R</td>
<td>-2.013</td>
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<td>1.014</td>
<td>0.965</td>
<td>1.152</td>
<td>1.527</td>
</tr>
</tbody>
</table>

Models were evaluated by 60 GPS control points distributed over diverse landscapes in the delta. [IR = imaging radar (SRTM), PL = profiling laser (ICESat), OSI = optical stereo imaging (ASTER), PL&R = profiling laser and radar (CryoSat), PS = positioning system (GPS)]. All models are at 90 m spatial resolution, except OSI (30 m).

Figure 8.1 shows the vertical error characteristics of mesotopographic models over the Okavango Delta. The highest range of elevation error (minimum and maximum) is for the

![Figure 8.1 Minimum, maximum and mean elevation errors of multiplatform technology-based mesotopographic models of the Okavango Delta. Models were evaluated by 60 GPS control points distributed over diverse landscapes. [Merged IR&PL = SRTM+ICESat; merged OSI&PL = ASTER+ICESat; integrated PL&R = ICESat+CryoSat; integrated PL&R and PS = ICESat+CryoSat+GPS].](image-url)
optical stereo image-based (ASTER) elevation model, while the lowest error range are for the integrated PL&R and PL& and PS models. Imaging radar (SRTM) model had a moderate error range, compared to other datasets.

Figure 8.2 shows the error budgets of multiplatform technology-based mesotopographic models of the Okavango Delta. Optical stereo image-based ASTER elevation model had the highest elevation error (RMSE), while GPS-based model and integrated models had the lowest vertical errors. The imaging radar (SRTM) model had a moderate elevation error, compared to other models. The best mesotopographic model based on vertical accuracy, topographic structure and representation is the integrated PL & R and PS (integrated ICESat, CryoSat and GPS) model. This was followed by the integrated PL & R (integrated ICESat and CryoSat) and SRTM models. Although GPS-based model produced high vertical accuracy, it lacks detail topographic structure compared to other models. ASTER model have poor vertical accuracy, although it provided good topographic structure (compared to other models).

![Figure 8.2 Vertical error budgets of multiplatform technology-based mesotopographic models of the Okavango Delta.](image)

**Water Surface Topography**

The water surface elevation from air- and spaceborne radar (AGS and SRTM) and ICESat laser showed two different scenarios. Both radar models produced −2.5 m elevation deviation over the delta water surface compared to GPS measurements, with SRTM being marginally better than the AGS model. However, frequency domain filtered SRTM data reduced the deviation to −2 m and thus produced an improved water surface model of the delta. But, elevation errors are higher over the main Okavango channel because of open water reflectivity of radar signals. These assessments are limited by time difference of datasets (AGS: 1999, SRTM: 2000, and GPS: 1998). However, these datasets showed potentialities for regional scale water level study. ICESat provided the best dataset for measuring water level elevation and water level changes over the Okavango Delta. The high precision laser data for the first
time provided measurements of water level trends over the delta (2003-2009) and seasonal fluctuations of water level.

8.2 Implications

Science

This study has made substantial original contributions to the advancement of a multiplatform approach to landscape topographic modeling. Approaches and methods developed in this study can be applied to other situations, globally and regionally, in particular to wetland landscape topographic modeling. The findings have implications for advancing the topographic modeling of complex wetland environments, and particularly better understanding of the Okavango delta topography. Topographic models of this study provided insight into the Okavango wetland structure and processes. This study improved the positional accuracy of all datasets, by effectively using all available mapping, measurement, and remote sensing technologies. The findings have many implications, among others for improved understanding of the Okavango Delta regions micro- and mesotopographic and biophysical characteristics, providing key inputs to improved modeling of hydrological and environmental processes, monitoring wetland processes and impacts of regional climate change. The multiplatform approach developed here has provided a comprehensive design to measure and model Okavango wetland topography. Further, the similarity in topographic patterns (at varied scales) of this desert mega-alluvial fan may well serve (as a terrestrial analogue) to improve understanding of the planetary fan-shaped features (e.g. Mars landscape features).

Policy

The research findings addressed several specific challenges faced by the Okavango Delta resource management programs. These challenges include conservation of the wetland, managing the hydrological regime, and understanding the wetland topographic structure and processes. The scientific knowledge and discoveries of this study need to be applied for impacting on the Okavango Delta regional development. The findings support the improved understanding of the delta environment and to devise approaches for sustainable management of the world’s largest Ramsar site (a wetland of international importance). These improved understandings aid the implementation of international agreements such as the Okavango River Basin Water Commission (OKACOM) and Ramsar Convention for preservation of the Okavango Delta ecosystem. This study will also aid recognition of the Okavango Delta as a common heritage of mankind and preserve under the United Nations Educational Scientific and Cultural Organization (UNESCO) World Heritage Convention, as requested by the Government of Botswana (http://whc.unesco.org/en/tentativelists/5554/). In short, the research findings provided important science information that aid in the Okavango Delta conservation policy.

8.3 Future Research

This study covers a spectrum of multiplatform approach-based landscape topographic modeling issues. The comprehensive nature of this study and diversity of technologies used has made it a pioneering work for future research in topographic modeling, and linking wetland topographic processes with hydrology and climate change. However, a few issues remained that need further investigations to improve the quality of topographic models. The following tasks are considered to be important for future research on topographic modeling over wetland environments, especially over the Okavango Delta region:
1) Incorporation of topographic parameters such as slope, aspect and land-vegetation information into elevation data fusion for further improving DEM quality. For example, incorporation of detailed land cover and biophysical information such as normalized difference vegetation index (NDVI), normalized difference moisture index (NDMI), and tree heights into SRTM model.

2) Incorporation of waterline (derived from high spatial resolution satellite images) into integrated DEM construction at a regional scale. Also incorporation of channels and islands as breaklines (from high resolution optical or fused optical-radar images) can aid in improving the DEM accuracy.

3) Incorporation of bathymetric (underwater depths) information of channels, lakes, and other water bodies into topographic model construction (Imhof, 2007). Future investigations should consider bathymetric surveys in the delta.

4) ICESat GLAS records vertical profiles of the returned laser energy from their footprints. These vertical profiles aid measuring vertical structure of forests or tree heights that can be used for further correction of SRTM and ASTER elevation data.

5) For improved landscape topographic modeling, the precise geo-registration of datasets is essential. For this, well distributed ground control points (GCPs) are needed. The future research over the delta region should focus on acquiring well-distributed GCPs using differential GPS.

6) The future research should focus on combining representative high spatial resolution satellite images with medium resolution images (Cihler et al., 2000a, 2000b) for improved land cover mapping of the Okavango wetland (e.g. combining high resolution images from IKONOS, CartoSat 1/2, and SPOT 5/6 with moderate resolution images from Landsat 7/8). As radar remote sensing provides better capability in detection and delineation of water features, future research should focus on fusion of optical and radar images.

7) Airborne laser scanning (ALS) is a proven technology for high resolution topographic modeling (Haugerud et al., 2003; Csatho et al., 2005; Knight et al., 2009). The future research should investigate ALS to construct Okavango wetland microtopographic model.

8) Future satellite missions such as the ICESat 2, scheduled for launch in 2016 (Abdalati et al., 2010) and Surface Water and Ocean Topography (SWOT), scheduled for launch in 2020 (Durand et al., 2010) are expected to improve the mapping of water surface topography and derivation of parameters such as surface water extent and stage of inland water at a higher spatial resolution. Future investigations should take into account these developments.

8.4 Conclusion

Observations from diverse platforms have considerably improved mapping and understanding of Earth’s landscape topography. This study addressed the statement formulated in Chapter 1 in measuring and constructing variable resolution landscape topographic models of wetlands from multiplatform observations, and integrating these observations to produce improved models. A multiplatform approach was devised and demonstrated the power of this approach in measuring and modeling landscape topography in general, and wetland topography in particular.

This study has made significant scientific contributions for advancing a multiplatform approach to landscape topographic modeling, with the first in-depth research on the Okavango Delta region. Examples of first time research work on the delta are: stereo-photogrammetric elevation modeling, comprehensive research on topographic modeling, evaluating the accuracy of globally available elevation data, measuring water level changes by
spaceborne laser altimetry, and constructing topographic models by spaceborne laser and radar altimetry. The research findings have many science and policy implications, e.g. in-depth understanding of the Okavango Delta topographic and biophysical characteristics, providing inputs to hydrological, environmental and climate modeling, and aiding sustainable wetland management. The approach of this study could be applied in other situations where multiplatform observation perspectives are needed, especially in regions that lack reliable topographic data.
Appendices

**Appendix I.** Aerial photography over the Okavango Delta and number of blocks used in this study.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>Okavango Delta, Botswana</td>
</tr>
<tr>
<td>Ground elevation</td>
<td>950 m amsl (approximately)</td>
</tr>
<tr>
<td>Flying height above ground</td>
<td>7650 m</td>
</tr>
<tr>
<td>Lens type</td>
<td>Wild Universal Aviogon II, No. 3045, Calibration date: 8-11-89</td>
</tr>
<tr>
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</tr>
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<td>Photo scale</td>
<td>1: 50,000</td>
</tr>
<tr>
<td>Overlap, side lap</td>
<td>60%, -20-30%</td>
</tr>
<tr>
<td>Number of strips *</td>
<td>2 (3 blocks)</td>
</tr>
<tr>
<td>Number of photos per strip *</td>
<td>2 (3 blocks)</td>
</tr>
<tr>
<td>Date of flight</td>
<td>29 August, 1991</td>
</tr>
<tr>
<td>Imagery type</td>
<td>Diapositive and contact</td>
</tr>
<tr>
<td>Scanner</td>
<td>Ultrascan 5000**</td>
</tr>
<tr>
<td>Ultrascan 5000</td>
<td>15 micron</td>
</tr>
</tbody>
</table>

*Photo strips and number of photos per strip, used in this study. **Scanner used for scanning diapositives.
Appendix II. GPS measured ground control points in the Okavango Delta.

Maunachira block

<table>
<thead>
<tr>
<th>Station</th>
<th>Ground control point coordinates and height (m)</th>
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<td></td>
<td>Northing</td>
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<tr>
<td>Maunachira 01</td>
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</tr>
<tr>
<td>Maunachira 02</td>
<td>7877584.302</td>
</tr>
<tr>
<td>Maunachira 03</td>
<td>7879840.891</td>
</tr>
<tr>
<td>Maunachira 04</td>
<td>7878681.219</td>
</tr>
<tr>
<td>Maunachira 05</td>
<td>7878657.411</td>
</tr>
<tr>
<td>Maunachira 06</td>
<td>7880437.023</td>
</tr>
<tr>
<td>Maunachira 07</td>
<td>7880367.702</td>
</tr>
<tr>
<td>Maunachira 08</td>
<td>7887033.563</td>
</tr>
<tr>
<td>Maunachira 09</td>
<td>7887182.798</td>
</tr>
<tr>
<td>Maunachira 10</td>
<td>7886806.894</td>
</tr>
<tr>
<td>Maunachira 11</td>
<td>7886852.893</td>
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<tr>
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<tr>
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<td>7872239.153</td>
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<tr>
<td>Maunachira 14</td>
<td>7874559.681</td>
</tr>
<tr>
<td>Maunachira 15</td>
<td>7874642.827</td>
</tr>
<tr>
<td>Maunachira 16</td>
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<td>7879301.502</td>
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<td>Thata island</td>
<td>7893885.430</td>
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Lower Xudum block

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<th>Ground control point coordinates and height (m)</th>
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<td></td>
<td>Northing</td>
</tr>
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<td>Xudum 01</td>
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<tr>
<td>Xudum 02</td>
<td>7784899.012</td>
</tr>
<tr>
<td>Xudum 03</td>
<td>7784642.941</td>
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<tr>
<td>Xudum 04</td>
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<tr>
<td>Xudum 05</td>
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<tr>
<td>Xudum 06</td>
<td>7794343.121</td>
</tr>
<tr>
<td>Xudum 07</td>
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</tr>
<tr>
<td>Xudum 08</td>
<td>7795655.024</td>
</tr>
<tr>
<td>Xudum 09</td>
<td>7795407.918</td>
</tr>
<tr>
<td>Xudum 10</td>
<td>7795406.091</td>
</tr>
<tr>
<td>Xudum 11</td>
<td>7804623.496</td>
</tr>
<tr>
<td>Xudum 12</td>
<td>7804560.857</td>
</tr>
<tr>
<td>Xudum 13</td>
<td>7803150.710</td>
</tr>
<tr>
<td>Xudum 14</td>
<td>7803124.462</td>
</tr>
<tr>
<td>Shashe 5746</td>
<td>7791313.619</td>
</tr>
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</table>
### Jao block

<table>
<thead>
<tr>
<th>Station</th>
<th>Northing</th>
<th>Easting</th>
<th>Orthometric height</th>
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<td>Jao 01</td>
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<td>663300.118</td>
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</tr>
<tr>
<td>Jao 02</td>
<td>7902245.982</td>
<td>663282.388</td>
<td>973.586</td>
</tr>
<tr>
<td>Jao 03</td>
<td>7895899.168</td>
<td>660277.600</td>
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<td>Jao 04</td>
<td>7895955.907</td>
<td>660253.597</td>
<td>974.405</td>
</tr>
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<td>Jao 05</td>
<td>7898021.329</td>
<td>664837.474</td>
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<td>659401.030</td>
<td>974.252</td>
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<td>973.585</td>
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<td>Jao 11</td>
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<td>Jao 14</td>
<td>7890469.290</td>
<td>657548.749</td>
<td>972.106</td>
</tr>
</tbody>
</table>

**Note:** Cartesian coordinates with orthometric heights (Ellipsoid: Clarke 1880)

**Transformation-parameter:**
- $dx: 135.4m$
- $dy: 106.7m$
- $dz: 291.7m$

**Geoid:** EGM96  
**Projection:** UTM, Zone: 34 South

**Scale:** 0.0ppm
### Appendix III. Characteristics of ASTER sensor system and bands used for creating GDEM.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>VNIR</th>
<th>SWIR</th>
<th>TIR</th>
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</thead>
<tbody>
<tr>
<td>Spectral range</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Band 1</td>
<td>0.52-0.60</td>
<td>1.600-1.700</td>
<td>8.125-8.475</td>
</tr>
<tr>
<td>Band 2</td>
<td>0.63-0.69</td>
<td>2.145-2.185</td>
<td>8.475-8.825</td>
</tr>
<tr>
<td>Band 3N</td>
<td>0.76-0.86</td>
<td>2.185-2.225</td>
<td>8.925-9.275</td>
</tr>
<tr>
<td>Band 3B</td>
<td>0.76-0.86</td>
<td>2.235-2.285</td>
<td>10.25-10.95</td>
</tr>
<tr>
<td>Ground resolution (m)</td>
<td>15</td>
<td>30</td>
<td>90</td>
</tr>
<tr>
<td>Data Rate (Mbits/sec)</td>
<td>62</td>
<td>23</td>
<td>4.2</td>
</tr>
<tr>
<td>Cross-track Pointing (deg.)</td>
<td>±24</td>
<td>±8.55</td>
<td>±8.55</td>
</tr>
<tr>
<td>Cross-track Pointing (km)</td>
<td>±318</td>
<td>±116</td>
<td>±116</td>
</tr>
<tr>
<td>Swath width (km)</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Quantization (bits)</td>
<td>8</td>
<td>8</td>
<td>12</td>
</tr>
</tbody>
</table>

*Source: Yamaguchi et al., 1998; Fujisada et al., 2005; http://asterweb.jpl.nasa.gov/.*

*Note: Bands used for creating ASTER GDEM (in bold).*
Appendix IV. ICESat Geoscience Laser Altimeter System instrument specifications.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser type</td>
<td>ND:YAG slab, 3 stage Q-switched, diode-pumped</td>
</tr>
<tr>
<td>Number of lasers</td>
<td>3 (Operate alternately)</td>
</tr>
<tr>
<td>Laser pulse firing rate</td>
<td>40 Hz</td>
</tr>
<tr>
<td>Laser pulse width</td>
<td>6 ns (nominal)</td>
</tr>
<tr>
<td>Laser energy (nominal)</td>
<td>75 mJ, 1064 nm (transmitted)</td>
</tr>
<tr>
<td>Laser divergence angle (1/e² pts)</td>
<td>70-110 urad (depends on laser)</td>
</tr>
<tr>
<td>Telescope diameter</td>
<td>100 cm</td>
</tr>
<tr>
<td>1064 nm Detector</td>
<td>Si APD- analog mode (1 prime+1 backup)</td>
</tr>
<tr>
<td>1064 nm Surface digitizer resolution</td>
<td>1 nsec (15 cm in range)</td>
</tr>
<tr>
<td>1064 nm Cloud digitizer resolution</td>
<td>500 nsec (75 m in range)</td>
</tr>
<tr>
<td>532 nm Detector</td>
<td>Si APD- Geiger mode (8 used in parallel)</td>
</tr>
<tr>
<td>532 nm Aerosol digitizer resolution</td>
<td>500 nsec (75 m in range)</td>
</tr>
<tr>
<td>Laser beam angle measurement</td>
<td>&lt;10 uradian relative to star field</td>
</tr>
<tr>
<td>Mass</td>
<td>330 kg</td>
</tr>
<tr>
<td>Power</td>
<td>310 W average</td>
</tr>
<tr>
<td>Instr. duty cycle</td>
<td>100%</td>
</tr>
<tr>
<td>Data rate</td>
<td>~500 kbps (uncompressed)</td>
</tr>
<tr>
<td>Physical size</td>
<td>~110x140x110 cm</td>
</tr>
<tr>
<td>Thermal control</td>
<td>Radiators with variable conductance heat pipes</td>
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Source: Zwally et al., 2002.

<table>
<thead>
<tr>
<th>Data processing level</th>
<th>Data acquisition (dd/mm/yyyy)</th>
<th>No. of laser shots</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Start date</td>
<td>End date</td>
</tr>
<tr>
<td>L1A</td>
<td>25/02/2003</td>
<td>29/03/2003</td>
</tr>
<tr>
<td></td>
<td>05/10/2003</td>
<td>16/11/2003</td>
</tr>
<tr>
<td>L2B</td>
<td>22/02/2004</td>
<td>19/03/2004</td>
</tr>
<tr>
<td>L2C</td>
<td>22/05/2004</td>
<td>18/06/2004</td>
</tr>
<tr>
<td>L3A</td>
<td>08/10/2004</td>
<td>04/11/2004</td>
</tr>
<tr>
<td>L3B</td>
<td>23/02/2005</td>
<td>22/03/2005</td>
</tr>
<tr>
<td>L3C</td>
<td>25/05/2005</td>
<td>20/06/2005</td>
</tr>
<tr>
<td>L3D</td>
<td>26/10/2005</td>
<td>21/11/2005</td>
</tr>
<tr>
<td>L3E</td>
<td>27/02/2006</td>
<td>25/03/2006</td>
</tr>
<tr>
<td>L3F</td>
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<td>12/04/2007</td>
</tr>
<tr>
<td>L3I</td>
<td>07/10/2007</td>
<td>02/11/2007</td>
</tr>
<tr>
<td>L3J</td>
<td>22/02/2008</td>
<td>19/03/2008</td>
</tr>
<tr>
<td>L3K</td>
<td>08/10/2008</td>
<td>16/10/2008</td>
</tr>
<tr>
<td>L3L</td>
<td>26/11/2008</td>
<td>15/12/2008</td>
</tr>
<tr>
<td>L2E</td>
<td>13/03/2009</td>
<td>09/04/2009</td>
</tr>
<tr>
<td>L2F</td>
<td>05/10/2009</td>
<td>06/10/2009</td>
</tr>
<tr>
<td>Total laser shots</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: ICESat data product used in this study: GLA14 – GLAS/ICESat L2 Global Land Surface Altimetry Data, Version 33. (See description of ICESat data products at: https://nsidc.org/data/icesat/data.html).
Appendix VI. SPOT 5 HRG multispectral image scene of part of the Okavango Delta, acquired on 12 November 2002.

Note: This image scene (1,2,3 band combination; 10 m spatial resolution) covers 60 km x 60 km area (see location of the scene in Figure 2.19 (Chapter 2). Corner coordinates represent latitude and longitude, corresponding corner coordinates in UTM Zone 34 S (Clarke 1880 ellipsoid, Cape datum) are:

NW: 668980.413/7932582.457
NE: 727511.899/7918741.534
SW: 655013.867/7874132.045
SE: 713537.480/7860317.469
Appendix VII. Offset correction of Geological Survey of Botswana GPS Survey data on the Okavango Delta region.

GPS survey done by the Geological Survey of Botswana in the late 1990s used a provisional EGM96 code, which provides elevation 0.529 m lower than the actual terrain height. The final EGM96 corrected this discrepancy and recommended to use -0.529 m as an offset (Lemoine et al., 1998). We found out this discrepancy on the Okavango Delta region GPS survey data while assessing ICESat laser altimetry elevation by GPS measurements. Figure A shows the systematic bias in the GPS data compared to ICESat elevations (both datasets used EGM96 ellipsoid and WGS84 datum). Figure B shows the systematic bias corrected GPS elevation compared to ICESat elevations.

Figure A. Uncorrected GPS elevation vs. ICESat laser altimetry elevation.

Figure B. Bias corrected GPS elevation vs. ICESat laser altimetry elevation.
Appendix VIII. Coordinate transformation parameters for images and topographic maps.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>UTM Zone 34</td>
</tr>
<tr>
<td>Projection</td>
<td>Universal Transverse Mercator (UTM)</td>
</tr>
<tr>
<td>Spheroid*</td>
<td>Clarke 1888</td>
</tr>
<tr>
<td>Unit of measurement</td>
<td>Metre</td>
</tr>
<tr>
<td>Meridian of origin</td>
<td>21°00' East of Greenwich</td>
</tr>
<tr>
<td>Latitude of origin</td>
<td>Equator</td>
</tr>
<tr>
<td>Scale factor at origin</td>
<td>0.9996 (on central meridian)</td>
</tr>
<tr>
<td>False co-ordinates of origin</td>
<td>500,000 m Easting</td>
</tr>
<tr>
<td>Datum*</td>
<td>Cape</td>
</tr>
</tbody>
</table>

*Cape Datum

- dX: -136 m
- dY: -108 m
- dZ: -292 m

Scale factor: 0 ppm

Source: NIMA: TR8350.2 2000

Clarke 1880 Ellipsoid

- semi-major axis (a) = 6378249.145 m
- flattening (1/f) = 293.465

Source: NIMA: TR8350.2 2000
Appendix IX. Geo-registration of air- and spaceborne images.

Aerial (B&W) and satellite images from IKONOS, SPOT 5 HRG and Landsat 7 ETM+ sensors were referenced to UTM projection Zone 34 S (Clarke 1880 ellipsoid, Cape datum) using a nearest neighbour resampling technique with first order polynomial transformation (see transformation parameters in Appendix VIII). A nearest neighbour resampling was used as it avoids altering the original input pixel values (Lillesand and Kiefer, 2008). The $X$ and $Y$ residuals and RMS errors for each dataset are given in the following section.

**Aerial Images**

Diapositives of aerial images (230 mm x 230 mm) at ~1:50,000 scales were scanned at 15 µm (object space resolution 0.76 m) using UltraScan 5000 V1.44.3.1 (Vexcel Imaging GmbH) scanner. Three aerial images (Maunachira, Jao, and Xudum test sites) represent diverse topographic characteristics and physiographic regions of the Okavango Delta. Jao site represent permanent swamps, Maunachira site permanent to seasonal swamps, and Xudum site seasonal to occasional swamps. The details about aerial images are given in Appendix I.

Aerial images were rectified with GPS GCPs (Table A). A first order polynomial transformation and nearest neighbour resampling were performed for each dataset. For each image rectification, well distributed GCPs are selected. The $X$ and $Y$ residuals and RMS errors for each image are given in Table A. RMS errors for three test site image ranges from 0.04 to 12.6 pixels because of differences in quality of GPS GCPs and diverse ground features. Xudum produced lowest registration error since the area is located in dry-grassland region with well-defined features for GPS GCP measurement. Image registration errors are higher for Jao and Maunachira sites, located in permanent swamp and permanent to seasonal swamp regions, respectively with no well-defined ground features for GPS GCP measurement.

**Table A. Georegistration accuracy of aerial images (0.76 - 0.78 m spatial resolution).**

<table>
<thead>
<tr>
<th>Image site</th>
<th>Number. of GCPs</th>
<th>Residual (pixel)</th>
<th>RMS error (pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maunachira</td>
<td>4</td>
<td>2.40</td>
<td>9.90</td>
</tr>
<tr>
<td>Jao</td>
<td>7</td>
<td>6.937</td>
<td>10.570</td>
</tr>
<tr>
<td>Xudum</td>
<td>8</td>
<td>0.019</td>
<td>0.036</td>
</tr>
</tbody>
</table>

**Satellite Images**

**IKONOS:**

IKONOS Pan/MS image covers an area of 5.9 km x 9.5 km (56.5 km$^2$). IKONOS Pan image was rectified using 5 well-distributed GPS GCPs with RMSE of less than half pixel (0.35 in object space). The $X$ and $Y$ residuals and RMS errors are given in Table B. IKONOS MS image was rectified using 10 well-distributed GCPs, 5 GPS GCPs and 5 taken from geo-registered IKONOS Pan image. The $X$ and $Y$ residuals and RMS errors are given in Table B. The overall rectification accuracy of MS image is 0.16 pixel (0.64 m in object space).
Table B. Georegistration accuracy of IKONOS panchromatic (1 m) and multispectral (4 m) images.

<table>
<thead>
<tr>
<th>Images</th>
<th>Number of GCPs</th>
<th>Residual (pixel)</th>
<th>RMS error (pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>Pan</td>
<td>5</td>
<td>0.257</td>
<td>0.244</td>
</tr>
<tr>
<td>MS</td>
<td>10</td>
<td>0.101</td>
<td>0.120</td>
</tr>
</tbody>
</table>

SPOT 5:
The Pan image was rectified with GPS GCP-based rectified aerial images (Table A), and rectified 1:50,000 scale topographic maps (Appendix X). To achieve good registration accuracy, 64 GCPs and 30 check points (CPs) well-distributed over the image (60 km x 60 km) were used.

The XS image was rectified with rectified 1:50,000 scale topographic maps (Appendix X) and rectified SPOT Pan image. Same number of well-distributed GCPs and CPs, as used for Pan image, were used for rectification of the XS image. The X and Y residuals and RMS errors of Pan and XS image rectification are given in Table C. For Pan image, overall 4.6 pixel (23 m in object space) accuracy was achieved; while for XS image, overall 2.3 pixel (23 m in object space) accuracy was achieved.

Table C. Georegistration accuracy of SPOT 5 HRG panchromatic (5 m) and multispectral (10 m) images.

<table>
<thead>
<tr>
<th>Images</th>
<th>Number of GCPs</th>
<th>Residual (pixel)</th>
<th>RMS error (pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>Pan</td>
<td>64</td>
<td>2.869</td>
<td>3.415</td>
</tr>
<tr>
<td>XS</td>
<td>64</td>
<td>1.572</td>
<td>1.678</td>
</tr>
</tbody>
</table>

Landsat 7:
Eight Landsat 7 ETM+ scenes – four Pan and four MS (Path/Row: 175/073, 175/074, 174/073, 174/074) were used in this study. The P/R 175/073 image covers most part of the delta, other three scenes cover remaining parts of the delta and its surrounding region (see Figure 2.19, Chapter 2).

To achieve better registration accuracy and to minimise error propagation, all ETM+ images were rectified using GPS GCPs, GPS GCP-based rectified aerial images (Table A), rectified SPOT 5 Pan image, rectified topographic maps of 1:50,000 and 1:250,000 scale (Appendix X). Image to image (i.e. Pan to MS) registration was done on regions where no detectable features were found in the above rectified datasets. Tables D and E shows the registration accuracy of Landsat 7 images.
Table D. Georegistration accuracy of Landsat 7 ETM+ panchromatic images (15 m spatial resolution). [10 April 2000: 175/073, 175/074; 03 April 2000: 174/073, 174/074].

<table>
<thead>
<tr>
<th>Path/Row</th>
<th>Number of GCPs</th>
<th>Residual (pixel) X</th>
<th>Residual (pixel) Y</th>
<th>RMS error (pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>175/073</td>
<td>121</td>
<td>1.987</td>
<td>1.789</td>
<td>2.674</td>
</tr>
<tr>
<td>175/074</td>
<td>42</td>
<td>0.867</td>
<td>1.001</td>
<td>1.324</td>
</tr>
<tr>
<td>174/073</td>
<td>53</td>
<td>1.040</td>
<td>0.966</td>
<td>1.419</td>
</tr>
<tr>
<td>174/074</td>
<td>55</td>
<td>0.912</td>
<td>0.962</td>
<td>1.326</td>
</tr>
</tbody>
</table>

Table E. Georegistration accuracy of Landsat 7 ETM+ multispectral images (30 m spatial resolution). [10 April 2000: 175/073, 175/074; 03 April 2000: 174/073, 174/074].

<table>
<thead>
<tr>
<th>Path/Row</th>
<th>Number of GCPs</th>
<th>Residual (pixel) X</th>
<th>Residual (pixel) Y</th>
<th>RMS error (pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>175/073</td>
<td>93</td>
<td>0.843</td>
<td>0.912</td>
<td>1.242</td>
</tr>
<tr>
<td>175/074</td>
<td>46</td>
<td>0.782</td>
<td>0.784</td>
<td>1.107</td>
</tr>
<tr>
<td>174/073</td>
<td>38</td>
<td>0.688</td>
<td>0.833</td>
<td>1.080</td>
</tr>
<tr>
<td>174/074</td>
<td>45</td>
<td>0.750</td>
<td>0.712</td>
<td>1.034</td>
</tr>
</tbody>
</table>
Appendix X. Topographic datasets of the Okavango Delta and their geo-registration.

Topographic maps (hard print) were scanned using Océ CS4000 Color Scanner (wide format color scanner). The 1:50,000 scale maps were scanned at 400 dots per inch (dpi, 63.5 µm) with an object space resolution (OSR) of 3.175 m, 1:250,000 scale maps at 300 dpi (84.667 µm) with an OSR of 21.167 m, and 1:350,000 scale maps were scanned at 400 dpi (63.5 µm) with an OSR of 22.225 m. The Okavango Delta topographic maps provide general topographic-biophysical characteristics of the landscape. These maps lack the fundamental attribute of topographic maps, i.e. contours that show terrain elevation.

All topographic maps were referenced to UTM projection Zone 34 S (Clarke 1880 ellipsoid, Cape datum) using a nearest neighbour resampling technique with first order polynomial transformation (see coordinate transformation parameters in Appendix VIII). Topographic map parameters are given in Table A. A few topographic maps were with South African datum, they were transformed into Cape datum.

### Table A. Parameters and specifications of topographic maps.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>UTM Zone 34</td>
</tr>
<tr>
<td>Projection</td>
<td>Transverse Mercator</td>
</tr>
<tr>
<td>Spheroid</td>
<td>Clarke 1888 (Modified)</td>
</tr>
<tr>
<td>Unit of measurement</td>
<td>Metre</td>
</tr>
<tr>
<td>Meridian of origin</td>
<td>21°00' East of Greenwich</td>
</tr>
<tr>
<td>Latitude of origin</td>
<td>Equator</td>
</tr>
<tr>
<td>Scale factor at origin</td>
<td>0.9996</td>
</tr>
<tr>
<td>False co-ordinates of origin</td>
<td>500,000 m Easting</td>
</tr>
<tr>
<td></td>
<td>10,000,000 m Northing</td>
</tr>
<tr>
<td>Datum*</td>
<td>South African</td>
</tr>
</tbody>
</table>

*In some topographic map sheets, datum is not mentioned.

Each topographic map was georeferenced using 8 to 14 GCPs. The RMSE resulted in 0.003 to 1.5 pixels for 1:50,000 scale maps, 0.004 to 0.3 pixels for 1:250,000 scale maps, and 2.2 to 3.9 pixels for 1:350,000 scale maps. Table B presents the overall rectification accuracy of topographic maps. For 1:50,000 scale maps, 0.03 – 1.5 pixel accuracy were achieved. For 1:250,000 scale maps, 0.04 – 0.32 pixel accuracy and for 1:350,000 scale maps, 2.2 – 3.9 pixel accuracy were achieved. The detail rectification results of topographic maps are given in Tables C, D and E, respectively for 1:50,000, 1:250,000 and 1:350,000 scale.

### Table B. Overall rectification accuracy of topographic maps.

<table>
<thead>
<tr>
<th>Map scale</th>
<th>Object space pixel dim (m)</th>
<th>Number of GCPs</th>
<th>Range of residuals (pixel)</th>
<th>RMS error (pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>Y</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1:50,000</td>
<td>3 to 4</td>
<td>8 to 12</td>
<td>0.003 - 1.2</td>
<td>0.003 - 1.48</td>
</tr>
<tr>
<td>1:250,000</td>
<td>20 to 21</td>
<td>11 to 13</td>
<td>0.003 - 0.27</td>
<td>0.003 - 0.17</td>
</tr>
<tr>
<td>1:350,000</td>
<td>22</td>
<td>6 to 14</td>
<td>2.14 - 2.33</td>
<td>0.64 - 3.09</td>
</tr>
</tbody>
</table>
### Table C. Specification and rectification accuracy of 1: 50,000 scale topographic maps.

<table>
<thead>
<tr>
<th>Map sheet (No.)</th>
<th>Year of publication</th>
<th>Object space pixel dim (m)</th>
<th>Number of GCPs</th>
<th>Residual (pixel) X</th>
<th>Residual (pixel) Y</th>
<th>RMS error (pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1823C3</td>
<td>1971</td>
<td>4</td>
<td>10</td>
<td>0.3456</td>
<td>0.5416</td>
<td>0.6425</td>
</tr>
<tr>
<td>1822D3</td>
<td>1971</td>
<td>3</td>
<td>12</td>
<td>0.8709</td>
<td>0.6751</td>
<td>1.1019</td>
</tr>
<tr>
<td>1822D4</td>
<td>NA</td>
<td>4</td>
<td>12</td>
<td>0.2642</td>
<td>0.2716</td>
<td>0.3789</td>
</tr>
<tr>
<td>1923A1</td>
<td>1989</td>
<td>3</td>
<td>8</td>
<td>1.2085</td>
<td>0.7047</td>
<td>1.3989</td>
</tr>
<tr>
<td>1922B1</td>
<td>1971</td>
<td>4</td>
<td>10</td>
<td>0.2779</td>
<td>0.3111</td>
<td>0.4172</td>
</tr>
<tr>
<td>1922B2</td>
<td>1989</td>
<td>4</td>
<td>11</td>
<td>0.5347</td>
<td>0.3693</td>
<td>0.6499</td>
</tr>
<tr>
<td>1922A2</td>
<td>1987</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1922A3</td>
<td>NA</td>
<td>3</td>
<td>11</td>
<td>0.003</td>
<td>0.003</td>
<td>0.0043</td>
</tr>
<tr>
<td>1822C4</td>
<td>1987</td>
<td>3</td>
<td>12</td>
<td>0.0026</td>
<td>0.0032</td>
<td>0.0042</td>
</tr>
<tr>
<td>1923D3</td>
<td>1988</td>
<td>3</td>
<td>12</td>
<td>0.0024</td>
<td>0.0019</td>
<td>0.0031</td>
</tr>
<tr>
<td>2023A1</td>
<td>1970</td>
<td>4</td>
<td>12</td>
<td>0.0045</td>
<td>0.0035</td>
<td>0.0058</td>
</tr>
</tbody>
</table>

### Table D. Specification and rectification accuracy of 1: 250,000 scale topographic maps.

<table>
<thead>
<tr>
<th>Map sheet no./Place name</th>
<th>Year of publication</th>
<th>Object space pixel dim (m)</th>
<th>Number of GCPs</th>
<th>Residual (pixel) X</th>
<th>Residual (pixel) Y</th>
<th>RMS error (pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Tsodilo (2nd Edition)</td>
<td>1989</td>
<td>21</td>
<td>11</td>
<td>0.003</td>
<td>0.0031</td>
<td>0.0044</td>
</tr>
<tr>
<td>2 Linyanti (2nd Edition)</td>
<td>1989</td>
<td>21</td>
<td>12</td>
<td>0.0088</td>
<td>0.0115</td>
<td>0.0145</td>
</tr>
<tr>
<td>5 Nokaneng (2nd Edition)</td>
<td>1988</td>
<td>21</td>
<td>12</td>
<td>0.006</td>
<td>0.0048</td>
<td>0.0076</td>
</tr>
<tr>
<td>6 Maun</td>
<td>1984</td>
<td>20</td>
<td>12</td>
<td>0.2765</td>
<td>0.1705</td>
<td>0.3249</td>
</tr>
<tr>
<td>SF:34.4</td>
<td>1981</td>
<td>21</td>
<td>13</td>
<td>0.0056</td>
<td>0.0056</td>
<td>0.0079</td>
</tr>
</tbody>
</table>

Note: Topographic maps of 1:250,000 scale were compiled from 1:100,000 and 1:50,000 scale photomaps (1970 to 1982), which were prepared based on aerial photography (acquired in 1969, 1973 and 1978).

### Table E. Specification and rectification accuracy of 1: 350,000 scale topographic maps.

<table>
<thead>
<tr>
<th>Map sheet no./Place name</th>
<th>Year of publication</th>
<th>Object space pixel dim (m)</th>
<th>Number of GCPs</th>
<th>Residual (pixel) X</th>
<th>Residual (pixel) Y</th>
<th>RMS error (pixel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Panhandle</td>
<td>1994</td>
<td>22</td>
<td>6</td>
<td>2.1402</td>
<td>0.6383</td>
<td>2.2334</td>
</tr>
<tr>
<td>Okavango Delta</td>
<td>1994</td>
<td>22</td>
<td>14</td>
<td>2.3274</td>
<td>3.0876</td>
<td>3.8665</td>
</tr>
</tbody>
</table>

\*Reprinted without revision 1994 (First published 1987).
Appendix XI. Statistical methods for assessing the accuracy of topographic data and models.

Approaches

Two approaches used for evaluating the accuracy of elevation data: point-based and image (or raster)-based. For the first approach, data are randomly distributed as points, while the second approach uses continuous data points (e.g. grid data) over an area.

**Point differencing** (point-based): In this technique, values at the georegistered elevation points \( z \) are subtracted, point by point, to derive error statistics such as the mean error (ME), standard deviation error (SDE), root mean square error (RMSE). An error distribution map can be produced by plotting error points. The measure of DEM accuracy can be expressed as:

\[
d(x,y) = p'(x,y) - p(x,y)
\]

where \( d(x,y) \) is the difference elevations, \( p'(x,y) \) is the derived elevation points, and \( p(x,y) \) is the reference elevation points.

**Image differencing** (raster-based): In this technique, georegistered elevation models, e.g. \( I_1 \) and \( I_2 \) are subtracted, pixel by pixel, to derive a difference image that represents the difference between the two models, and expressed as:

\[
D_{xy} = x_{ij}(I_2) - x_{ij}(I_1)
\]

where \( D_{xy} \) is the difference image, \( x_{ij} \) is the pixel value for band \( x \) and \( i \) and \( j \) are lines and columns in the image, \( I_1 \) is the reference image, \( I_2 \) is the derived image. A constant can be added to the equation to produce positive difference values.

**Similarity Measurement**

**Correlation:** The coefficient of correlation (\( \rho \)) gives the strength of the linear relationship between two sets of attribute values, \( x \) and \( y \) (e.g. elevation from two datasets), and expressed as:

\[
\rho = \frac{\sum_{i=1}^{n} (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n} (X_i - \bar{X})^2 \sum_{i=1}^{n} (Y_i - \bar{Y})^2}}
\]

where \( \bar{X} \) and \( \bar{Y} \) are the sample means of \( X_1, X_2, ..., X_n \) and \( Y_1, Y_2, ..., Y_m \) respectively. The value \( \rho \) is a summary measure relating to an entire set of paired observations.
Cross-correlation: This method gives the relationship between two spatially referenced images and the strength of similarities, and expressed as:

\[
\rho = \frac{\sum_{i=1}^{m} \sum_{n=1}^{n} \left( f(\xi,\eta) - \mu_1 \right) \ast \left( g(\xi,\eta) - \mu_2 \right)}{\sqrt{\sum_{i=1}^{m} \sum_{n=1}^{n} (f(\xi,\eta) - \mu_1)^2} \ast \sqrt{\sum_{i=1}^{m} \sum_{n=1}^{n} (g(\xi,\eta) - \mu_2)^2}}
\]

\[-1 \leq \rho \leq 1\]  

where \( f(\xi,\eta) \) = individual elevation values of DEM1  
\( \mu_1 \) = average elevation value of DEM1  
\( g(\xi,\eta) \) = individual elevation values of DEM2  
\( \mu_2 \) = average elevation value of DEM2  
\( m,n \) = number of rows and columns in the elevation models.

Error Measurement

Several quantitative measures exists to assess the accuracy of elevation data. Most commonly used are standard deviation (\( \sigma \)), variance (\( \sigma^2 \)), semivariance (\( \gamma \)), mean square error (MSE), and RMSE.

**Standard deviation (\( \sigma \)):** A measure of the variability or dispersion of values around the mean of a normal distribution, and expressed as:

\[
\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (x_i - \mu)^2}
\]

where \( N \) is the total number of pixels, \( x_i \) is the pixel intensity, and \( \mu \) is the mean of the values \( x_i \).

**Variance (\( \sigma^2 \)):** A measure of dispersion that determines the contents of the error in the elevation model, and expressed as:

\[
\sigma^2 = \frac{1}{N-1} \sum_{i=1}^{N} (x_i - \mu)^2
\]

where \( N \) is the total number of pixels, \( x_i \) is the pixel intensity, and \( \mu \) is the mean of the values \( x_i \).
Semivariance (γ): A measure of the spatial dependence between two observations as a function of the distance between them, and is defined as:

\[
\gamma_h = \frac{\sum_{i=1}^{n-h} (Z_i - Z_{i+h})^2}{2(n-h)}
\]

(A.7)

where \(Z_i\) = values of the attribute at control points, \(h\) = multiple of the distance between control points, \(n\) = number of sample points.

Mean square error (MSE): Indicates the mean difference of the pixels throughout the model, i.e., error throughout the image, and expressed as:

\[
MSE = \frac{1}{N-1} \sum_{i=1}^{N} (z_i - w_i)^2
\]

(A.8)

where \(z_i\) is the elevation recorded in the DEM; \(w_i\) is the elevation at the higher precision; and \(N\) is the number of ground elevation points tested.

Root mean square error (RMSE): A global measure of error, and expressed as:

\[
RMSE = \sqrt{\frac{1}{N-1} \sum_{i=1}^{N} (z_i - w_i)^2}
\]

(A.9)

where \(z_i\) is the elevation recorded in the DEM; \(w_i\) is the elevation at the higher accuracy or precision; and \(N\) is the number of ground elevation points tested.
Glossary of Technical Terms

**Accuracy**: The degree of conformity to the true value, i.e. the closeness of an estimated value to a standard or accepted value. A value that is very close to the true value has high accuracy, and a value that is far from true has low accuracy.

**Datum** (e.g. Cape datum): A means of relating coordinates determined by various ways to a well-defined reference frame. A geodetic datum is a model by an ellipsoid and the relationship between the ellipsoidal and the surface of the earth.

**Easting**: X coordinates in the UTM grid system; distance in meters east or west from the central meridian of the UTM.

**Elevation**: The vertical distance from the datum, usually mean sea level (msl), to a point or object on the Earth’s surface.

**EGM96**: The Earth Gravitational Model 1996 is a geopotential model of the Earth, developed jointly by NASA GSFC and National Geospatial-Intelligence Agency (NGA) of United States (previously known as NIMA, National Imagery and Mapping Agency). EGM96 applies only to the WGS 84 reference ellipsoid.

**Ellipsoid**: A mathematical figure approximating the shape of the Earth, used as a reference frame for computations in geodesy, and earth and planetary sciences. Examples of earth ellipsoidal models such as WGS84 and Clark1880.

**Ellipsoidal height**: The distance from ellipsoid of reference to a point on the Earth’s surface as measured along the perpendicular from the ellipsoid. GPS heights are ellipsoidal.

**Error**: The difference between a particular value and the true value; error can be categorized as random errors, systematic errors, and mistakes.

**GCP** (ground control point): A geographical feature of known location that is recognizable on image, and used to determine geometric corrections.

**Geoid** (meaning earth-like): Also known as the sea level equipotential surface, i.e. the surface on which gravity is everywhere equal to its strength at mean sea level. The geoid surface is everywhere perpendicular to gravity.

**Geoidal height**: The distance from the ellipsoid of reference to the geoid measured along a perpendicular to the reference.

**Horizontal accuracy**: The positional accuracy of features in a dataset with respect to a horizontal datum.

**Horizontal datum**: A model that is used to measure positions on the earth (e.g. WGS84, a common standard datum).
**Horizontal error:** The magnitude of the displacement of a feature’s recorded horizontal position in a dataset from its true or more accurate position, as measured radially and not resolved into x, y.

**Horizontal resolution:** Specifies the pixel or grid size \((x,y)\) of an images covering the earth surface (e.g. air or spaceborne images, DEMs).

**Laser** (Light Amplification by Stimulated Emission of Radiation): A device that emits light (electromagnetic radiation) through a stimulated emission. Laser is a key component of the lidar (Light Detection And Ranging). Lidar measures distance (from an aircraft or spacecraft to the object surface) by illuminating a target with a laser and analyzing the reflected light. A laser altimeter uses a lidar to measure the height of the instrument platform above the surface.

**Northing:** Y coordinates in the UTM grid system; distance in meters north from the equator.

**Optical:** A remote sensing device that uses visible, near infrared and short-wave infrared sensors to detect solar radiation reflected from targets on the ground to form images. Target materials reflect and absorb differently at different wavelengths. It rely on the sun as an energy source, and detect only naturally occurring energy.

**Orbit:** The path of one object around a larger one (e.g. remote sensing satellites orbit around Earth).

**Orthometric height:** The vertical distance from geoid to the surface of the Earth.

**Platform:** Stage based on which observations are acquired (e.g. ground, airplane, and satellite).

**Positioning:** A space-based satellite navigation system provides location (xyz coordinates) and time information anywhere on earth surface and above. Two major such systems are US GPS and Russian GLONASS.

**Precision:** The degree of refinement of a quantity.

**Radar** (RAdio Detection And Ranging): An active remote sensing device that measures the time between pulses and their reflected components to determine distance. Different pulse intervals, wavelengths, geometry and polarizations can be combined to roughness characteristics of the earth surface. It act as their own energy source, and detect backscattered energy.

**Reliability:** The trust or confidence given to a set of map data based on the available metadata and inspections by the users.

**UTM** (Universal Transverse Mercator): A map projection system based on 60 east west zones between 84°N and 84°S latitudes, each 6 degrees wide in longitude. X,Y coordinates in the grid is recorded in meters and is seven-digit numbers, increasing as one move from east and north. Its coverage is completed by the addition of two polar zones.

**Vertical accuracy:** The measure of the positional accuracy of a dataset with respect to a specified vertical datum.

**Vertical datum:** used for measuring elevations of points on the sea level. Vertical datums are either: tidal (based on sea levels), gravimetric (based on a geoid), or geodetic (based on the same ellipsoid models of the earth used for computing horizontal datums).
**Vertical error:** The displacement of a feature's recorded elevation in a dataset from its true or more accurate elevation.

**Vertical resolution:** Specifies the precision of measurements of three-dimensional points or grids \((x,y,z)\) on the earth surface (e.g. DEM).

**Weight:** The relative worth of an observation compared to any other observation.

**WGS84:** A world geodetic earth-centred, earth-fixed terrestrial reference system (TRS). The origin of the WGS84 reference frame is the center of mass of the Earth.

*Note:* Some glossaries are adapted from various sources.
This bibliography includes books, articles and papers to which reference are made in the text and also certain other works that provided valuable ideas, and may be useful to the future researchers. The following abbreviations are used:

- PE&RS: Photogrammetric Engineering & Remote Sensing
- RSE: Remote Sensing of Environment


Dozier, J. and Frew, J. (1990) Rapid calculation of terrain parameters for radiation modeling from

Agency's Earth Explorer Mission CryoSat: Measuring variability in the cryosphere. *Annals of


Dunn, R., Harrison, A.R. and White, J.C. (1990) Positional accuracy and measurement error in


and Gopal, S. (Eds.) *The Accuracy of Spatial Databases*. London: Taylor & Francis Ltd,
pp.125-140.


134.


Everett, J. and Simonett, D.S. (1976) Principles, concepts, and philosophical problems in remote

characterization of the vertical accuracy of digital elevation models from the Shuttle Radar


*Science* 310(5754): 1674-1678.

G


K


L


N


Neuenschwander, A.L., Crawford, M.M. and Ringrose, S. (2005) Results from the EO-1 experiment – A comparative study of Earth Observing-1 Advanced Land Imager (ALI) and


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About the Author

Krishna Talukdar was born in Assam, India, and is a citizen of India. He studied science at the secondary school level. He received his B.Sc. (First Class First Honours) degree from Gauhati University (India), Post Graduate Diploma (Remote Sensing and Photogrammetry) from Indian Institute of Remote Sensing/Indian Space Research Organization, IIRS/ISRO (India), M.Sc. (Geoinformation Science and Earth Observation) from International Institute for Aerospace Survey and Earth Sciences/University of Twente (Netherlands), and M.Sc. (Space Studies/Space Science and Technology) from International Space University (France) with thesis research at the National Aeronautics and Space Administration/Goddard Space Flight Center, NASA/GSFC (USA).

Talukdar have many years of experience in Earth science remote sensing, satellite systems, and geomatic engineering. His major professional experiences include research at the NASA/GSFC (Greenbelt, USA); Centre for Applications of System Simulation/Indian Agricultural Research Institute, CASS/IARI (New Delhi, India); Centre National d’étude des Environnements Terrestre et Planétaires/Centre National de la Recherche Scientifique, CETP/CNRS (Paris, France); and Institute of Geodesy and Photogrammetry/Swiss Federal Institute of Technology, IGP/ETH (Zurich, Switzerland). His Ph.D. research was initiated at the ETH Zurich where significant part of the dissertation was done. At the Delft University of Technology (Netherlands), the research was carried out at the Faculties of Aerospace Engineering, and Civil Engineering and Geosciences. The Ph.D. dissertation: Multiplatform Observations for Measuring Wetland Landscape Topography is the outcome of many years of international experience and interdisciplinary expertise.
I hope that posterity will judge me kindly, not only as to the things which I have explained but also as to those which I have intentionally omitted so as to leave to others the pleasure of discovery.

– René Descartes (1596-1650)
Quotes of Personalities used in the Dissertation

Swami Vivekananda (1863–1902) philosopher and spiritualist, India
Theodore Roosevelt (1858–1919) American President and naturalist, United States
Krishnaswamy Kasturirangan (1940–present) space scientist, India
Henri Poincaré (1854–1912) mathematician, physicist and geodesist, France
Galileo Galilei (1564–1642) physicist, mathematician and astronomer, Italy
Yuri Gagarin (1934–1968) pilot and cosmonaut, Russia
Richard Feynman (1918–1988) physicist, United States
Robert H. Goddard (1882–1945) rocket scientist and physicist, United States
Carl Friedrich Gauss (1777–1855) mathematician and physical scientist, Germany
René Descartes (1596–1650) philosopher, mathematician and writer, France
Stellingen bij het proefschrift

1. Digitale oppervlaktemodellen (DSMs) zijn dynamische representaties van de landschapstopografie van de Aarde. (*Dit proefschrift*)

2. Het informatieverlies in beeldfiltering (bijv. DEM) wordt beloond met verbetering van de weergave van de werkelijkheid. (Kuhn, 1970). (*Dit proefschrift*)

3. Hoe meer complementair de multiplatform-hoogtedata, hoe beter het resultaat van de datafusie. (*Dit proefschrift*)

4. De topografie van verre planetachtige hemellichamen (bijv. Mars, de Maan) is beter gekarteeerd dan (de meeste delen van) ons aardoppervlak.

5. De Okavangopoivanaier is een exemplarische aardse analogie van planetaire waaiervormige landschapsstructuren (bijv. Mars).

6. Een hydrologisch model zonder topografische informatie (oppervlak en bathymetrie) is een onrealistische weergave van de werkelijkheid.

7. Topografie (hoogte, boven of onder gemiddeld zeeniveau) bepaalt de lengte van mensen in een regio. (Tripathy en Gupta, 2007).

8. Het zijn rede en logica die wetenschap definiëren en niet de beslissing van de geleerde(n).

9. De politiek vormt de wetenschap meer dan de wetenschap de politiek vormt.

10. Mensen die vergelijkbaar denken stemmen vergelijkbaar. [naar de hypothese van Miller (1977) ‘mensen die met elkaar praten stemmen vergelijkbaar.’]

"Deze stellingen worden opponeerbaar en verdedigbaar geacht en zijn als zodanig goedgekeurd door de promotor prof. dr. M. Menentl."
Propositions of the dissertation

Multiplatform Observations for Measuring Wetland Landscape Topography

Krishna K. Talukdar

1. Digital surface models (DSMs) are dynamic representations of the Earth’s landscape topography. *(This thesis)*

2. The information loss in image filtering (e.g. DEM) is rewarded by improvement of the representation of reality. *(Kuhn, 1970)*. *(This thesis)*

3. More complementary the multiplatform elevation data, the better the result of data integration. *(This thesis)*

4. The topography of distant planetary bodies (e.g. Mars, Moon) is better mapped than (most part of) our Earth’s surface.

5. The Okavango alluvial fan is an exemplary terrestrial analogue to planetary fan-shaped landscape features (e.g. Mars).

6. A hydrological model without topographic (surface and bathymetry) information is an unrealistic representation of reality.

7. Topography (elevation, above or below mean sea level) determines the height of people in a region. *(Tripathy and Gupta, 2007)*.

8. It is reason and logic that defines science, and not the decision of the scholar(s).

9. Politics shapes science more than science shapes politics.

10. People who think similar vote together. [following Miller’s (1977) hypothesis that ‘people who talk together vote together.’] *(This thesis)*

“These propositions are regarded as opposable and defendable, and have been approved as such by the supervisor prof. dr. M. Menenti.”