Spaceborne Remote Sensing for Near-Eastern Archaeology
A case study on archaeological site-detection in Jordan’s Black Desert

V.C.G. Liem
SPACEBORNE REMOTE SENSING FOR NEAR-EASTERN ARCHAEOLOGY

A CASE STUDY ON ARCHAEOLOGICAL SITE-DETECTION IN JORDAN’S BLACK DESERT

by

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in partial fulfillment of the requirements for the degree of

Master of Science
in Geomatics

at the Delft University of Technology,
to be defended publicly on Friday January 31, 2014 at 15:00 AM.

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An electronic version of this thesis will be made available at http://repository.tudelft.nl/.
There was a time when I was in high school when I wanted to become an archaeologist. The architectural works and myths of ancient civilizations fascinated me to no end. In the end however, my interest in science did happen to win out. Imagine my surprise and joy when I heard that there was actually a graduation topic available in which I could combine my studies with the my old field of interest of archaeology!

This thesis reflects on the work I did during the period of December 2013 till January 2014 as graduation project for the M.Sc. Geomatics at the Geoscience and Remote Sensing department. The research offers insight into the use of optical and radar spaceborne remote sensing for the automatic detection of archaeological structures in Jordan's Black Desert. The area of interest is unusual, because most archaeological interest is focused on the western Jordan Valley rather than the barren east. The Near Eastern Archaeology department of Leiden, however, has proven in earlier fieldwork that a wealth of information is still waiting to be discovered within the Black Desert. In their 'Jebel Qurma Archaeological Landscape Project' the cultural developments within the region during the particular time period of 1000 BC to 500 AD are investigated. Spaceborne remote sensing has the potential to help the systematical investigation of the area by means of automatic structure detection, as well as provision of additional information as height and slopes of the area.

There are a lot of people who I would like to thank for their help and contribution to this project. First of all, I would like to thank my graduation professor Ramon Hanssen, for offering me this research topic in the first place, his critical comments about my research and practical insight during the fieldwork. Without his insistence, I would never have dared to cross half of Jordan packed in a local bus to marvel at the wonders of Petra. I would like to thank my daily supervisor, Lorenzo Iannini, as well, for his support and availability for lengthy discussions on research at any time, coming up with the idea of placing corner reflectors in the field and actually helping with bending the corner reflector sides into shape.

I am very grateful to the department of Near Eastern Archaeology of Leiden, for giving me the opportunity to participate in this project and even join the fieldwork for a week during May 2013. I would especially like to thank professor Peter Akkermans and Harmen Huigens for their time and effort in explaining the archaeological background to me.

Of the Geoscience and Remote Sensing department I would like to thank Hans van der Marel for his insights in GPS, professor Peter Hoogeboom for his experiences in the design of corner reflectors and Ben Gorte for always being available for questions on fast algorithms. Furthermore, I would like to thank Anneleen Oyen, Manu Delgado Blasco, Prabu Dheenatayalan, Miguel Caro Cuenca, Sami Samuel Esfahany and Ling Chang for their kind suggestions, help and patience with the processing issues I encountered. Of the Stevinlab III of Civil Engineering, I would like to thank Kees Baardoff. His practical knowledge was crucial in building the corner reflectors. Without his connections, the aluminum plates would have been a whole lot more difficult and expensive to come by.

Then, there are also my friends who have been helping with helpful suggestions, fruitful discussions, morning coffee sessions and all kinds of other forms of emotional support (including crazy random happenstance): Bart van Osnabrugge, Jelte van Oostveen, Sjors Donkers, Roeland Boeters, Peter Pietrzyk, Danbi Lee, Sina Montazeri, Robin de Vries, Marcel Kleinherenbrink and Michael Riegler.

Last, but not least, I would also like to thank my dearest sister, Cynthia Liem and my dear parents for their patience and compassion. I would not have made it without their support throughout my studies at the Delft University of Technology. It seems I inherited even more from dad's side than we initially expected, is it not?

Vera C. G. Liem
Delft, January 2014
ABSTRACT

The Black Desert in the east of Jordan has recently gained attention in the archaeological domain due to the discovery of pre-historical structures and a vast amount of rockart depictions. The Department of Near Eastern Archaeology of the University of Leiden has started investigating the cultural developments within this area from c. 1000 BC to 500 AD under the 'Jebel Qurma Archaeological Landscape Project'. The main archaeological structures of interest are known as ‘The Works of the Old Men’. These structures are clearly visible from an aerial perspective, but hard to recognize at ground level. Furthermore, they are extensive in scale as they are known to occur throughout the whole Arabian peninsula. Until now, structures have been mainly documented based on human visual inspection of aerial and spaceborne optical remote sensing. This research covers the results of a case study on the use of spaceborne optical and radar remote sensing imagery for archaeological site detection in the Near East in an automatic way. This will facilitate faster analysis of the area of interest, as well as the Arabian peninsula as a whole.

For the research, imagery from several spaceborne optical and radar imagery was acquired, most notably from the CORONA, IKONOS, ALOS and TerraSAR-X satellites. Fieldwork was performed in the region of interest as well, to place corner reflectors and perform GPS measurements of structures of interest. As the corner reflectors were captured in the last two acquisitions of the ordered TerraSAR-X imagery, they could served to improve the geo-referencing of the radar imagery.

All imagery was processed to form a co-registered, geo-referenced imagery stack for use in feature detection. Based on observations during fieldwork and the literature available, the main structures of interest were parametrized. An automated test using the GPS measurements was used to determine the suitability of layers of the imagery stack for automatic feature detection based on their normalized cross-correlation. However, the currently obtained radar imagery proved to have insufficient spatial resolution to allow for automatic feature detection. Two different kinds of detection algorithms were designed for feature detection: the Direction of Constant Gradient (DoCG) and the Laplacian of Gaussian (LoG) approach. Of these two, the LoG approach performed better in the detection of structures.

The end result provides a faster way to analyze large areas in an intuitive way. Possible archaeological sites can thus be directly identified and documented.
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>AD</td>
<td>Anno Domini</td>
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<tr>
<td>ALOS PALSAR</td>
<td>Advanced Land Observation Satellite Phased Array type L-band SAR</td>
</tr>
<tr>
<td>ASTER GDEM</td>
<td>Advanced Spaceborne Thermal Emission and Reflection Radiometer Global DEM</td>
</tr>
<tr>
<td>BC</td>
<td>Before Christ</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital Elevation Model</td>
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<tr>
<td>DGPS</td>
<td>Differential GPS</td>
</tr>
<tr>
<td>DLR</td>
<td>Deutsches Zentrum für Luft- und Raumfahrt</td>
</tr>
<tr>
<td>DoCG</td>
<td>Direction of Constant Gradient</td>
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<tr>
<td>Envisat</td>
<td>Environmental Satellite</td>
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<tr>
<td>ESA</td>
<td>European Space Agency</td>
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<tr>
<td>GCP</td>
<td>Ground Control Point</td>
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<tr>
<td>GIS</td>
<td>Geographic Information System</td>
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<td>GPS</td>
<td>Global Positioning System</td>
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<td>Laplacian of Gaussian</td>
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<tr>
<td>SAR</td>
<td>Synthetic Aperture Radar</td>
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<tr>
<td>StaMPS</td>
<td>Stanford Method for Persistent Scatterers</td>
</tr>
<tr>
<td>SRTM</td>
<td>Shuttle Radar Topography Mission</td>
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<td>TanDEM-X</td>
<td>TerraSAR-X add-on for Digital Elevation Measurement</td>
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INTRODUCTION

The use of spaceborne remote sensing imagery has become increasingly popular in archaeological reconnaissance [1–4]. Optical imagery provides archaeologists an intuitively understandable, extensive overview of large areas, while radar imagery is useful to gain more insight into the geometry of the (sub)surface and its material properties.

This master thesis presents the results of research into the archaeological application of spaceborne remote sensing imagery in Jordan’s Black Desert. Currently, the Near Eastern Archaeology department of Leiden University is investigating this area as part of the ‘Jebel Qurma Archaeological Landscape Project’. The main goal of this project is to investigate several cultural developments within the Black Desert between the time period of c. 1000 BC to 500 AD. Jordan’s Black Desert is of particular interest, as it lacks systematical investigation [5–7]. Spaceborne remote sensing imagery has the potential to implicitly help this project by offering ways to automatically detect structures of interest within the region. Additionally, it can provide information on features of the landscape, such as height and slopes.

This chapter serves as an introduction to the thesis work. First of all, the area of interest is described in Section 1.1. Section 1.2 introduces ‘The Works of the Old Men’, archaeological structures which are of particular interest in the Jebel Qurma Project. Section 1.3 lists the research objectives and questions. The thesis methodology and outline can be found in Section 1.4.

1.1. THE AREA OF INTEREST

The area of interest of the Jebel Qurma Archaeological Landscape Project spans roughly 300 km² east of the city of Amman in Jordan, near the border with Saudi Arabia (Figure 1.1). The location is strategically based at the crossroads of several ancient trade routes and covers a range of hills of which the Jebel Qurma is the most prominent one. Several riverbeds (wadis) run through the area; the Wadi Rajjil is situated on the western side, while the Wadi al-Qataffi borders the eastern side (Figure 1.2). These riverbeds stay dry for most of the year, but often contain sub-surface water and sparse vegetation [5–7]. The area covers part of the border between two characteristic geological sections of the Black Desert: the harra (basalt wasteland) and the hamad (open gravel plains).

The broken, rock-strewn landscape of the harra forms one of the largest intra-continental lava plateaus of the Arabian plate. The rocks on this plateau are dominantly alkali basalts. The ground underneath the rocks consists of a layer of silty quartz and calcite containing loess. Local loess erosion has filled depressions in the terrain, producing mudflats. Wadis in the area have cut deeply through the rocks, sometimes forming depressions which can hold moisture [5, 9]. As the plateau provided shelter, grazing and seasonal water, the region was traditionally used by sheep and goat herders [10].

The bedrock of the hamad is made out of limestone, covered by chert gravels. The chert gravel layer protects the surface from wind and sheet erosion. Wadis within the hamad do not run very deep because of the general low slope of the area and the general lack of water [9]. The open gravel plains were mainly used for camel herding in the past. They were also used for ancient ‘backdoor’ trade routes as it provided means to avoid major centers of population situated closer to fertile land [10].
Figure 1.1: The location of the area of interest in Jordan; the harra of the Black Desert itself is marked by the dark gray area. It can be seen that the area is situated at the crossroads of several ancient trade and communication routes (marked in red). These trade routes ran from the Mediterranean to Mesopotamia and Arabia. An overview of the Near East in general is shown in the bottom right corner [8].

Figure 1.2: Detailed overview of the area of interest; the research area is bordered by the riverbeds of the Wadi Rajji and the Wadi al-Qatafi. The Jebel Qurma is the most prominent hill in the range. The dark regions belong to the harra while the lighter colored plains belong to the hamad. Within the harra some light colored playa flats are visible.
The climate of the area is arid, with temperatures ranging from 45°C to -10° and precipitation less than 70 mm per year [10].

Preparatory surveying work done for the project in 2012 and 2013 has uncovered a broad range of archaeological remains in the area like circular stone dwellings, corrals, burial cairns, desert kites, rock drawings and Safaitic and Arabic inscriptions on stone [7].

1.2. The ‘Works of the Old Men’
Circular stone dwellings, burial cairns and desert kites are typical archaeological structures found in the harra. According to local Bedouin the structures are ‘The Works of the Old Men’ and considered pre-Islamic in nature. Reminiscent of the Nazca Lines of Peru, they are clearly visible from an aerial perspective, but hard to recognize at ground level. However, compared to the Nazca lines, the works are much older and far more extensive in scale. The Works of the Old Men are not limited to Jordan only, but are known to occur throughout the Arabian peninsula [10–12]. In the following sections each category of the ‘Works of the Old Men’ will be described.

1.2.1. Kites
The kites are the most extensively documented structures of the the Works of the Old Men. The name is based on the appearance of the structure; its aerial view reminded its discoverers of a kite [11]. A kite usually consists of two or more long guiding walls converging into a kite head enclosure situated on the crest of a ridge of hill (Figure 1.4). In terms of size, the walls can be several kilometers long and the enclosure spans approximately a hectare, in contrast, the walls are often not higher than 30-50 cm (Figure 1.5) [9]. The shape of the head enclosure area varies based on geographical location as well as building period (Figure 1.3). In the Jebel Qurma area, the star-shaped head enclosure type has been predominantly found. Kites are usually found as chains with their tails linking one to the next. Their orientation is often in the same direction with the funnel opening out to the south-east.

Kites are often built directly on bedrock out of boulders from the surrounding area, making them difficult to date without findings of other dated archaeological structures or artifacts in the neighborhood [13].

The common accepted use of the kites is that of hunting traps. The guide walls could be used to drive game into the enclosure. Due to local topography, animals would not see the enclosure until they were driven into it. Once enough animals were driven into the enclosure, it either would be closed off to kill or trap the animals [13, 14]. As kites are often found with signs of modification throughout their lifetime, the notion of a long period of use with varying purposes has come up recently [15].

Although many publications have covered the subject of kites, encompassing studies are still ongoing [7, 9, 12, 14].

1.2.2. Cairns
Cairns serve a burial purpose and can be categorized based on their building method. The simplest type consists of stones piled over a body. Chambered Cairns (also known as Towers or Turret Tombs) consist of dry-built stone slabs in a circular pattern with a roof covering the body. The Bulls-Eye variant also has an outer encircling stone ring wall. A Pendant consists out of a large Chambered or Bulls-Eye Cairn with a tail of smaller cairns (Figure 1.6b). The length of pendants can run up to 20-30 m [12].

Cairns are often the most visible structures of the Works of the Old Men as they are built on high locations and can be seen on skylines. Safaitic rock art is often reported in their surroundings [12].

1.2.3. Wheels
Wheels are often found in between kites and, like the kites, resemble their namesake. They consist of a central hub with radiating spokes and an encircling ring. Sometimes cairns are situated within the spokes or outside of the rim (Figure 1.7). Their sizes vary from 25-70 m in diameter. An example of a wheel formation occurring in Jordan can be seen in the right bottom corner of Figure 1.4.

Wheels themselves are actually a special case of the less-examined enclosure type, which sports a more amorphous shape and does not feature spokes. The exact function of enclosures and wheels is still unknown [12].
Figure 1.3: Different kite enclosure types including their proposed usage period as proposed by Betts and Helms [13]. Type D is the star-type.

Figure 1.4: Detailed aerial overview of a kite within the area of interest; in the right bottom corner two wheel structures are visible. The kite head enclosure itself is of the star-shaped type. Around the enclosure head modifications can be seen: the west side has been extended with smaller grouped enclosures, while the opening in the north-east has been closed of with an enclosure group.
1.3. RESEARCH OBJECTIVE AND QUESTIONS

The main research objective of the Jebel Qurma Archaeological Landscape Project is to reach a comprehensive understanding of the cultural ways of pastoral societies in life, death and literacy in Jordan’s Black Desert with a main focus on the time period of c. 1000 BC to 500 AD. This master thesis research contributes to this project as a case study in the use of radar and optical imagery to detect the archaeological structures within this area. It is assumed that within the neighborhood of these structures relevant information concerning the culture of ancient pastoral societies can be found.

The main research question within this research project is:

“How can archaeological sites in the harra be automatically detected from spaceborne optical and radar remote sensing imagery?”
This main question can be split into different sub-questions based on five categories:

- **Feature parametrization**
  What characterizes the features of interest (the ‘Works of the Old Men’) and their environment? Can these be parametrized e.g. in size, orientation, composition, etc.?

- **Data acquisition**
  Which spaceborne remote sensing imagery can be used to be able to detect the features of interest? Can sufficient imagery be obtained for analysis? Can other sources of information (e.g. topographic maps, digital elevation models) be used in the detection of objects?

- **Image enhancement**
  Does the optical or radar imagery need to be enhanced to obtain better results in the detection of objects? How can resolution be preserved despite filtering data?

- **Algorithms**
  Which algorithms can be used to detect objects? Are they generally applicable to different situations? Do optical and radar imagery need different algorithms for detecting features?

- **Validation**
  When does a detected object belong to an archaeological site? How can this be translated into a quality description? How can the archaeological site be intuitively visualized? Does mapping of the detected sites provide added value compared to the archaeological research already done within the research area?

### 1.4. **Thesis outline**

This thesis is structured as follows. First of all, the fundamentals of spaceborne remote sensing and its previous use in archaeological applications are described in Chapter 2. The following chapter, Chapter 3, focuses on the acquisition of spaceborne remote sensing imagery and the fieldwork done within the region of interest. Data pre-processing, which mainly covers the co-registration of the spaceborne remote sensing imagery, is described in Chapter 4. Chapter 5 focuses on the feature characteristics of the archaeological structures, the ground penetration capabilities of the radar data and the geometric feature detection of archaeological sites in the optical imagery. Finally, conclusions and recommendations based on the research question and its sub-questions can found in Chapter 6.

Appendix chapter A covers information on additional fieldwork done within the research project.
This chapter aims to introduce essential background overview in optical and radar spaceborne remote sensing, Section 2.1 and discusses previous related work of spaceborne remote sensing in archaeological research (Section 2.2), and describes the data selected for use within this research project (Section 3.1).

2.1. SPACEBORNE REMOTE SENSING

Within this research project, the term spaceborne remote sensing is used to describe the measurement of electromagnetic radiation from satellite sensors in order to infer Earth, atmosphere and surface properties. The electromagnetic spectrum covers the full range of electromagnetic radiation and can be categorized based on its wavelength. Different sensors cover different parts of the electromagnetic spectrum. Optical remote sensing focuses on the range from visible to near infrared light, while radar remote sensing focuses on the use of microwaves [16, 17]. In Figure 2.1, the part of the spectrum used by optical and radar remote sensing is illustrated.

Electromagnetic radiation gets either reflected, absorbed and/or transmitted when it reaches material.
The ratio of reflected, absorbed and transmitted energy varies for different materials and at different wavelengths, making it possible to distinguish different materials based on their spectral reflectance signatures [16, 19]. Next to wavelength, remote sensing systems can also be defined by its spatial resolution and its spectral or radiometric resolution. Spatial resolution is the size of the smallest object on the ground discernible by the sensor. Spectral or radiometric resolution denotes the smallest detectable change in wavelength change which can be detected by respectively optical and radar systems. The received reflections can be processed into images by imaging remote sensing systems. The difference between optical and radar imagery will be discussed in the following sections.

2.1.1. Spaceborne Optical Remote Sensing

Optical remote sensing systems used for imaging purposes are mostly passive systems, detecting the solar radiation reflected or transmitted by objects on earth. They can be classified into different types based on the number of spectral bands of the electromagnetic spectrum simultaneously measured during the imaging process [19]. In panchromatic imaging systems, one spectral band with a broad wavelength range is measured. The resulting image yields information on the apparent brightness of objects. In contrast, in multispectral imaging systems, several spectral bands are measured with a narrow wavelength range. Because of this narrower range, brightness information can be distinguished for different spectral ranges (typically different color bands). Finally, in hyperspectral imaging systems, hundreds of spectral bands are measured with very narrow wavelength ranges. These are so narrow, that information on the chemical composition of materials can be obtained. A general trade-off exists between spatial and spectral resolution. The spatial resolution of multispectral imagery can be enhanced with help of information of panchromatic imagery by employing pan-sharpening techniques to enhance spatial resolution [16].

Due to its short wavelengths, optical remote sensing is susceptible to dispersion or attenuation due to atmospheric effects, making it impossible to image regions with cloud cover [16, 19, 20].

2.1.2. Spaceborne Radar Remote Sensing

Imaging radar systems are active systems, emitting pulses of microwave energy in the direction of interest and recording the amplitude and phase information of backscatter received from objects within the system's line of sight. The two-way travel time of the pulse is used to determine the range from satellite to the detected object while backscatter intensity allows for determination of surface and roughness qualities [16, 21]. Radar imagery uses a coordinate system using azimuth and range as axes. Azimuth resolution is determined by antenna beam width, while range resolution is determined by pulse length. The geometry corresponding to radar imaging systems can be seen in Figure 2.2.

The amplitude and phase values for a single ground resolution cell are determined by the coherent summation of all the backscatter responses received from that cell. Radar pulses are transmitted coherently, which means that initially, the transmitted waves are oscillating in phase with one another. As the geometry of the satellite is slanted however, the backscatter waves from a ground resolution cell will not travel the exact same distance back to the satellite. Therefore, random interference can occur between returns, which causes speckle noise in radar images [16, 22].

The spatial resolution of radar images has improved since the introduction of Synthetic Aperture Radar (SAR), a technique which synthesizes the effect of using a long antenna beam by making use of multiple backscatter returns of the same object along the orbital track [22].

Due to their longer wavelengths, microwaves are less susceptible to atmospheric effects, making it possible for radar to penetrate cloud cover. Rain can still influence the radar signal of radar bands with wavelengths shorter than 4 cm (K- and X-band), causing attenuation or scattering of the microwaves [16, 23]. Subsurface imaging occurs when microwaves penetrate low electrical loss cover material and encounter a surface below that is sufficiently rough to generate backscatter. The penetration depth of microwaves increases with longer wavelengths, higher incidence angles and lower dielectric constant of the surface top layer [22–24]. A low dielectric constant (permittivity) of soil indicates low attenuation of electromagnetic waves, which leads to maximum ground penetration [25]. As water moisture influences the dielectric constant of soils, subsurface imaging can only succeed in arid regions [23, 24].

Independent of wavelength, microwaves can be transmitted and received in different modes of polarization. Polarization describes the geometric plane in which its electrical field is oscillating. A radar signal can be filtered in such a way that its electrical wave vibrations are restricted to a single plane perpendicular to the direction of wave propagation. Usually, radar signals are transmitted in a plane that is either parallel to the
2.2. RELATED WORK

Figure 2.2: The basic geometry corresponding to radar imaging systems [22]. The radar emits electromagnetic pulses illuminating a swath parallel to the ground track.

2.2. RELATED WORK

In this research project, the main interest lies in the automated detection of archaeological structures. Some examples of previous research projects concerning the use of spaceborne optical and radar remote sensing for the detection of structures are discussed in this section.

Spaceborne optical remote sensing imagery was successfully used in the detection of the ancient city of Ubar. The city was detected through combinations of optical data from the CORONA, SPOT and LandSat satellites [2, 27]. To visualize ancient trade routes, image enhancement techniques were used, including various band combinations, ratios of various band combinations, histogram normalization, spatial filtering and edge enhancement techniques [27].

Spaceborne radar remote sensing imagery was used in research on the temples of Angkor. Polarimetric radar imagery from the SIR-C/X-SAR and AIRSAR shuttle missions played an important role in the analysis of the ancient hydrological systems of the temples, due to the radar’s sensitivity to moisture and vegetation [1, 28]. A model was used to classify polarimetric radar observations in relation to three scattering mechanisms. This decomposition allowed differentiation between different landforms; dikes and mounds could be separated from areas prone to flooding. The volume scatter of mounds through this method was sampled and compared to other ancient tropical sites, which proved to offer more insight into the nature of the mounds [29].
In [30], LandSat imagery was used to estimate the likelihood of archaeological sites based on environmental parameters. This was done through a logistic regression model. Environmental parameters used for this model included: distance to closest minor stream, distance to major stream or river, distance to openland rated (well-drained) soil, local gradient, convexity of the landscape and distance to present marshes.

A way to automatically obtain more information on the geophysical information of subsurface targets was offered in [25], in which a subsurface structure within the desert of Egypt was investigated. In this work, optical and radar imagery were combined through Principal Component spectral sharpening, a method normally used for pan-sharpening images. This hybrid image was then classified to obtain information on the surface sediments covering the hidden target. As nothing was known about the surface types beforehand, unsupervised classification was used. The classification result contained information on surface composition and texture.
In Chapter 1, the characteristics of the ‘Works of the Old Men’ were described. In Chapter 2, this explanation was followed by the fundamentals of spaceborne optical and radar remote sensing and their previous use in the field of archaeology. In this chapter, the data acquisition of the project is described. The data acquisition consists of the acquisition of spaceborne optical and radar remote sensing imagery (Section 3.1), as well as the fieldwork measurements performed to improve the and provide additional ground truth as well as the fieldwork done in the region of interest to supply for missing information (Section 3.2).

3.1. IMAGERY ACQUISITION

The spaceborne remote sensing imagery available for this project is described in Tables 3.1 and 3.2. Considering the application of the project, imagery with high spatial resolution is desired based on the dimensions of the archaeological structures of interest.

Table 3.1: Overview of spaceborne optical remote sensing imagery available for the project. MS = Multi Spectral, NIR = Near Infrared, Pan-S = Pan-Sharpned, Pan = Panchromatic. The spatial resolution can differ per band of the same image. In the case of the CORONA imagery, two images were needed to cover the whole research area.

<table>
<thead>
<tr>
<th>satellite</th>
<th>type</th>
<th>nr. of bands</th>
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<th>quantity</th>
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<td>2</td>
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<td>IKONOS</td>
<td>MS</td>
<td>4</td>
<td>0.8 (Pan-S), 3.2 (NIR)</td>
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<tr>
<td>Landsat</td>
<td>MS</td>
<td>8</td>
<td>15 (Pan), 30 (MS)</td>
<td>1</td>
</tr>
</tbody>
</table>

All the optical imagery was provided pre-processed state by the University of Leiden prior to the start of this research project. Of this imagery it should be noted that the IKONOS image was pre-processed by the Shell B.V./Jordan oil surface shale company.

Due to their higher spatial resolution, the CORONA and IKONOS imagery had already been used in the visual detection of archaeological sites by the archaeologists representing therefore the reference imagery usable for automated feature detection. In the case of Landsat data, the resolution was deemed too coarse to be directly of use in feature detection. The 8 different bands could be used for terrain classification, but considering the geometry of the structures of interest as well as the fact that they are built out of surrounding...
rocks, it was decided not to process the data.

The TerraSAR-X imagery was specifically ordered for this research project to obtain radar imagery of high resolution. This opportunity yielded the possibility to place corner reflectors in the field between the different acquisitions (Section 3.2.2). The TerraSAR-X StripMap product (3 m spatial resolution) was chosen instead of the higher resolution SpotLight mode, as the swath of the latter one would be insufficient to cover the whole research area. Due to the budget constraints of the project the request consisted of two interferometric single polarimetric pairs under different incidence angles. The decision of single polarimetric images was based on the geometry of the features of interest: using dual polarimetric images acquired by the TerraSAR-X satellite would degrade the spatial resolution by half. Even though the resolution of the Envisat and ALOS imagery was coarse, they could still be useful in the project. The quantity of the Envisat imagery makes it possible to improve the radiometric resolution of the images without influencing spatial resolution, by combining them into a single Multi-Reflectivity Map. ALOS imagery is mainly of interest due to its long wavelength and therefore possible ground penetration capabilities. If kite walls would have sufficient roughness to generate significant backscatter in a ground resolution cell, they could be visible in a low resolution radar image due to the coherent addition of the signals upon return.

The spatial distribution of all the spaceborne remote sensing imagery selected for use in the project can be seen in Figure 3.1.

Next to optical and radar imagery, several other sources of information are available. These include a scanned topographic map of the area, DEMs of the area of 90 m resolution (SRTM) and 30 m resolution (ASTER GDEM) and information on the locations of sites found in IKONOS and CORONA data based on visual inspection.

Figure 3.1: Spatial distribution of the spaceborne remote sensing imagery selected for use within the research project. The two optical images of the CORONA are shown in their merged state. The area of archaeological interest is indicated by the border of red line dashes.
3.2. FIELDWORK

Fieldwork for the project was carried out between the period of 12-19 May 2013. The main goals for the fieldwork were to aid the co-registration and georeferencing of all the satellite imagery by measuring Ground Control Points (GCPs) within the area of interest as well as obtaining more detailed information on the shape, orientation and location of kites as additional ground truth. As the date of the acquisitions of TerraSAR-X could be planned in advance, it gave the possibility for placement of corner reflectors in the field.

These goals were met by the following actions:

- Placing corner reflectors in the field to serve as GCPs in the TerraSAR-X acquisitions of May and June;
- Obtaining static GPS measurements of these GCP locations;
- Obtaining kinematic GPS measurements in the field by following the shape of the kites.

Additionally, photographs taken with a digital camera with hybrid-GPS functionality served as reference to interesting locations found during the fieldwork. While not in the main scope of this research project, close range photogrammetry was performed to obtain more information on the profile of structures. As the findings can be useful to the application domain of archaeology, the results of these measurements are presented in Appendix A.1.

This section will cover the GPS measurement results in Section 3.2.1 and the specifics of the corner reflectors (design and placement procedure) in Section 3.2.2.

3.2.1. GPS MEASUREMENTS

Two Trimble R7 GPS dual frequency receivers were used for measuring the locations of corner reflectors and kite walls, both programmed to measure GPS coordinates at a 1 Hz interval. One receiver served as the base station in the base camp (Figure 3.2), while the other one served as rover in the field (Figure 3.3). The Differential GPS (DGPS) measurements made in this way, can measure locations up to cm accuracy [31, 32].

Figure 3.2: The base station construction; the GPS receiver (situated below the window) was plugged into a socket to ensure continuous measurements, the GPS antenna (situated in the right upper-corner) was situated above roof height to limit multipath noise from nearby metal bunkers. The GPS antenna height is 3.3 m above ground level.

The base station coordinates were determined with help of PPP (Precise Point Positioning) processing. For PPP to obtain accuracy in cm range, an initialization period of at least 12 hours was needed [31]. Rover positions were obtained by post-processing the rover measurements with help of either differential static (corner measurements) or differential kinematic (kite walls) processing. The initialization period for rover measurements is less (in the order of several minutes) as they are calculated with help of the base station measurements. The rover had to stay within 20 km range of the base station to provide accurate results.

The general processing chain of the GPS measurements is illustrated in Figure 3.5. The raw data of the measurement logfiles of the GPS receivers are first adjusted for antenna height and converted to RINEX format. The PPP processing of the base station measurements is done through the online PPP service of National Resources Canada (NRCan) [33]. PPS (Post-Processed Static) and PPK (Post-Processed Kinematic) calculations for the rover measurements was performed by the RTKPOST program of the RTKLIB open source software package [34]. The resulting position files were filtered based on satellite visibility and converted to
3. DATA ACQUISITION

Figure 3.3: The DGPS rover measurements in the field. Kinematic measurements were used to obtain the location and shape of the kite-walls, while static measurements were used to obtain the location of the corner reflectors.

Figure 3.4: The GPS processing results superimposed over Google Earth SPOT imagery: the corner reflector placed in the field is indicated by the red dot, kite QUR-21 by the blue dots and kite QUR-26 by the purple dots. One of the kite tails of kite QUR-26 suffered from bad satellite visibility, hence the low density of valid points.

ESRI shapefile in MATLAB for use in general GIS software. In all cases, the accuracy of the measurements was reported by the software to be on sub-decimeter level.

The processed GPS measurements were given in the International Terrestrial Reference Frame 2008 (ITRF2008), which is slightly different from the desired WGS84 reference system. While both systems share the same definition, the practical realization of the coordinate systems is based on a different set of station coordinates. The WGS coordinate system has been kept consistent to ITRF realizations, however, which means that the differences between them are in centimeter range worldwide [35]. For the mapping purpose of this project the difference between the two is considered negligible, and as such, no correction will be applied. The final results superimposed over Google Earth imagery can be seen in Figure 3.4. Although the general position of the kites seems to be correct, closer inspection of the GPS measurements in IKONOS and CORONA imagery shows significant offsets still remain (Figure 3.6). How the problem of these offsets were solved is described for in Section 4.1.
3.2. FIELDWORK

3.2.2. THE CORNER REFLECTORS

Corner reflectors are generally used in radar remote sensing for radar calibration and performance verification. As corner reflectors are designed to provide a known RCS (Radar Cross-Section) response significantly larger than background clutter, they can be detected within a radar image [36, 37]. Within this research, two triangular trihedral corner reflectors have been placed within the area of interest, to serve as GCP in the last two acquisitions of TerraSAR-X SAR images. The purpose of these GCPs was to aid the co-registration and the georeferencing of all the radar imagery.

CORNER REFLECTOR DESIGN

Several practical considerations had to be taken into account considering the construction of the corner reflectors. Due to the period of fieldwork, the reflectors had to stay a month out in the field without significant displacement or deformation occurring to the construction. Accumulation of sand in the reflector due to frequent sandstorms in the area also had to be taken into account.

Trihedral reflectors are less sensitive to alignment compared to other reflector types [37]. As design and construction time was limited to a month, a simple triangular pane variant was chosen due to its robustness.
and angular coverage (Figure 3.8). The formula to calculate the maximum RCS ($\sigma_{\text{max}} [m^2]$) of a triangular trihedral corner reflector is

$$\sigma_{\text{max}} = \frac{4\pi L^4}{3\lambda^2}, \tag{3.1}$$

where $L [m]$ is the length of the reflector axis and $\lambda [m]$ the radar wavelength [38].

Figure 3.7: Maximum RCS ($\sigma$) formulas for different corner reflector types, where $L$ is the axis length, $r$ is radius, $w$ is width, $h$ is height and $\lambda$ is wavelength of the radar signal [39].

Figure 3.8: Angular coverage of a trihedral corner reflector with triangular panels [36]. As coordinate system a global coordinate system is used, depicted on the left side. The graph on the right shows the effect of displacement in incidence angle ($\theta'$) and azimuth angle ($\phi'$) on the RCS of the corner reflector (see also Figure 3.11).

If the desired RCS is known, the minimum length of the reflector panes can be deduced from equation (3.1). Considering the accuracy of equipment available for construction, some loss in RCS was expected in practice, due to imperfections in the straightness of the reflector panes and internal corner reflector angles.
From the TerraSAR-X acquisitions of February and March it was deduced that sand covered areas had an average RCS value of 0 dB m$^2$, while TerraSAR-X areas covered with basalt rocks had a normalized RCS average of 5 dB m$^2$. In general practice, corner reflectors are often build to differ 20 dB with the expected background clutter of the area. Considering equation (3.1), for a maximum RCS ($\sigma_{max}$) of 25 dB and wavelength ($\lambda$) of the TerraSAR-X satellite of 31 mm, a reflector axis length of at least 52 cm is needed for the corner reflector. The final design of the corner reflector panes can be seen in Figure 3.9.

![Corner reflector design](image)

**Figure 3.9:** Basic design of the corner reflector; the corner is made out of 3 aluminum side triangular panes of which a separate front and side view can be seen on the left. The final design can be seen on the right.

The triangular panes of the corner reflector were created from aluminum sheets of 3 mm thickness. The panes were connected with shrews of 5 mm diameter. Sunken shrews were used to lessen surface imperfections which could influence the RCS response. A small hole is drilled at the intersection of panes to mitigate the sand accumulation within the corner reflector. To keep the design simple, the supporting construction consisted of three angle irons of 1.6 m long which could be adjusted to the corner with help of the shrews on the side panes (see also Figure 3.12b and Figure 3.12d).

**Corner reflector placement**

The locations of the corner reflectors needed to be easily accessible by the archaeologists to check the status of the reflectors before the time of acquisition, as well as remove them after all acquisitions had taken place. One corner reflector was therefore placed near the base camp, the other one at the entrance of the archaeological survey area. Care was taken to place the corner reflectors in relatively flat areas with little roughness.

![Corner reflector locations](image)

**Figure 3.10:** Corner reflector locations within the research area. The distance between the two is approximately 9 km as the crow flies.
The heading of the satellite at the acquisition dates is important to the positioning of the corner reflectors. In Figure 3.8 an overview of the effect of errors in placement to the RCS could already be seen. For TerraSAR-X acquisitions, incidence and azimuth angles for corner reflector placement can be determined through the online DLR SAR calibration service [40] (Figure 3.11). Normally, however, the calculation of the heading would require the determination of the satellite position in orbit [41], as well as the location of corner reflector on the ground.

The entire placement procedure of the corner reflector is illustrated step-by-step in Figure 3.12. Magnetic declination had to be taken into account as a magnetic compass was used to determine the azimuth angle of the corner reflector. In the case of the location of the Jebel Qurma range, there was a magnetic declination of 4.3° to the east. The elevation angle was determined by using a level in combination with a piece of cardboard cut to the size of the elevation angle.

Both corner reflectors were supposed to be protected by plastic against the elements. However, in the field it became apparent that the plastic cover attracted unwanted condensation on its inner side. The plastic veil was kept in the field, but at the base camp a slightly different construction was made. To ensure the elevation and azimuth angle, a base of rocks was made to support the corner reflector.
Figure 3.12: Placement procedure of the corner reflector in the field, this corner reflector was covered by plastic for protection against the elements. The steps were: a) measure and mark the correct azimuth direction; b) create space for the central iron angle; c) align corner with the correct azimuth angle; d) align the corner with the correct elevation angle; e) cover angle irons for better support; f) cover sharp corners to avoid tearing of the plastic cover; g) install simple mechanism to be able to check for displacements; h) cover the corner reflector; i) cover part of the plastic sail for protection.
The overall data preparation of the spaceborne optical and radar imagery is described in this chapter. The main goal of this preparation is to have all optical and radar imagery within the same coordinate reference frame with the same positional accuracy. It is therefore necessary to align both the optical and the radar imagery to the GPS measurements, which have been measured in the WGS84 coordinate reference system.

Section 4.1 describes the alignment of the optical imagery with the GPS measurements. Section 4.2 describes the pre-processing as well as the alignment with GPS measurements of the radar images.

4.1. ALIGNMENT OF OPTICAL IMAGERY

As described in Section 3.1, the optical images were pre-processed prior to the start of this research project. However, between the processed GPS measurements and the optical imagery, clear offsets were seen in Section 3.2.1 (Figure 3.6). It is assumed that the offset between each optical image and the GPS measurements is a rigid shift.

To find the offsets, a template matching technique was developed applying normalized cross-correlation to find parts of the GPS measured kites in optical imagery. The total processing chain for finding these offsets is illustrated in Figure 4.1. The template matching technique is discussed in Section 4.1.1, the template creation process necessary to perform the template matching in Section 4.1.2, image enhancement techniques to improve the matching technique in Section 4.1.3 and finally, the alignment results, in Section 4.1.3.

![Processing chain of the optical imagery alignment process. Grey boxes denote Matlab processing, green ones processing done in Quantum GIS.](image-url)
4.1. Template matching
Template matching is a technique used to determine the position of a pattern within an image. It works by shifting a template of the pattern over an image and calculating the correspondences between the template and image over each pixel position. The location of the pixel with the best correspondence resembles the center position of the template within the image.

Different methods of calculating correspondences exist; in this case normalized cross-correlation is used. This method is not affected by differences in brightness or contrast in an image [43, 44]. A definition of the normalized cross correlation $\gamma$ for an image $f$ of size $M_x \times M_y$, template $t$ of size $N_x \times N_y$ and shift $(u, v)$ can be defined as [44]:

$$
\gamma(u, v) = \frac{\sum_{x,y}(f(x,y) - \bar{f}_{u,v})(t(x-u, y-v) - \bar{t})}{\sqrt{\sum_{x,y}(f(x,y) - \bar{f}_{u,v})^2 \sum_{x,y}(t(x-u, y-v) - \bar{t})^2}},
$$

(4.1)

in which $f(x,y)$ is the intensity of the image at pixel position $(x,y)$, $\bar{f}_{u,v}$ the average intensity of the image area covered by the template at shift $(u,v)$ and $\bar{t}$ the average template intensity value. The best correspondence between image and template will have the highest $\gamma$ value.

4.1.2. Template creation
The GPS point measurements needed to be converted to lines to serve as suitable templates for the template matching process. As can be seen in the processing chain (Figure 4.1), the GPS measurement points of each kite were connected to each other by buffering the GPS points. The GPS points were buffered with a radius of 1 m to ensure they occupied at least one pixel. To be able to compare these lines with the optical images, the vector format of the buffered lines was converted to raster format and skeletonized to obtain the core line parts. As a kite can consist of several disconnected kite walls, 8-connected component labeling is used to identify the separate kite walls.

These separated kite walls could already be used as templates for the template matching process. To get a better feel about the accuracy of the results however, it is better to partition the walls into smaller line pieces to obtain more templates for the matching process. To achieve this, a dedicated algorithm was developed.

A separate kite wall can be divided into template line pieces if:

- it has one start and end point;
- following the start to the end point requires passing all the pixels of the kite wall once.

This means a pixel can only have up to two neighbors, as otherwise ambiguity would occur in following the line. Pixels of the separate kite walls are therefore filtered based on their number of 8-connected neighbors to obtain lines of which start and end points are known (see Algorithm 1). These lines can then be partitioned in template lines based on their number of pixels. In this case a threshold for maximum (50 pixels) and a minimum number of pixels (7 pixels) per acceptable template was set. For the GPS measurements from the kites, this partitioning resulted in 4718 templates for the IKONOS image and 1691 templates for the CORONA image.

4.1.3. Image enhancement
To improve the performance of the template matching algorithm, edge enhancement was performed on the optical imagery. In the case of the IKONOS image, the RGB bands were converted to grayscale before the matching process. The Laplacian of Gaussian (LoG) filter was used for image enhancement: an isotropic filter of which the filtering result is the 2nd spatial derivative of an image after it has been Gaussian smoothed. The analytical function of this filter can be defined as [43]:

$$
\text{LoG}(x,y) = -\frac{1}{\pi \sigma^4} \left[1 - \frac{x^2 + y^2}{2\sigma^2}\right] e^{\frac{x^2 + y^2}{2\sigma^2}}
$$

(4.2)

in which $x$ and $y$ represent the pixel coordinates of the filter centered around zero and $\sigma$ represents the Gaussian standard deviation.

The filter was effective in highlighting regions of rapid intensity change, while being less sensitive to noise due to the Gaussian smoothing. The cross-section of the filter resembles the optical intensity profile of a
Algorithm 1 Pseudocode of part of the kite wall filtering to obtain suitable templates for matching. The algorithm keeps track of the neighbors of every point and categorizes or removes points based on their number of neighbors. Input is a list of coordinates of points with the same connected component label (labeled `point` for simplicity here). Output is a look-up table containing the locations of all neighbors for each pixel location (`pointinfo`).

```plaintext
while anomallist not empty do
    empty anomallist
    empty endlist
    for each point do
        find 8-connected neighbors of point
        store point with neighbors in pointinfo
        if point has more than 2 neighbors then
            store point in anomallist
        else
            if point has 1 neighbor or less then
                store point in endlist
            end if
        end if
    end for
    if anomallist not empty then
        remove points in anomallist and endlist from pointinfo
    end if
end while
```

cross-section of a kite wall, therefore enhancing the kite wall values compared to their background (see Figures 4.2 and 4.3).

Figure 4.2: Shape of the Laplacian of Gaussian filter used for filtering the IKONOS and the optical imagery.

Figure 4.3: Example of 1D Laplacian of Gaussian filtering. The profile on the left resembles a typical cross-section of a kite wall, which location is marked by the red line. The right image shows the result after filtering with the Laplacian of Gaussian filter.
ALIGNMENT RESULTS

For each template, an area from the enhanced optical image is taken centered around the template location of which the normalized cross-correlation is computed (Figures 4.4 and 4.5).

Figure 4.4: Example of template matching for the IKONOS image. The location of the center of the template according to the maximum normalized cross-correlation is indicated by a red asterisk.

Figure 4.5: Example of template matching for the CORONA image. The location of the center of the template according to the maximum normalized cross-correlation is indicated by a red asterisk. Due to the lower image resolution and the lower contrast between kite walls and background, the LoG filter is less effective in highlighting the kite walls in the images. In the case on the right, the template fits better over a local hillside border because of its higher contrast.

The offset with the highest frequency of occurrence is deemed to be the constant offset between the optical imagery and the GPS measurements. Results for both the IKONOS as the CORONA image are visualized in Figure 4.6.

The offsets found from Figure 4.6 correspond to the offsets estimated in Figure 3.6, which show the GPS measurements before alignment. Figure 4.7 shows the end result of the optical alignment process. In both cases the offset has reduced significantly.

4.2. RADAR REMOTE SENSING

The goal of the pre-processing of the radar images is to create a co-registered radar imagery stack which can be used directly for feature detection. To this end, the radar images need to be transformed from their radar coordinate system to the WGS84 coordinate system used by the GPS measurements. Since the corner reflectors placed during fieldwork were present in the field during the last TerraSAR-X acquisitions of May
4.2. RADAR REMOTE SENSING

Figure 4.6: Frequency of offsets found between template and optical image. The offset with the highest frequency is deemed to be the offset between the image and the GPS measurements. Due to the spatial resolution of the images, the number of templates partitioned in the IKONOS and CORONA imagery is different. The offset in the case of IKONOS is (4, -9) pixels, the offset for CORONA (-19, 32) pixels in respectively latitude- and longitude-direction.

Figure 4.7: Results of IKONOS (left) and Corona imagery (right) after adjustment of their extent. The offsets have considerably lessened compared to the offsets seen in Figure 3.6, especially in the IKONOS case.

and June, their GPS measurements can serve to further refine the alignment between the radar imagery stack and the GPS measurements.

The methodology to co-register all the radar imagery data is described in Section 4.2.1, the processing of the corner reflector results in Section 4.2.2.

4.2.1. CO-REGISTERING THE RADAR IMAGERY

To create the radar imagery stack, standard pre-processing consisting of co-registration and orthorectification operations needs to be performed. In the case of the TerraSAR-X and ALOS imagery, this is handled by the NEST toolbox (Next ESA SAR Toolbox) of ESA [45, 46]. The processing of these radar images is illustrated in Figure 4.8.

In the case of the TerraSAR-X imagery, acquisitions from the same satellite orbit are first automatically co-registered, after which the Terrain-Doppler correction function was applied for calibration, orthorectification and georeferencing of the data [46].

The ALOS imagery required a slightly different pre-processing approach. As the annotated times in ALOS L1.1 level imagery were not in the zero Doppler notation, it needed a deskewing operation for correction. The ALOS imagery was oversampled to the TerraSAR-X resolution with help of bisinc interpolation.
Additional co-registration was needed, as the standard NEST routines did not provide sufficient results. The TerraSAR-X acquisition of May 2013 was treated as the master acquisition to which all other imagery needed to be aligned. The alignment was done by treating the radar images as different color bands in a color composite and visually adjusting the extent of these separate bands until they were co-registered correctly (Figure 4.9).

In the case of the Envisat imagery, co-registration was handled by the Stanford Method for Persistent Scatterers (StaMPS) software ([47]), which can automate the bulk processing of SAR images. Unfortunately, the magnitude of the offsets between the images obtained from the co-registration of the 38 images appeared unrealistically large considering the usual values. The reason for this could not be investigated within the time frame of this research project, making it impossible to create a Multi-Reflectivity Map for feature detection.
4.2.2. PROCESSING THE CORNER REFLECTOR RESULTS

The GPS measurements of the corner reflector locations were used to enhance the geo-referencing of the radar imagery stack. In order to estimate the shifts between the TerraSAR-X image coordinates and the GPS measurements on sub-meter level, the TerraSAR-X acquisitions containing the corner reflectors needed to be oversampled. As with the previous co-registration, the NEST toolbox was used for the oversampling operation.

The oversampling was applied in the radar coordinate system to the real and imaginary components of the image by zero-padding in the frequency domain, thus preserving the spectral properties of the imagery. The DEM used for the geo-referencing of the datasets was the 90 m SRTM DEM. The resampling of the DEM as well as that of the radar image during the orthorectification step was performed with bilinear interpolation.

The accuracy of the georeferenced TerraSAR-X imagery can be determined by two error components: the error in the estimation of the corner reflector position in the SAR image, \( e_{\text{SAR}} \), and the accuracy in the GPS measurements, \( e_{\text{GPS}} \). These can be described by the relationships:

\[
e_{\text{SAR}} = \hat{x}_{\text{SAR}} - x_{\text{SAR}} \quad (4.3)
\]

\[
e_{\text{GPS}} = \hat{x}_{\text{GPS}} - x \quad (4.4)
\]

where \( x \) refers to the true corner location, \( x_{\text{SAR}} \) is the exact phase center of the corner reflector in the SAR image and \( \hat{x}_{\text{GPS}} \) and \( \hat{x}_{\text{SAR}} \) are the estimated coordinates respectively from the GPS measurements and SAR image. By registering the SAR image upon the GPS reference, i.e. by accounting for the rigid coordinate shift \( x_{\text{SAR}} \to x_{\text{SAR}} + (\hat{x}_{\text{GPS}} - \hat{x}_{\text{SAR}}) \) (4.5)

\[
x - x_{\text{SAR}} = e_{\text{GPS}} + e_{\text{SAR}}. \quad (4.6)
\]

which can be assumed constant around the corner location if the area is flat. Note that the equations (4.3-4.6) can refer either to latitude or longitude as they can be applied to both components.

The accuracy of the SAR estimates can be modeled for the observed amplitude response \( g \) of the CR along the generic spatial coordinate \( x \) as

\[
g(x) = \left| \text{sinc}(Bx) \ast \left[ \sqrt{\sigma_{\text{CR}}} \delta(x - x_{\text{SAR}}) + \sqrt{\sigma_{\text{CL}}/2} n(x) \right] \right| \quad (4.7)
\]

with \( n(x) = n_R(x) + n_I(x) \), \( n_R, n_I \sim \mathcal{N}(0, 1) \), \( E[n_Rn_I] = 0 \),

where \( \ast \) stands for the convolution operator, \( B = 1/\rho_x \) is the sensor bandwidth, of which \( \rho_x \) is the reciprocal of the spatial resolution, \( \delta \) is the Dirac impulse pointing to the true corner reflector phase center location \( x_{\text{SAR}} \). \( n \) is a series of independent and identically distributed complex random variables. The real and imaginary components of \( n, n_R \) and \( n_I \), are both distributed according to \( \mathcal{N}(0, 1) \), the normal distribution with zero mean and unit variance. \( E \) denotes the expectation operator. \( \sigma_{\text{CR}} \) and \( \sigma_{\text{CL}} \) are the RCS of the corner reflector and of the background clutter respectively.

If the Signal to Clutter Ratio (SCR) is high enough, the observations \( g(x) \), can be reasonably approximated with \( \tilde{g} = \sqrt{\sigma_{\text{CR}}} \text{sinc}(B(x - x_{\text{SAR}})) + \sqrt{\sigma_{\text{CL}}/2} n_R(x) \). This simplifies the calculation of the Cramer-Rao Bound (CRB) on \( x_{\text{SAR}} \), which is derived [48] as

\[
\text{CRB}_{x_{\text{SAR}}} = \frac{3 \cdot \text{SCR}^{-1}}{2\pi^2 B^2} \quad (4.8)
\]

and represents the lowest variance achievable by an unbiased estimator in absence of additional a priori information. It can be noticed that the accuracy is related to the corner reflector through the SCR as well as to the sensor resolution \( 1/B \). The estimation method employed within this work consists of detecting the coordinates of the impulse response peak, which can be formulated as

\[
\hat{x}_{\text{SAR}} = \text{argmax}_x \{ g(x) \}. \quad (4.9)
\]
The representation in Figure 4.10 shows how the presence of the clutter and a finite bandwidth affect the position of the signal peak. It should be noted that in practice, axis $x$ is sampled. The accuracy of equation (4.9) is therefore dependent on the SCR, but also on the oversampling factor adopted. The error standard deviation of equation (4.9) has been assessed through Monte Carlo simulations for different SCR and oversampling configurations and has been compared with the lower bound provided by (4.8). The results, shown in Figure 4.11, convey that for the TerraSAR-X Stripmap resolution of 3 m (in both the projected latitude and longitude components) an SCR of 20 dB is enough to achieve an accuracy in location determination of 0.2 m. In practice, such an accuracy is more than sufficient for the intended use for archaeological site detection.

Figure 4.10: Simulated impulse response function (IRF) of a 25 dB RCS reflector superimposed to a 10 dB background clutter. In the right panel the central part of the IRF has been enlarged to highlight the effect of the noise on the shift of the peak position.

Figure 4.11: Accuracy of the corner reflector peak estimation for the 3 m ground resolution TerraSAR-X Stripmap images. The standard deviation has been evaluated as a function of the corner SCR for two different resampling configurations: with an oversampling factor of 12, corresponding to 0.25 m spacing (dotted line) and with an oversampling factor of 100, thus yielding a 0.03 m spacing (dashed line). The lower bound provided by the CRB is also reported (solid line).

The corner reflectors in the TerraSAR-X acquisitions of the 22nd of May are shown in Figure 4.12. The difference between the locations of the detected corner reflectors in the oversampled TerraSAR-X imagery and the GPS measurements of the corner reflectors can be found in Table 4.2.

Table 4.1: The GPS measurement results for the corner and base camp reflector.

<table>
<thead>
<tr>
<th>Field reflector</th>
<th>St. Dev.</th>
<th>Base camp reflector</th>
<th>St.Dev</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lat [°] Lon [°]</td>
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<td>Lat [°] Lon [°]</td>
<td>y[m] x[m]</td>
</tr>
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<td>31.7637912</td>
<td>37.1865655</td>
<td>&lt;0.01 &lt;0.01</td>
<td>31.7169400</td>
</tr>
</tbody>
</table>
Figure 4.12: The areas around the corner reflectors in the TerraSAR-X Stripmap acquisition of the 22nd of May used to estimate the corner reflector locations. The detected location of the corner reflectors is indicated by the red squares. The TerraSAR-X imagery is oversampled to a resolution of 0.25 m.
Table 4.2: The locations of the corner reflectors in the processed TerraSAR-X images and their offsets with the GPS measurements. The TerraSAR-X image was oversampled to a resolution of 0.25 m.

<table>
<thead>
<tr>
<th>Acquisition date</th>
<th>Field reflector</th>
<th>Offset</th>
<th>Base camp reflector</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lat[°] Lon[°]</td>
<td>y[m]</td>
<td>x[m]</td>
<td>Lat[°] Lon[°]</td>
</tr>
<tr>
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<td>-1.89 9.62</td>
<td>31.7169496 37.1105099</td>
<td>-1.06 7.73</td>
</tr>
</tbody>
</table>

Considering the results from Table 4.2, there is an offset between the geo-referenced TerraSAR-X corner reflector locations and the GPS measurements. Considering the orbital track of the satellite, this can be translated into an offset of 8 to 10 m in range direction. Radar azimuth and range coordinates are based on the time of the closest approach of sensor and target as well as the signal travel time.

The atmosphere can delay this signal, due to electrons in the Ionosphere and dry air and water vapor in the Troposphere. In the case of Ionospheric delay, the delays usually cause offsets around mm level and can be considered negligible in this case. However, Tropospheric delays can cause a shift in range direction of 2.5 to 4 meters [49]. According to the archaeologists, there was very light cloud cover on the 22nd of May, while the weather on the 2nd of June was clear. Indeed, for the 22nd of May the offsets are slightly larger than on the 2nd of June. Deformation of the solid Earth due to gravitational forces of Sun and Moon can also cause differences in location up to dm level over the course of a day [49].

However, the atmospheric effects and Earth-tide phenomena are not sufficient to explain the large range offset encountered. Another possible explanation of the significant range offset could be a constant height offset (bias) between the SRTM DEM used by NEST for the geo-referencing of the radar imagery and the actual height in the field, as is illustrated in Figure 4.13. Theoretically, for the bias to cause a range offset of 8 m, the height difference in the case of an incidence angle of 30° should be around 14 m. The biggest height difference found between the SRTM DEM and the GPS measurements on the corner reflector locations was however 3 m.

![Figure 4.13: Illustration of range offset in corner location due to a constant height difference between the SRTM DEM and the GPS measurement.](image)

As the primary objective of the preprocessing steps was to co-register all the data sources with respect to the GPS measurements, rather than determining the absolute location of the corner reflectors, the offsets with the GPS measurements will not undergo further analysis. To enhance the alignment of the radar image stack to the GPS measurements, the extents of the image stack were adjusted based on the average offsets between the geo-referenced corner reflector locations and the GPS corner reflector measurements.
As described in Chapter 1, the archaeological structures of interest within the area of interest are ‘The Works of the Old Men’. This chapter gives an overview of the feature characteristics of these archaeological structures of interest (Section 5.1), the investigation concerning potential ground penetration in the radar imagery (Section 5.2) and the geometrical feature detection methodology used to detect the archaeological structures (Section 5.3).

5.1. Feature Characteristics

Of the ‘Works of the Old Men’, the kite structures are the most thoroughly documented ones. Comparing the shape and length of kites, cairns and enclosures, kite walls would have the highest possibility of detection due to their similarity to line features. Considering the time scope of this project, the feature detection will be mainly focused on detecting kite walls.

Based on the information from the previous chapters as well as practical field observations, several characteristics of the kite could be deduced, which influence the detection of kites:

- As was stated in Section 1.2, kites are built out of the basalt rock of the surrounding area. Terrain classification will therefore not be capable of distinguishing between kite-walls and the surrounding rocks.
- The dimensions of the kite structures have been documented in literature (Section 1.2), and were measured in the field during fieldwork (Section 3.2.1). The dimensions of standard kite-walls were determined to be: height ≈ 0.5 m, width ≈ 0.5-1.0 m and a length of up to 5 km. Especially considering the width of the kite structures, high-resolution optical imagery is needed to be able to distinguish the shapes.
- Considering their shape in optical spaceborne sensing imagery and aerial photographs, kites are determined to be funnel-shaped: a kite consists at least of two outer walls which converge towards a head enclosure. Inner kite walls can occur, which are not connected to the general structure, but also lead towards the head enclosure. Based on the fact that walls can be disconnected, it is better to detect kite walls separately from the head enclosures.
- Based on the GPS measurements (Section 3.2.1), the maximum curvature (κ = 1/R, where R is the radius a circle) of the kite walls was determined to be 0.01. Considering the curvature found, it seems that it should be possible to find kite walls through line approximations, as circles can be approximated by tangent lines as well.
- Topography often features in the description of kite structures in literature. As the kite structures were meant as hunting traps, the animals would not see the enclosure until it was too late (Section 1.2). The GPS measurements were partitioned and analyzed based on the heights of the available DEMs (Figure 5.1). In general, the kite walls seem to follow a downward motion towards the head enclosure, which is situated much steeper below. Based on this knowledge, the direction of kite walls can be
5. Feature detection

(a) ASTER GDEM

(b) SRTM

Figure 5.1: An overview of the GPS-measured kites and their respective heights according to the ASTER GDEM (30 m) and SRTM (90 m) digital elevation models. The kite wall line pieces were obtained using the ‘component filtering based on the number of neighboring pixels’ described in Section 4.1. In both cases the head enclosures are situated at the lowest point. The SRTM is more effective in showing the general trend.

5.2. Investigating of potential radar ground penetration

One of the reasons why radar imagery is interesting for archaeological applications, are its ground penetration capabilities (Section 2.1.2). To see whether subsurface features would be possible to detect, the available imagery should first be analyzed. A total of 13 regions were selected which were suspected to contain subsurface features: 4 regions had been indicated by the archaeologists, the remaining 9 were regions where kite walls crossed the local mudflats (Figure 5.2). The latter regions were found during the fieldwork, as it was observed that kite walls were either partially buried or absent on the mudflats themselves while they did continue clearly from the banks of the mudflats (Figure 5.3). An overview of one of the regions of interest can be seen in Figure 5.5.

Subsurface imaging requires surface cover material to be extremely dry. Next to that, subsurface imaging can only occur if the radar wave encounters a surface underground which is rough enough to generate radar
5.2. **INVESTIGATING OF POTENTIAL RADAR GROUND PENETRATION**

Precise surface conditions in the region of interest are unknown, as no fieldwork was done on the soil properties within the area.

**Figure 5.3:** Example of a kite wall ‘ending’ on a mudflat. The kite wall can be seen running from the basalt rock formation in the middle of the horizon till the border of the mudflat. The trace of partial buried basalt rocks in the middle and at the bottom of the image seem to suggest that the kite wall continues straight on through the mudflat. The basalt rock formation is not part of the Works of the Old Men, but a location marker made in less ancient times.

**Figure 5.4:** Example of a region of interest indicated by the archaeologists illustrated by the IKONOS image. The area is mainly of interest due to the transition from sandy plains to basalt hills. Possible sand accumulation at the hillside might have obscured archaeological structures from view. A few enclosures are still visible on the hillside, though.

Considering the L-band wavelength of the ALOS imagery, deeper ground penetration would be expected
than for the TerraSAR-X imagery. In both cases however, no significant subsurface features could be found. Kite walls on the surface on the mudflats (as is the case in Figure 5.5) could not be detected with certainty from the radar imagery. As kite walls on the surface could not be detected, it seems that the results are at least influenced by the lack of spatial resolution.

Figure 5.5: Overview of one of the regions of interest: the colored mudflat from Figure 5.2. The radar images are all presented in RCS [dB]. The kite walls cross the mudflat in its left upper corner and middle part, marked by the blue borders in the IKONOS images. The kite walls visible in the IKONOS image cannot be clearly distinguished from background clutter in the radar images. The diagonal line visible at the end of the mudflat in the right bottom corner of the TerraSAR-X images is part of a bulldozer track through the area. These tracks were apparently made after 2008, as they are not visible in the IKONOS image.
5.3. GEOMETRIC FEATURE DETECTION

Geometric feature detection consists of detecting the structures based on their shape characteristics. First, suitable imagery is selected (Section 5.3.1). Secondly, line candidates are sought using two different methods and parametrized to gain insight in the quality of detected lines (Section 5.3.2).

5.3.1. DATA SELECTION

To objectively determine which images should be used for the geometric feature detection, it necessary to know how distinguishable the targets (kite walls) are from their background. The template matching method devised in Section 4.1 could be used to this end, as it calculates the normalized cross-correlation of template and image (equation (4.1.1)). As the images have already been aligned to the GPS measurements, it is assumed that the normalized cross-correlation (NCC) will be highest at the template center point location.

The definition of target and background is illustrated in Figure 5.7: the target is the NCC associated with
the template position, while the average background value is calculated from the template part which does not contain the kite wall nor the best template location. In the case of the radar imagery, images of the same satellite mode were averaged to obtain a better radiometric resolution.

The distribution of target and background normalized cross-correlation values of all the spaceborne remote sensing imagery can be seen in Figure 5.8.

![Template](image1)

**Figure 5.7: Relation between template, geo-referenced image and the target and background values.** The blue square symbolizes the location of the values representative to the target, the brown area symbolizes the locations of values associated with the background. The black dotted line indicates the ideal location of the template within the image.

![Histograms](image2)

**Figure 5.8: Histogram of the target (blue) distribution compared to the background (red) distribution for all spaceborne remote sensing imagery.** Only the IKONOS imagery has a significant distribution in target and background NCC.

Only spaceborne remote sensing images for which the distribution of target and background is significantly different can be used for automatic feature detection. Considering the results of Figure 5.8, only the IKONOS image qualifies for the use in automatic feature detection.

### 5.3.2. Obtaining Line Candidates

In Section 5.1, it was determined that based on the characteristics of the kite structures line detection should be pursued for the automatic detection of kite walls. Two different algorithms were developed to obtain the line candidate areas for this purpose: the Direction of Constant Gradient (DoCG) and the Laplacian of Gaussian (LoG) approach. The DoCG method was specifically developed based on the feature characteristics of the kite walls found in Section 5.1. The Laplacian of Gaussian (LoG) approach is an approach based on standard image processing techniques and was used due to its previous successful use in the template matching algorithm (Section 4.1). In both cases a grayscale version of the IKONOS image was used for processing.

**The Direction of Consistent Gradient (DoCG) Approach**

The goal of the DoCG approach was to find the areas of an image where vectors of either maximum or minimum gradient intensity change were consistent. The advantage of this method is that it is less dependent on
the exact shape of line features within an image.

Figure 5.9: Direction of maximum gradient \( \theta \) for the area around kite QUR-21. The head enclosure of kite QUR-21 can be seen in the left corner of the image. The kite walls of the kite have either a blue or red color and run from the top left of the image to the bottom right. From the color of the kite wall lines it can be deduced that the direction of maximum gradient intensity perpendicular to the length of the kite wall points in opposite directions.

To calculate the coherence of the direction of gradient change, the following steps were taken:

1. Calculate direction of the maximum and the minimum gradient based on the image intensity change in \( x \)- and \( y \)-direction (respectively \( \frac{\delta I}{\delta x} \) and \( \frac{\delta I}{\delta y} \)) for image \( I \):

\[
\theta_{\text{max}} = \text{atan2} \left( \frac{\delta I}{\delta y}, \frac{\delta I}{\delta x} \right), \quad \theta_{\text{min}} = \theta_{\text{max}} + \frac{1}{2} \pi. \tag{5.1}
\]

Both the minimum as the maximum gradient.

2. Adjust the directions such that all \( \theta_{\text{min}}, \theta_{\text{max}} \in [0, \pi] \). This step is necessary, as the general width of the kite walls is small compared to the resolution of the image. As the direction of the gradients on the different sides of a straight line are supplementary (Figure 5.9), the coherence of the direction vectors of a kite wall would be zero without the adjustment.

3. It is assumed that along a kite wall line element, the direction of gradient is constant, therefore yielding a higher coherent sum than if the area of random noise. The unit circle representation for the direction vectors can used for the coherent summation:

\[
\text{coh} = \frac{1}{m^2} \sqrt{\left( \sum_{i=1}^{m^2} x_i \right)^2 + \left( \sum_{i=1}^{m^2} y_i \right)^2},
\]

\[
x = \cos(\theta), \quad y = \sin(\theta), \tag{5.2}
\]

where \( m \) is the window size of the summation area and \( \theta \) is either \( \theta_{\text{min}} \) or \( \theta_{\text{max}} \).

The results of the coherence calculations can be found in Figures 5.10. Considering the values at the GPS measured kite locations, the thresholding was set at \( \text{coh} \geq 0.75 \) (Figure 5.11). As the results of these areas were still noisy, connected component labeling was performed to identify...
The maximum gradient intensity direction ($\theta_{\text{max}}$) is more sensitive to horizontal components, while the minimum gradient intensity direction ($\theta_{\text{min}}$) is more sensitive to vertical components.

All 8-connected areas (components) with a unique identifier. Each component obtained in such a way, could then be filtered based on their area size. As our goal was to obtain line-like components, the areas could be further filtered by calculating the eccentricity of the components (i.e. the eccentricity of an ellipse fitted around the area of a component). As a line element generally has an eccentricity of 1, the most line-like components could be obtained in this way. The final results for the line candidate selection can be seen in Figure 5.12.

A line can be fitted through each component, with help of the Hough transform [50]:

$$\rho = x\cos(\theta) + y\sin(\theta).$$

(5.3)

where $\theta$ is taken as the direction of gradient change and $x$ and $y$ respectively the centroid coordinates of the component.

By keeping the values of $\rho$ and $\theta$ consistent, the line shape can be further extended in x- and y-direction. To regulate the line growth the following rules were applied:

- Line width is taken constant (5 pixels) to make the visualization of the lines easier;
- A bounding box of 250 x 250 pixels centered around the centroid was used to constrain the line length;
- Weight of the component line was set as the length of the major axis of an ellipse fitted around the component to apply a quality description to the line.

Lines will have a high weight if they cross other lines or if their original line candidate component had a long length 5.13).

Considering the results of Figure 5.13, although signs of the kite walls are present, they could not be automatically distinguished from noise in the image. Due to time constraints, the method could not be further developed. Considering the results in the earlier Figure 5.12, the method has potential in tracing kite shapes. Furthermore, as it is not limited to a high image resolution, it would be worthwhile to further pursue.

**The Laplacian of Gaussian (LoG) approach**

In this approach, line candidates are obtained by filtering the IKONOS image with the Laplacian of Gaussian filter and thresholding the results based on the values of the kite walls on the GPS measurement locations. The results are further refined similarly as in the DoCG approach: first connected component labeling is performed to uniquely identify all 8-connected areas in the image, after which a selection based on the area of a component and the eccentricity of an ellipse fitted around the component is performed (Figure 5.14).

As the line candidates already resemble lines, the Hough transform of all LoG line candidates is taken (Figure 5.15).

Information on the lines formed by the LoG line candidates can be obtained by combining the LoG candidate line result with the calculated Hough transform:
Figure 5.11: Thresholded coherence for both cases (maximum and minimum gradient taken together).

Figure 5.12: Best line candidate components represented by their median maximum gradient direction in degrees around kite QUR-21. The kites can be clearly distinguished based on the direction of the lines.
Figure 5.13: Result of line parametrization of the coherence method line candidates. Lines from the kite walls of QUR-21 are visible, but difficult to distinguish from noise.

Figure 5.14: Line candidate components around kite QUR-21 obtained selected based on the LoG approach. The candidate components already resemble thin lines.
• A threshold is set to filter out the \((\rho, \theta)\)-pairs from the calculated Hough transform based on their occurrence. A pair is accepted if it occurs at least 5 times before it is further parameterized. This threshold is mainly set to limit the processing time and avoid needless fitting of lines.

• For each \((\rho, \theta)\)-pair all associated pixels are checked on their Euclidean distance with respect to each other, if this distance is sufficiently small, the pixels are treated as a line element of which beginning and end point is stored.

To try to re-obtain the kite shape and assess the quality of the lines, the component lines are extended in a similar manner as in the DoCG approach parameterization of the coherence method:

• The centroid of the line component is taken as the center point of the line extension;

• The length of the line is constricted to a bounding box of 250 x 250 pixels around its center coordinate;

• Line width is taken constant (5 pixels);

• The lines are weighted according to their original detected line length.

The result for these lines can be seen in Figure 5.16. The weight of the line describes the line quality: a high line weight indicates either a high frequency of lines overlapping or a long original line length. Compared to the coherence method, the quality is sufficient to detect kite walls as they are clearly distinguishable from the background.

5.4. RESULTS

The results of the LoG approach can be directly used to create a map with a quality indication of detected results, by using it as a direct transparent overlay on the optical imagery. The best line features have the highest saturation and are easier to spot than less qualifying line features. The map therefore gives immediate insight into regions of archaeological interest.

As the IKONOS image is under licensing conditions, it may not be published as a whole. Parts of the map however, can be seen in Figures 5.17, 5.18 and 5.19. Not only kite walls are detected; in some cases pendant cairns as well as parts of enclosures are marked. Due to using the results as an overlay, false positives can be immediately recognized. The LoG approach works well for the IKONOS imagery: at least parts of every kite in the area are detected in the overlay map.
Figure 5.16: End result of the line parametrization of the LoG approach around kite QUR-21. The extension of the candidate lines has results in a clearer view on the kite shape.

Figure 5.17: Results in detecting kite walls of kite QUR-21. Not only kite walls are detected, but also a part of the enclosures in the neighborhood (left bottom corner).
5.4. **Results**

Figure 5.18: Pendant cairns detected by the LoG approach.

Figure 5.19: Kite structures detected within the transition from harra to hamad. The detected parts cover the funnel opening of the head enclosures of the kites. The stone ridge can immediately be recognized as a false positive.
The main research question of this master thesis project was stated as:
“**How can archaeological sites in the harra be automatically detected from spaceborne optical and radar remote sensing imagery?**”

In this chapter, this question will be answered based on the sub-questions posed in Section 1.3. For each sub-question, conclusions and dedicated recommendations are given. The general conclusions and recommendations can be found in Section 6.6.

### 6.1. Feature Characteristics

“What characterizes the features of interest (‘Works of the Old Men’) and their environment? Can these be parametrized e.g. in size, orientation, composition, etc.?”

#### 6.1.1. Conclusions

The Works of the Old Men mainly occur in the basalt wastelands of the harra and can be categorized into three categories: kites, cairns and enclosures (Section 1.2). The detection of kite structures was pursued rather than cairns and enclosures, as these are not only the most thoroughly documented of ‘The Works of the Old Men’, but also have the highest chance of detection considering their size. As described in Section 5.1, kite wall characteristics were found based on shape, size, orientation and slope direction. Of these characteristics, shape was decisive in the automated detection of archaeological sites. The shape of kite walls were parametrized according to the line definition of the Hough transform (Section 5.3.2).

#### 6.1.2. Recommendations

While this work only focused on kite walls, in future work it should also be possible to parametrize the circular shapes of enclosures. One of the line selectors mentioned in Section 5.3.2 for example is eccentricity. A high eccentricity was used to obtain line-like shapes. Similarly, a low eccentricity could be used to obtain circular shapes.

### 6.2. Data Acquisition

“What spaceborne remote sensing imagery can be used to be able to detect the features of interest? Can sufficient imagery be obtained for analysis? Can other sources of information (e.g. topographic maps, digital elevation models) be used for the detection of objects?”

#### 6.2.1. Conclusions

Optical spaceborne remote sensing imagery consisted of acquisitions from the CORONA (panchromatic), IKONOS (multi-spectral, 4 bands) and LandSat (multi-spectral, 8 bands) satellites. Radar SAR imagery consisted of images from the ALOS PALSAR (L-band wavelength), Envisat (C-band wavelength) and TerraSAR-X (X-band wavelength) satellites (Section 3.1).

Fieldwork was performed in the area of interest, which consisted of GPS measurements and the placement of corner reflectors (Section 3.2). In the case of the spaceborne optical remote sensing imagery, data
was selected based on its spatial resolution. The spatial resolution of the Landsat image was deemed too coarse for use in direct feature detection (Section 3.1).

It was hypothesized that kite walls would be detectable in radar imagery if their roughness would create sufficient backscatter in a ground resolution cell (Section 3.1). This was shown however not to be the case in the region of the interest for the radar imagery available (Section 5.3.1). The ground penetration capabilities of the radar imagery were also investigated, but deemed impossible to quantify due to the limited amount of images available (Section 5.2).

Additional data consisted of a scanned topographical map, the 90 m resolution SRTM DEM, the 30 m resolution ASTER GDEM and information from archaeological sites found through visual inspection (Section 3.1). Care should be taken in comparison of the DEMs with GPS measurements, as the heights of the DEMs are orthometric, while the heights of the GPS measurements are geodetic.

Of these additional datasets, mainly the SRTM DEM was useful in co-registration of the radar imagery. The direction of the kites could also be determined based on the height information from the SRTM DEM and ASTER GDEM (Section 5.1). The information on archaeological sites through visual inspection was useful for a general indication of archaeological structure locations, but did not trace the shapes of the structures in question to make it usable for automatic validation of the results.

6.2.2. RECOMMENDATIONS
Considering the results of the data selection process, insufficient radar imagery was available for the project. A higher quantity of the radar images can be used to improve the radiometric resolution of the images, which should make it at least possible to distinguish kite walls from their background on the local mudflats. This would be specifically of interest in the case of ALOS imagery, as L-band wavelength has the deepest ground penetration and therefore could possibly give additional information which optical imagery would lack. It should be noted that the area of interest is generally poorly covered in the archives of radar satellite missions, making it more expensive to obtain suitable imagery. The success rate of using high-resolution optical imagery is much higher, as the structures can immediately be seen from a single acquisition.

Considering other radar satellite missions currently available, the TanDEM-X mission could provide very useful data for the Jabal Qurma project. The WorldDEM product, which is scheduled for release this year, has a resolution of 12 x 12 m with a vertical accuracy of 2 m (relative) and 10 m (absolute) [51]. Compared to currently existing DEM models, this is a significant improvement. The quality of the product would also be higher than performing repeat-pass radar interferometry on the Envisat imagery as well, as the resolution of this imagery is 20 m at best and still suffers from atmospheric effects after processing.

6.3. IMAGE ENHANCEMENT
"Does the optical or radar imagery needs to be enhanced to be able to obtain better results in the detection of objects? How can spatial resolution be preserved despite filtering data?"

6.3.1. CONCLUSIONS
The Laplacian of Gaussian (LoG) filter proved to be a useful technique to filter the IKONOS imagery (Sections 4.1.3 and 5.3.2). Because of its resemblance to a kite wall intensity profile it preserves the spatial resolution of the kite walls, while filtering out unwanted noise from surrounding rocks.

CORONA imagery is more difficult to enhance as the lower resolution of the image in combination with lower contrast differences between pixels causes degradation in spatial resolution during filtering: the shape of the archaeological structures tends to become more fragmented and is therefore easily lost (Sections 4.1.3 and 5.3.1).

6.3.2. RECOMMENDATIONS
The processing of the Envisat SAR imagery could unfortunately not be finished during the time frame of the research project. As the data is already available, however, the creation of the Multi-Reflectivity Map should be pursued to offer more insight in the use of radar imagery for archaeological structure detection and the ground penetration capabilities of C-band wavelength.

In case that radar imagery would be available for direct feature detection, most likely the would not
6.4. **ALGORITHMS**

"Which algorithms can be used to detect objects? Are they generally applicable to different situations? Are different algorithms needed for detecting features in optical and radar imagery?"

6.4.1. **CONCLUSIONS**

Two semi-automatic algorithms were specifically developed for the detection of line features within the harra (Sections 5.3.2): the Direction of Constant Gradient (DoCG) approach and the Laplacian of Gaussian (LoG) approach. The DoCG approach mainly depends on the intensity changes in an image. It works as long as the gradient of intensity along a structure stays constant (e.g. along straight lines). Resolution is less important in this method.

The LoG approach performance depends on the contrast difference between structure and background. The method is mainly suitable for high-resolution imagery in which the contrast differences are large. Of these two methods, the LoG approach delivered the best results in the processing of the IKONOS image (Section 5.4).

6.4.2. **RECOMMENDATIONS**

Although the LoG approach performed better within this research project, it would be interesting to pursue the development of the line parametrization part of the DoCG approach further in future work. As the line candidates inherently contain information on their direction, it should be possible to connect separate line parts if they are pointing in the same direction. This offers possibilities in the automatic tracing of structure shapes.

Furthermore, the mentioned algorithms were designed for the use with optical imagery, as the radar imagery obtained was deemed unsuitable for feature detection (6.2.1). As the LoG approach is mainly suitable for the analysis of high-resolution data, it is most likely not suitable for the use with radar imagery. The DoCG approach could be applicable, however the line parametrization part of the algorithm should be improved to obtain better results.

6.5. **VALIDATION**

"When does a detected object belong to an archaeological site? How can this be translated into a quality description? How can the archaeological site be intuitively visualized? Does the mapping of the detected sites provide added value compared to the archaeological research already done within the research area?"

6.5.1. **CONCLUSIONS**

As purely geometric feature detection based on shape was performed, an object belongs to an archaeological site if its locations coincides with a line feature detected in the IKONOS image. The lines are weighted: weight is determined on the length of the original line candidate and the number of lines which cross the same location. The site detection can be intuitively visualized by using the feature detection results as a transparent overlay on top of its original image (Section 5.4). However, of all the kites known in the area, parts were detected by the LoG approach (Section 5.4). Furthermore, the methods provide a faster way to analyze areas in the future. No new archaeological sites were found in the area of interest by using the feature detection methods, although it is unknown whether further kite structures exist within the area.

6.5.2. **RECOMMENDATIONS**

There was no time to significantly test the robustness of the feature detection algorithms at various spatial resolutions, nor to fully assess the line weight depiction.

However, the processing does not have to stop at the transparent overlay. The results from the overlay map could be made ‘followable’ by processing them with the line partitioning algorithm (Section 4.1.2). These lines could then be used in combination with DEMs to obtain information on the direction of kites as well as the possible locations of head enclosures.

6.6. **GENERAL CONCLUSIONS AND RECOMMENDATIONS**

The ‘Works of the Old Men’ are mainly difficult to detect due to their dimensions and composition. The magnitude of width of the structures is often sub-meter, limiting the filtering possibilities as these often also affect
the spatial resolution of the end result. The structures are made from the same material as their surroundings, limiting the methods to distinguish them from the background properly. Nonetheless, our method was capable of detecting fragments of all kite walls known, as well as some pendant cairns and parts of enclosures in the area of interest.

For future work, it is important to test the algorithms on different areas to further confirm their validity and check whether they can practically be of use to archaeologists. Besides, it would help to further develop the algorithms to work on lower resolution imagery to make the practical use of the algorithms more feasible.
In this appendix, the results of the additional fieldwork concerning close-range photogrammetry will be discussed. Close-range photogrammetry can be an interesting for use in the field of archaeology as it offers a way to document archaeological structures in 3D.

A.1. CLOSE-RANGE PHOTOGRAMMETRY

Photographs taken with the Canon EOS 350D SLR Camera were used for close range photogrammetry with the 3DIAS software package of GeoDelta. The SLR camera was borrowed from the optical remote sensing department of. 3DIAS has originally been designed to reconstruct traffic accident sites; archaeological application within this project provided an interesting new test case. The camera was calibrated beforehand at the GeoDelta office (Table A.1). Four features were captured for reconstruction: two location markers, the base camp corner reflector and a part of a kite wall (Figure A.1). Pictures had to be taken with a camera with fixed focal length and as little angular displacement as possible between consecutive pictures.

Table A.1: Calibration parameters of the Canon EOS 350D SLR Camera.

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</tbody>
</table>

The 3DIAS software can deduce the 3-dimensional location of automatically detected tiepoints in pictures. After processing the picture series in the 3DIAS software it became clear that the automatic detection of tiepoints was insufficient to properly obtain a 3D reconstruction of the features captured. In the case of the location markers and the kite wall the contrast between the rocks out of which the structures were built was lacking. In the case of the corner reflector, the shine of the corner reflector panels limited the automatic detection of tiepoints (Figure A.2).

Although manual assignment of tiepoints is possible in the program, it was deemed too time-consuming to be of use within the research.
Figure A.1: Capturing pictures out in the field. The black markers plates positioned at the base of the location marker are specially designed to be uniquely recognizable by the 3DIAS software package and can serve to measure scale as well as provide fixed tiepoints in pictures.

Figure A.2: Screenshot of the 3DIAS program. A 3D reconstruction of tiepoints can be seen in the window in the right bottom corner. The red dots within the reconstruction indicate points of which the 3D coordinates are known, the yellow ‘pins’ indicate the locations and directions from which pictures were taken. It can be seen in the picture overview that the reflector itself lacks tiepoints for reconstruction.
BIBLIOGRAPHY


