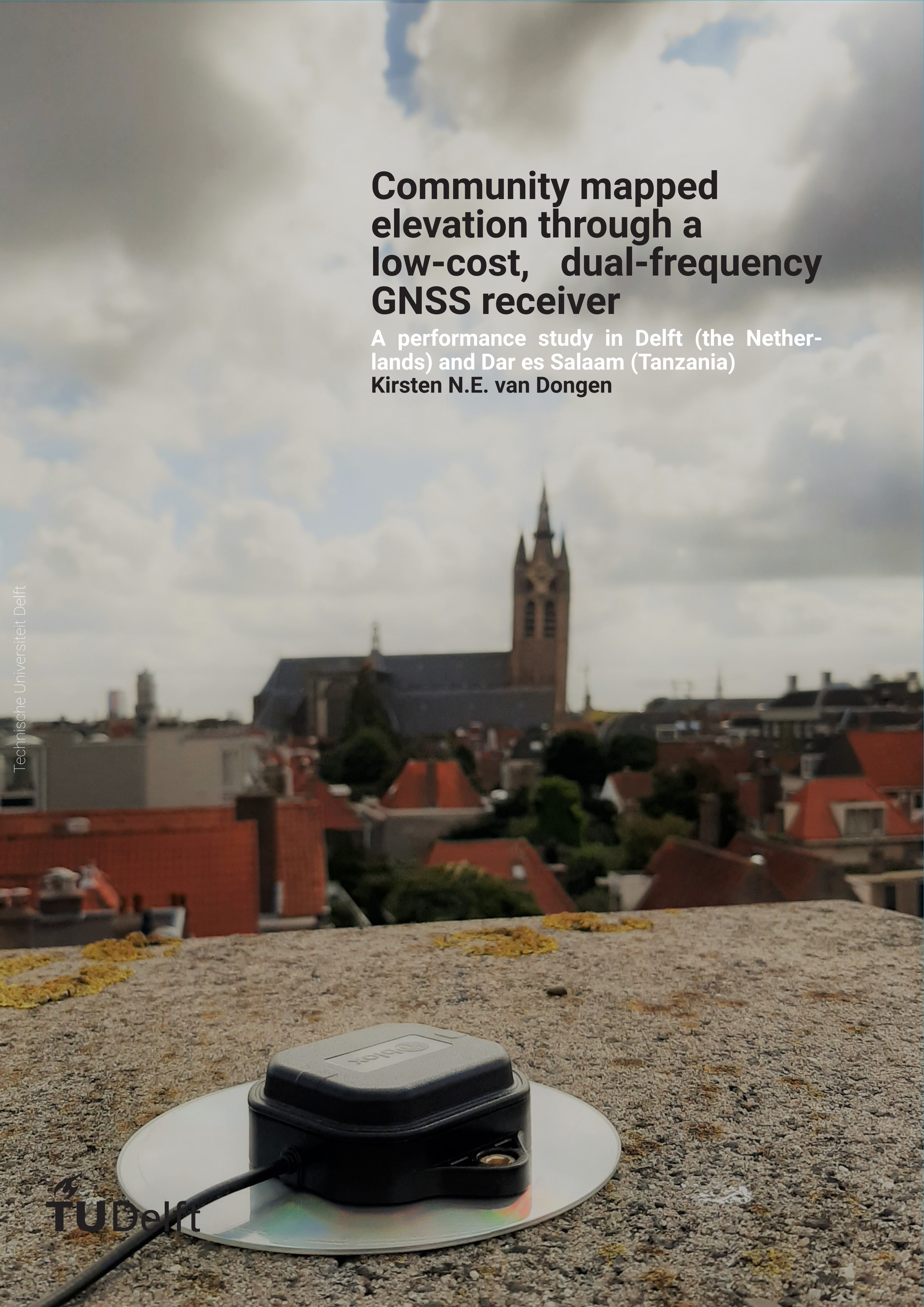

Community mapped elevation through a low-cost, dual-frequency GNSS receiver

A performance study in Delft (the Netherlands) and Dar es Salaam (Tanzania)

Kirsten N.E. van Dongen

Technische Universiteit Delft

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by

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Preface

This graduation has brought with it many "first times". Conducting a scientific study, reading a paper all the way through, visiting Tanzania, putting so many words and effort into a report and this list could go on for a while. Partly thanks to the people around me, I have never lost confidence in this project. And now that I have this report in front of me, the confidence in a successful outcome appears not to be misplaced. With some bravura, my childhood idol (Pipi Longstocking) once said;

"I have never done it before,
so I think I can do it"

This little phrase applies perfectly to my graduation. This quote is from a somewhat stubborn girl who goes, full of confidence and with a smile on her face, on an adventure. I take guidance from that, and take the instructive lessons of my graduation into the next phase of my life.

Many people encouraged me, helped me end guided me to graduate. First of all, I want to thank Christian Tiberius. Your supervision has steered me in the right direction in a positive and pleasant way. Your thorough expertise in GNSS has proven valuable for me to execute the performance study and fully understand the differential GNSS positioning. Secondly, I want to thank Hessel Winsemius for sharing your viewpoints, which were enriching mine. When the programming became close to being overwhelming, you helped me to stay focused on the real life application. I also want to thank the other members of my committee, Rolf Hut and Ramon Hanssen. In addition to my committee, I want to express my gratitude to Andreas Krietemeijer; dankeschön for answering all my questions.

Throughout my entire research, but mainly in Tanzania, I received support from Ivan Gayton. You made me realize that in every research concessions have to be made. It is not a matter of giving up, it is a matter of weighing up alternatives and opting for progress. I would also like to thank Immaculate and Glory, you were very enjoyable company in Dar es Salaam, both during the experiments and in the weekends. Aaron, the same goes for you, you made my time in Dar es Salaam more fun and almost every time I see a microwave I think of you.

Finally, there were numerous people that sharpened my report through their questions and enhanced the pleasure of writing it by providing inspirational and liberating breaks. In this regard I want to express my gratefulnesses to Agnes and Maarten -who were there with my along all the way. Also Mireille, Vivien, Cyrus have been supportive in the process of graduating. Linde, Isabel, Corne, my roommates, Dennis and other friends have been so helpful on the personal side of things. Lastly, a big gracias, merci, dankjewel, thank you to my friends from climbing, who have supported and encouraged me while travelling and while ploughing to my work in Delft.

And now I am ready for my next adventure!

Kirsten N.E. van Dongen
Delft, October 2019

Abstract

Heavy rainfall, combined with expanding (unplanned) urban settlements in flood prone areas, expose Dar es Salaam (Tanzania) to the risks of flooding. The urbanisation is so rapid in many areas that it is not beneficial to carry out expensive surveys which are quickly out of date. The work carried out by community-mapping project Dar Ramani Huria (Swahili for "Open map") aims to make a detailed map of Dar es Salaam, to enable the hydrologic models to approach the real situation more closely. However, the surveying methods used until recently are not sufficiently accurate. However, an alternative emerges in the form of community members using a low-cost, dual-frequency global navigation satellite system (GNSS) receiver during surveys. However, before this receiver can be implemented a detailed research has to be done. In this thesis the horizontal and vertical performance of the U-blox ZED-F9P receiver in Delft (the Netherlands) and Dar es Salaam is studied.

The research is divided into two parts: performance and case study. For the performance study a series of post-processed kinematic (PPK) experiments were conducted in Delft and Dar es Salaam. The experiments have been designed in order to provide a variety of location, antenna-performance, baseline length, software package and movability. In addition, two re-initialisation experiments were conducted to measure how fast the interrupted GNSS signal is regained by the receiver. The case study focused on the desirability and feasibility, mainly focussing on accuracy, of implementation in the project of Dar Ramani Huria. Structured and unstructured interviews with employees of the Humanitarian OpenStreetMap Team (HOT) Tanzania were held to find out the requirements of implementation.

The positioning performance of the receiver varies between the different experiments. The conclusions regarding the positioning performance are based on the scatter plots in the horizontal plane and the positioning over time for the three separate directional components; East, North and Up. The values for the horizontal performance (RMS East, RMS North) and for the vertical performance (RMS Up) of the fix solutions insofar as they fall inside the 95% confidence ellipse are decisive. Only the relevant experiments, namely those who can map a larger area with a single reference station are taken into consideration.

The horizontal positioning performance ranges from **1.13** till **16.83**mm. However the latter, high value is from the *9*km *baseline Dar es Salaam* experiment with a very low percentage of fixed solutions. If we disregard the experiments with low percentage of fixed solutions then the horizontal positioning performance ranges van **1.13** till **9.42**mm. The vertical positioning performance shows less accuracy ranging from **3.56** till **14.75**mm. If we compare this performance with the requirements for Dar Ramani Huria's project, even the strictest of $2cm$, the performance is more than adequate according to the "few cm accuracy" requirement. The experiment with the high-end antenna shows with values **2.44**mm (RMS East) and **3.42**mm (RMS North) the best horizontal and with the value **3.75**mm (RMS Up) the best vertical performance. Another factor influencing the performance is the location, in particular the aspect of atmospheric delay that varies between Dar es Salaam and Delft.

This research thesis concludes that the implementation of the receiver in Dar Ramani Huria's project is well possible and that the performance of the receiver is adequate. This conclusion is confirmed by what is actually occurring in the field: HOT Tanzania and Dar Ramani Huria already started using the GNSS receiver and carrying out surveys with this receiver.

Keywords: *community mapping, performance study, post-processed kinematic, low-cost dual-frequency GNSS receiver, GNSS, hydrological model, Dar Ramani Huria, Humanitarian OpenStreetMap Team*

Symbols and Swahili

List of symbols

τ	(travel) time	(s)
ρ	range	(m)
c	speed of light	(m/s)
T, T_r^s	Tropospheric delay	(m)
I, I_r^s	Ionospheric delay	(m)
e, e_r^s	(un-modelled) errors	(m)
N, N_r^s	Integer carrier-phase ambiguity	(-)
λ	Wavelength	(m)
δ	Phase delay	(-)
ψ	Carrier-phase range	(m)
ϵ, ϵ_r^s	(un-modelled) errors for the carrier-phase	(m)
f	Frequency	(Hz)
M, M_r^s	Real-valued carrier-phase ambiguity	(-)
R	Radius	(m)
C/N_0	Carrier-to-noise ration	(dB-Hz)

Words in Swahili

Bajaj	Local mode of transport; tricycle
Dar Ramani Huria	Dar Open Map
Shina	Trunk
Wajumbe	Community leader

Abbreviations

ARNS	Aeronautical Radio Navigation Service
BSPK	Binary Phase Shift Keying
DGNSS	Differential GNSS
DLOS	Direct Line Of Sight
DOP	Dilution of Precision
ECEF	Earth Centered, Earth Fixed
ENU	East, North and Up
GDOP	Geometric DOP
GIS	Geo-Information System
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HDOP	Horizontal DOP
IF	Inospheric Free
IGS	Internation Geodesy service
ITU	International Telecommunication Union
JOSM	Java OpenStreetMap
LBS	Location Based Services
MSL	Mean Sea Level
NGO	Non-Govermental Organisation
NTRIP	Networked Transport of RTCM via Internet Protocol
ODK	OpenDataKit
OMK	OpenMapKIt
OSM	OpenStreetMap
PDOP	Position Dop
PPK	Post-Processed Kinematic
PPP	Precise Point Positioning
PRN	Pseudo-random noise
RAIT	Resilience Academy Industrial Training
RGNSS	Relative GNSS
RMS, RMSE	Root-mean-square, Root-mean-square-error
RNSS	Radio Navigation Satellite Service
RTCM	Radio Technical Commission for Maritime Services
RTK	Real-Time Kinematic
SP experiment	Starting Point experiment
SPP	Single Point Positioning
TDOP	Time DOP
UAV	Unmanned Aerial Vehicle
VDOP	Vertical DOP

List of Figures

1.1 The group with from right to left: Iddy (employee HOT), Benjamin (employee HOT), Immaculate (employee HOT), Wicho (employee HOT), Glory (employee HOT), Aaron (exchange student from the USA) and Kirsten (author). 1
1.2 Map of the research area in the Netherlands. 5
1.3 Photos of the city of Delft. 6
1.4 Map of the research area in Tanzania. Upper left is the world, the bigger country in green is Tanzania. Lower left is Tanzania with the blue dot the location of Dar es Salaam. On the right is a zoomed-in map of Dar es Salaam. 6
1.5 Photos of the city of Dar es Salaam. 7

2.1 Ground track of one satellite that navigates around the earth in 24h, for different satellite constellations. The red line represents the Glonass, blue Galileo, yellow BeiDou and black is GPS. The white, orange and the eight-shaped yellow line are not relevant for this study. 14
2.2 Skyplots, at three different locations [39]. 14
2.3 The upper wave is the carrier wave, represented by $f(t)$. The second component is the PRN code, shown with $C(t)$. Below that is the navigation message, displayed with $D(t)$. The lower wave is a combination of the top three signals. This shows that the direction of the signal is reversed when changing the PRN code. Source image; [2] 15
2.4 Basic principle of the pseudorange code measurements; the time τ is the time it takes for a GNSS signal to propagate from satellite to receiver. 15
2.5 The simultaneous measurement of the ranges to three satellites is sufficient to determine a receiver's position in three dimensions. 16
2.6 Determining the clock offset in the receiver and user position, based on the intersection of the coloured circles that are centred on the satellites. 17
2.7 Phase delay, δ in the carrier-phase measurements, with N as the integer amount of cycles. . . . 18
2.8 Effect of the rotation of the Earth in the signals transit time; sagnac error. The satellite position is at the time of transmission. 20
2.9 The effect of multipath, the yellow lines represents the DLOS and the blue lines the signals reflected by tall buildings near the antenna. 21
2.10 According to the GNSS Handbook [57]; frequency bands used by different satellite constellations for GNSS applications. The blocks with a red outline are used in the receiver used for this study. 22
2.11 Single- and double- difference of the carrier-phase measurements. 24
2.12 Step-by-step approach of resolving the ambiguity resolution, starting with the float solution and via an integer mapping process to the float solution. 25
2.13 A simplified visualisation of the standard deviation of the position determination with pseudorange and carrier-phase measurements compared. In carrier-phase the difference between the fixed and the float solution can be seen. In both graphs the yellow line is the Up-, red and blue the North- and East- component. The time is logarithmically indicated here and only two epochs are shown. 26
2.14 Differences in short- and long-baselines for RTK and PPK positioning modes. 27
2.15 Comparison between different GNSS positioning modes, focus on difference between DGNSS and RTK. Based on a figure from Novatel [26] 28
2.16 Cartesian coordinate systems. 29
2.17 Spherical and ellipsoidal coordinates. 30
2.18 Comparison of the geoid in Tanzania and The Netherlands, with in the middle a worldwide overview. The scales are different, but all in meters. [55] [20] 31
2.19 The different vertical heights visualized in one figure. 31

3.1 Difference between accuracy and precision. 36
3.2 Difference in geometry, there is a 95% probabilit that observed position will be in the dark yellow area. 37

4.1 Design of the positioning mode 41
4.2 Visualization of the experiment process, these steps form the starting point of every experiments done in this study. 44
4.3 Impression of the static experiments in Dar es Salaam. The pictures on the left side show respectively the $4km$ and $6km$ baseline experiments. The two picture on the right side show the measurement done on the wall surrounding HOT's office. 44
4.4 Impression of the kinematic experiment in Dar es Salaam. The picture on the left side shows the bajaj, the picture in the middle and on the right shows the antenna on the roof of the bajaj. . . 45
4.5 The three pictures on the left side show the high-end antenna, the other picture depicts the low-end antenna. 45
4.6 Examples of locations where the antenna and receiver are placed in Dar es Salaam and Delft. . . 46
4.7 Two different methods of disrupting the signal, one is with a above mentioned equipment-cover the other one is a (kitchen) pan. The experiments with the pan are done at the $6km$ baseline in Delft, the other at a meter baseline. 46

5.1 Location of the rover stations for the sensor performance study, in Delft and Dar es Salaam. The yellow line presents the reference station and the blue line the rover. 47
5.2 Location of the rover stations for the system performance study, in Delft and Dar es Salaam. The yellow line presents the reference station and the blue line the rover. 48
5.3 Satellite Tracking for starting point experiment. 50
5.4 Positioning over time and scatter plot of the fix and float solutions of the *SP experiment*. 51
5.5 Histogram of the fix and float solutions together. 52
5.6 Positioning over time and scatter plot of the fix solutions of the *SP experiment*. 53
5.7 Positioning over time and scatter plot of the fix solutions of the *SP experiment* were the outliers are removed. 54
5.8 Positioning over time and scatter plot of the fix solutions inside the confidence ellipse of the *SP experiment* were the outliers are removed. 55
5.9 Carrier-to-noise density over time for all GPS, Galileo and Glonass satellites in view. 56
5.10 PDOP for all fixed solutions inside confidence ellipse 56
5.11 Residuals for both the code- and phase-measurements. 57
5.12 Atmospheric delay of the experiment in Delft with a baseline of $6km$ 58
5.13 Tracking of the experiment in Dar es Salaam with a baseline of $6km$. 59
5.14 Positioning over time and scatter plot of the fix solutions of the experiment in Dar es Salaam on a baseline length of 6km. 60
5.15 Positioning over time and scatter plot of the fix solutions inside the confidence ellipse of the $6km$ Dar es Salaam experiment were the outliers are removed. 61
5.16 PDOP for all fixed solutions inside the confidence ellipse. 62
5.17 Atmospheric delay of the experiment in Dar es Salaam with a baseline of $6km$ 62
5.18 Tracking of the experiment in Dar es Salaam with a baseline of $9km$ 63
5.19 Positioning over time and scatter plot of the fix and float solutions of the experiment taking place in Dar es Salaam on a baseline length of 9km. 64
5.20 Atmospheric delay of the experiment in Dar es Salaam with a baseline of $9km$. 65
5.21 Number of satellites in view. 66
5.22 Positioning over time and scatter plot of the fix solutions of the high-end antenna experiment. . 67
5.23 Positioning over time and scatter plot of the fix solutions inside the confidence ellipse of the high-end antenna experiment were the outliers are removed. 68
5.24 PDOP for all fixed solutions inside confidence ellipse 69
5.25 Map of the walked route PPK kinematic experiment in Delft. 69
5.26 Interestingness parts of the walked route in Delft PPK kinematic experiment in Delft. 70
5.27 Number of satellites for the moving experiment in Delft. 70
5.28 Map of driven track PPK kinematic experiment in Dar. 71
5.29 Interesting parts of the driven route PPK kinematic experiment in Dar es Salaam. 72

5.30 Ambiguity ratio test over time, for the experiment at a meter distance from the reference station. 72
5.31 Ambiguity ratio test over time, for the experiment at $6km$ distance from the reference station. . 73

6.1 Comparison of the ionospheric delay for three highlighted experiments. 76
6.2 Progression from floated point solutions to fixed solutions according to GNSS handbook [57]. . 77
6.3 Conclusion of Liu et al's study in the performance of a GNSS receiver with different amount of satellite's in view [37]. 78
6.4 Comparison of the ionospheric delay for three highlighted experiments. 79

7.1 Simplification of the hydrosphere in both a rural and urban environment. [4] 86
7.2 Timeline of the development of Dar Ramani Huria. 87
7.3 Management hierarchy in HOT Tanzania. 87
7.4 The steps that need to be taken in the Dar Ramani Huria project, to be able to make a sophisticated map of the city. Risk modelling is optional, the maps can be used for different purposes. 88
7.5 Sphere impressions of mapping in a suburb of Dar es Salaam and the industrial training of July 2019. 88
7.6 The various persons involved in a project; starting with collecting data in the field and ending with the customer or the donor. 89
7.7 Visualisation of the concept community mapping according to llifle [28]. 90

8.1 Impression of the working environment during the workshop. 94
8.2 Impression of the atmosphere during the brainstorm. 94
8.3 Casing for the GNSS receiver. 95

9.1 Summary of the three most popular categories during the brainstorm. 100

B.1 Google sketch-up design of the shelter. 132
B.2 Pictures of the shelter. 132

C.1 Supported signals from both the upper- and the lower L-band, the red blocks show which frequencies the receiver can process into a position. 134
C.2 Lay-out of the Ardusimple, with an explanation of the components 134
C.3 NTRIP information; caster and client. 136

D.1 Casing for the GNSS receiver. 143

List of Tables

2.1 Summary of the described errors. 22
2.2 Overview of the dual-frequency pairs. 23

4.1 Overview of all the experiments performed during this research. 43
4.2 Starting point of experiments - rover. 44

5.1 Summary of static experiments in Delft and Dar es Salaam. 49
5.2 Starting point of experiments - rover. 50
5.3 Experiment in Dar es Salaam with a baseline length of $6km$. 59
5.4 Experiment in Dar es Salaam with a baseline length of $9km$ 63
5.5 High-end antenna experiments - rover 66
5.6 Re-initialisation experiment in Dar es Salaam with a baseline length of few meter. 72
5.7 Re-initialisation experiment in Dar es Salaam with a baseline length of $6km$. 73

9.1 Summary of the interviews with people closely involved with Dar Ramani Huria's project. 97
9.2 Summary of the interviews with people form the Innovation Department. 98
9.3 Summary of interview with Operations. 99
9.4 Summary of interview with the facility manager. 99

11.1 Combinging results performance- and case study; the conclusion 104

C.1 Performance of the U-blox ZED-F9P receiver in different GNSS modes. 133
C.2 Overview of the software requirements 135

Contents

List of Figures xi

List of Tables xv

1 Introduction 1
- 1.1 Research context . . . 2
- 1.2 Problem statement . . . 2
- 1.3 Research motivation . . . 2
- 1.4 Acknowledgement of previous work . . . 3
- 1.5 Aim and research questions . . . 4
- 1.6 General description of the area . . . 5
- 1.7 Scope . . . 7
- 1.8 Outline of the report . . . 7

I Performance study 9

2 Concept of Global Navigation Satellite System positioning 13
- 2.1 Global Navigation Satellite Systems; an introduction . . . 13
- 2.2 Concept of GNSS positioning . . . 14
- 2.3 GNSS errors sources . . . 19
- 2.4 GNSS frequency bands . . . 22
- 2.5 Differential GNSS . . . 23
- 2.6 Positioning modes . . . 26
- 2.7 Reference systems . . . 29

3 Literature review and performance indicators 33
- 3.1 Comparative studies . . . 33
- 3.2 Key-performance indicators . . . 36
- 3.3 Extra performance indicators . . . 39

4 Methodology 41
- 4.1 Design of positioning . . . 41
- 4.2 Implementation of the installation of the stations. . . . 42
- 4.3 Structure of the experiments . . . 43

5 Results 47
- 5.1 Positioning of the rover . . . 47
- 5.2 Summary of the experiment results . . . 48
- 5.3 Starting point experiment. . . . 50
- 5.4 Highlighted experiments . . . 58

6 Discussion 75
- 6.1 Missing ground truth . . . 75
- 6.2 Differences between Dar es Salaam and Delft . . . 75
- 6.3 Practical objections of experiments . . . 76
- 6.4 Fix solutions . . . 77
- 6.5 Vertical component in the GNSS performance study . . . 79
- 6.6 Impact of the geoid in hydrological modelling . . . 80
- 6.7 Promising results; application of position determination . . . 80

II Case study 81

7 Current process of surveying and map-making 85
7.1 Flood modelling in urban areas . . . 85
7.2 Dar Ramani Huria's community mapping project . . . 86
7.3 Step-by-step approach to map the (sub)wards in Dar es Salaam . . . 87
7.4 Quality assurance . . . 89
7.5 Dar Ramani Huria related to literature . . . 91

8 Methodology 93
8.1 Interviews . . . 93
8.2 Workshop . . . 93
8.3 Brainstorm . . . 94
8.4 Python course . . . 94
8.5 Protection and user-friendliness of the receiver . . . 95

9 Results 97
9.1 Interviews . . . 97
9.2 Brainstorm . . . 100

10 Discussion 101
10.1 Language . . . 101
10.2 Cultural differences . . . 101
10.3 Difference in the level of education . . . 101

11 Conclusion 103
11.1 Implementation of the reciever, in community mapping context . . . 103
11.2 Answers of the research questions . . . 105

12 Recommendations 107
12.1 Policy recommendations . . . 107
12.2 Recommendations for further research . . . 108
12.3 Detailed application GNSS receiver . . . 109

Bibliography 111

Appendices 115

A Results 117
A.1 Positioning over time . . . 117
A.2 Scatter plot . . . 119

B Setting up the experiments 121
B.1 Positioning mode choice and set-up . . . 121
B.2 Manual; how to conduct the experiments . . . 124
B.3 Shelter of reference station in Dar es Salaam . . . 132

C Technical details equipments 133
C.1 NTRIP information . . . 136

D Community mapping aspects 137
D.1 Fully detailed interviews . . . 137
D.2 Fully detailed brainstorm sticky-notes . . . 141
D.3 Casing design . . . 142

E Research day poster 145

1
Introduction

This report contains the findings of a master thesis project in Delft (the Netherlands) and Dar es Salaam (Tanzania), which ran from mid-March 2019 to the end of October 2019. During the two months in Tanzania, the company Humanitarian OpenStreetMap Team hosted me at their office in Dar es Salaam.

This study is part of the Dar Ramani Huria project, which is Swahili for "Dar Open Map" and is a community-based mapping project in Dar es Salaam. This program is training local university students and community members to create highly-accurate maps by using local devices such as smartphones, and making data available freely and openly through OpenStreetMap. Dar Ramani Huria activities form part of the Tanzania Urban Resilience Program, a partnership between the United Kingdom's Department for International Development (DFDI) and the World Bank, with the aim of supporting the Government of Tanzania in increasing the country's resilience to climate and disaster risks. The project is supported by the World Bank's Global Facility for Disaster Reduction and Recovery (GFDRR), and implementation is guided by the Humanitarian OpenStreetMap Team (HOT). In addition to the World Bank, the following parties are involved: COSTECH, City of Dar es Salaam, UDSM, Ardhi University, BUNI, Danish Red Cross, Tanzania Red Cross, American Red Cross, Tanzania Open Data Initiative,and HOT. The expertise of different companies is sometimes called upon to provide the necessary knowledge, this is how Deltares and the University of Technology Delft became involved. In Figure 1.1 a photo of different team-members is shown.

Figure 1.1: The group with from right to left: Iddy (employee HOT), Benjamin (employee HOT), Immaculate (employee HOT), Wicho (employee HOT), Glory (employee HOT), Aaron (exchange student from the USA) and Kirsten (author).

1.1. Research context

Every year during the rainy season, Dar es Salaam suffers from devastating floods that destroy (public) buildings, houses, and private assets and may even result in deaths [34]. The damage these floods cause, could be -partly-prevented using hydrologic models, such models are simplifications of a real-world system that aids in understanding, predicting and managing water resources and flows [36] [35]. Flood modelling experts and other users can run scenarios that demonstrate what happens if a certain amount of rainfall occurs, a river bursts its banks or drainage infrastructure is constructed. These models require accurate mapping data of roads, streams, floodplains and residential areas, both the planned and the unplanned and the elevation [35]. In Dar es Salaam much of the city is made up of unplanned settlements [16].
Surveying is often done remotely by experienced cartographers, but these have often not been physically present in the area they are mapping. This can result in misinterpreted or inaccurate data. More importantly, ground surveys can be performed with smartphone applications, but these lack accuracy in obtaining geographical survey information [48]. Professional survey equipment and the presence of survey specialists are very costly. To provide data that better meets the requirements of the hydrological models; the Dar Ramani Huria project took a different approach: local university students and community members are taught how to make sophisticated maps of the city, using OpenStreetMap - a web platform working to create a free and open map of the entire world. By this Dar Ramani Huria includes areas that were previously off the map [27] [1], improving the hydrological models for the Dar es Salaam region [36] [35].
The first step in creating maps is to collect the data. For this purpose, the parties involved make use of an internet connection and two smartphone applications; OpenMapKit (OMK) and OpenDataKit (ODK). The next step is that Dar Ramani Huria mappers help to develop the maps by digitizing their content via OpenStreetMap. When the maps of the different neighbourhoods are finished, they will be combined with other data to make a hydrologic model and enables users to run (more) realistic scenarios for natural hazards. A positive side effect of this project is that it will bring awareness of the need for flood prevention and risk reduction to the local level, and the future generation will be made aware of the possibilities to contribute to their own city. [56] [1]

1.2. Problem statement

The heavy rainfall, combined with expanding (unplanned) urban settlements in flood prone areas, expose an increasing part of the world to the risks of flooding [38] [31]. Parts of the world, mainly countries in Africa, Asia and Latin America, still lack basic geographical and hydrological data [11]. In addition, the urbanisation is so rapid in many areas that it is not beneficial to carry out expensive surveys that are quickly out of date [11] [38].
The work carried out by Dar Ramani Huria aims to make a detailed map of Dar es Salaam, to enable the hydrologic models to approach the real situation more closely [1]. However, the surveying methods used until recently are not sufficiently accurate, and for this reason an alternative has to be found.
The alternative that emerges is: community members using a low-cost, dual-frequency global navigation satellite system (GNSS) receiver that recently has been launched on the market, during surveys. Before this can be implemented a scientific research has to be done into the performance of the GNSS receiver.

1.3. Research motivation

Across the globe, there is a demand for ways to determine an accurate position [11]. This could be, as with Dar Ramani Huria, to be included in different flood models. But it can also be, as in Colombia, to map the territory of farmers [43]. Or, as in Indonesia, to find out the flow of waste in rivers [63]. There are a lot of applications to be thought of, some of which are for the purpose of making maps, others as a medium to continue other research.
There are already many different GNSS receivers on the market that can do this position determination [58], but this specific receiver is -according to the manufacturers- substantially cheaper without the performance deteriorating. However, insufficient scientific research has been done into the performance of this specific GNSS receiver; this is desirable before the receiver can be implemented in Dar Ramani Huria's project.
Much of the research on the performance of GNSS receivers takes place in America, Europe or Australia. The atmosphere and therefore the atmospheric delay is different than areas around the equator or on the Southern Hemisphere [32]. That is why it is of added value to be able to carry out part of this research in Tanzania and to identify the differences with the performance in the Netherlands. In addition to the technical

part of the study, it is of importance to see whether it is desirable to implement the receiver in Dar Ramani Huria's project. If it is applicable in this project in Dar es Salaam, it may later be applied elsewhere in the world with a different purpose.
In the context of this water management related project, the vertical component of a positioning is given extra attention. This component, put in the hydrologic model, makes a prediction of how the water might flow through the city. If the accuracy of the horizontal and vertical component, is improved with the new receiver, a step forward in the development of the hydrologic models is achieved. Besides drainage mapping, low-cost GNSS will open up a range of new use cases for GNSS in low-resource settings.

1.4. Acknowledgement of previous work

The mapping of flood hazards and the modelling of floods requires a certain amount of knowledge and understanding about the drainage network and the flow of water, i.e. the height measurements [9] [10]. On a global scale, elevation information can be collected using satellite data [30], and used for flood modelling covering large areas. There are some limitations to the use of these remote sensing data, so is -in general- the horizontal and vertical resolution too low to use the data for flood modelling on a local scale.

A reliable flood model in the urban environment requires detailed and accurate geospatial information, in which the dimensions, connectivity and elevation of the drainage network are essential [38] [16]. Not only the water infrastructure needs to be studied, but also the risk areas need to be mapped in order to gain insight in the flood hazard and its possible consequences. Detailed surveys as well as elevation mapping using e.g. LiDAR are needed to obtain information. Only when this information is available can urban planning and disaster resilience be developed. However, collecting all this information is problematic in many cities around the world, especially in cities where informal settlements are rapidly emerging and being demolished [61].

Until now this scenario of water behaviour modelling in Dar Ramani Huria's project is done by simple methods that includes Geo-information system (GIS) terrain contouring methods, based on unmanned aerial vehicle's (UAV's) gathered data [1]. They can be used to determine the relative height between a road and drainage canal or other point, and can be used to predict which areas are likely to flood and the possible consequences [3]. To study the flow through a neighbourhood, and where flooding may occur; a more advanced hydrodynamic model is required, as L. Petersson did for her thesis at the TU Delft [49]. In order to make such a model even more valuable, an accurate height map should be included. The to be included accurate elevation information is missing so far, but this data may be collected using GNSS.

Initially, the new method of determining altitude consisted of using low-cost barometers. This is done by using a Arduino combined with a barometric pressure sensor, designed for mobile applications, in a watertight box. The noise and the errors from the sensors are cancelled out to get an accurate and usable elevation reading to implement in the hydrologic models. However, the method based on barometer measurements is still inconvenient to determine the altitude. With this approach; reliable height measurements can only be made when the environment is in such a state that the environmental noises can be determined and corrected. The challenge here is that the state of the environment is fluctuating during the day. The idea has arisen that the height measurements could possibly be more accurate, making the hydrolic model even more realistic. In order to achieve this, a new surveying approach must be developed.

In the context of community mapping in a rapidly changing city as Dar es Salaam, where safety risks should not be underestimated, a consideration should be given to which equipment can be used. The solution of centimetre accurate altitude in the context of Dar Ramani Huria might be in using a GNSS receiver that has just been launched on the market. This low-cost, multi-band real-time kinematic GNSS receiver delivers centimetre level accuracy in seconds. For Dar Ramani Huria's project to determine the heights in Dar es Salaam, this receiver is probably suitable; it seems that the measurements can be done rapidly enough, with sufficient accuracy and the use is easy, because the receiver can be linked to a smartphone or laptop. However, there is still a lot of research to be done. The implementation of the GNSS receiver in the Dar Ramani Huria project is to be investigated, therefore a performance study is required.

1.5. Aim and research questions

The overall aim of this research is **to investigate the vertical and horizontal positioning performance of the u-blox ZED-F9P and how this GNSS receiver can be practically setup in context to Ramani Huria's project of community mapping in Dar es Salaam.** To achieve this from a master thesis perspective several questions have been formulated. Although they all contribute to the overall aim, they do so from different angles. Therefore, to guide the research process in the right direction, the research questions have been divided into two different sections; the performance study and a case study. Following this paragraph, a brief explanation of each section is given and which research questions are applicable.

1.5.1. Performance study; horizontal and vertical positioning

In order to comply with the overall aim at the end of the research, a study is first carried out into the horizontal and vertical performance of the low-cost receiver. The corresponding research question is:

What is the horizontal and vertical positioning performance of the receiver, and what factors influence this performance? And what are the differences in these aspects between Delft and Dar es Salaam?

Research into positioning performance goes hand in hand with setting up a network, for which the following question applies;

Where to establish the reference stations and how to design the infrastructure of a network, taking into account the key performance indicators that need to be established and the rapidly changing situation in Dar es Salaam. What is the most suitable method of communication between the rovers, the reference station and other components?

The answers to these questions will be given by a literature study and by means of various experiments, using five different variables: location, movability, software, antenna performance and, last but not least, the vector between the different components in a GNSS network. It it -unfortunately- too time consuming to carry out all experiments in such a way that only one variable changes at the time. In order to be able to come to a well-founded conclusion, a selection was made. Several key indicators have been used to determine the performance of the receiver, some of these key indicators are based on information from the literature and some have been developed for this study. All the experiments carried out were compared with all the information provided by the key indicators, after which the relevant information was presented.

1.5.2. Case study; implementing the receiver in Dar Ramani Huria

Another aspect of this research is that Dar Ramani Huria has intensive contact with volunteers, local students and community members. In order to make the working method as easy as possible for these people and to ensure that the results are of the highest possible quality, the following research question will be taken into account:

How can the receiver best be implemented in Dar Ramani Huria's project in Dar es Salaam, thinking of a user-friendly design, with local low-cost materials and a way of working with the receiver in such a way that the quality of the data is sufficiently high?

The answer to this question is also based on various sub-questions; The transfer of knowledge took place mainly during the stay in Dar es Salaam. In order to involve the employees of HOT in the project and to transfer the knowledge, a workshop was organized. The workshop discussed step-by-step how to set up a (PPK) network, how to deal with the antenna and the GNSS receiver and how to set up the software. In addition, the experiments were done in collaboration with two Dar Ramani Huria team members; Immaculate and Glory, so that they have seen the entire process several times. At the end of the research period in Dar es Salaam a brainstorm was organised, in this way the employees of HOT were stimulated to think about different applications of the GNSS receiver and what steps still need to be taken to actually implement the receiver in the various humanitarian projects.

1.5.3. Note of writer

A remark should be made is that there might be confusion about the difference between an observation and a measurement. A measurement consists of several observations, where the observation is one moment that the receiver determines a position. The solutions is, as one could expect, the position-solution after doing the positioning calculations.

Another remark concerns details about the GNSS receiver and its attributes. Many of the technical details are described on the u-blox and Ardusimple website, but in Appendix C there is a summary of these technical specifications. During the reporting of this research, reference was made to the GNSS receiver, i.e. the u-blox ZED-F9P receiver mounted on an Ardusimple.

On 9 October 2019, in collaboration with the Geoscience and Remote Sensing and Water Management Department, a research day was organised. In order to present my research there, as a textbook example of the collaboration between these two departments, I made a poster. This has been included in Appendix E.

1.6. General description of the area

The study area includes two cities, in two different countries; Dar es Salaam in Tanzania and Delft in The Netherlands. Between mid-May and mid-July, the research took place in Dar es Salaam, the time remaining in Delft. Although the period of residence in Dar es Salaam was substantially shorter than in Delft, this is the city on which the research is focused, therefore the description of that area is more detailed.

1.6.1. Delft

Delft is located in the mid-West of the Netherlands, in the province of Zuid Holland. It is located approximately 60km South-West of the capital of the Netherlands; Amsterdam. It is located between Rotterdam to the South-East and The Hague to the North-West. The Netherlands has a Marine West Coast Climate "Cfb" according to the Köppen climate classification [62]. The location of Delft can be seen in Figure 1.2

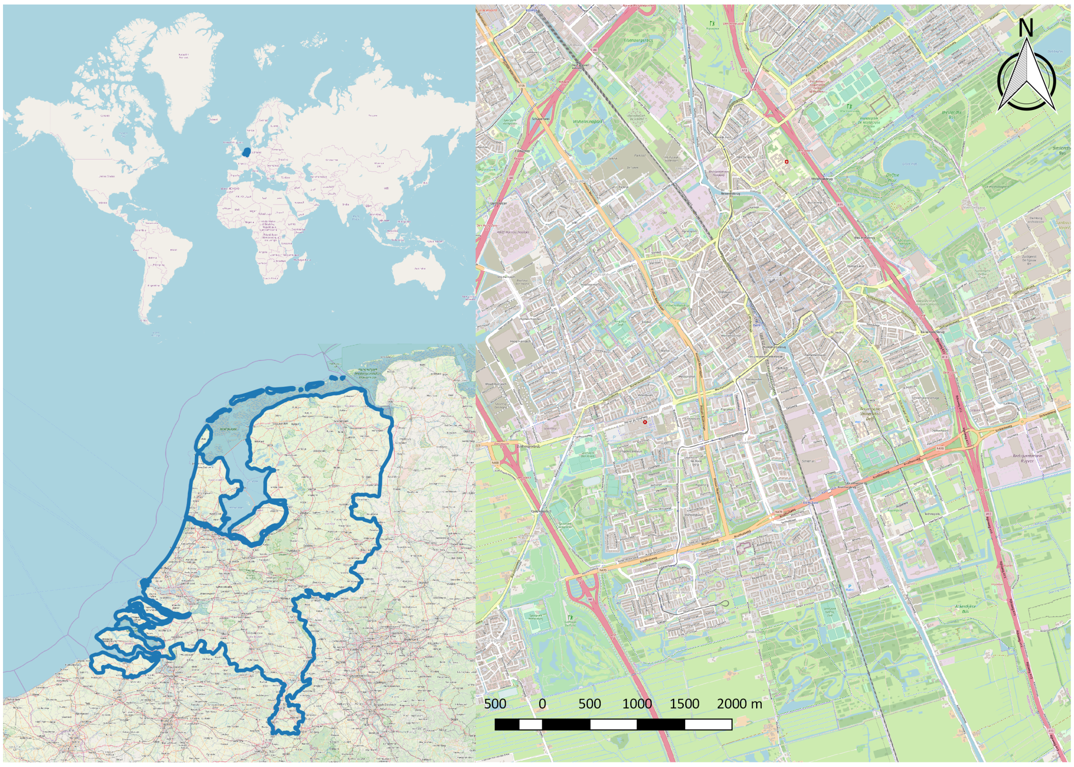


Figure 1.2: Map of the research area in the Netherlands.

With regard to the 'elevation profile'; the city of Delft is surrounded by meadows. The landscape is very flat; there is hardly any height difference. According to the Actueel Hoogtebestand Nederland [52], the height of

Delft is in general 0m. The centre of the city is characterized by monumental buildings, with striking towers of three different churches. In many streets there are canals, with most of the canal houses have three floors. In the more southerly neighbourhoods of the Poptahof and Voorhof there are several blocks of flats. Figure 1.3 shows some canal houses and park De Delftse Hout.

Figure 1.3: Photos of the city of Delft.

1.6.2. Dar es Salaam

Dar es Salaam is located in the mid-East of Tanzania, on the Swahili (Eastern) coast. It is the former capital, as well as the most populous city in Tanzania. It is located approximately 400km west of Dodoma, the capital of Tanzania. Tanzania has many different climates, but is dominated by the Tropical Savanna Climate "AW", according to the Köppen climate classification [62], this classification is also valid for Dar es Salaam. The location of Dar es Salaam can be seen in Figure 1.4.

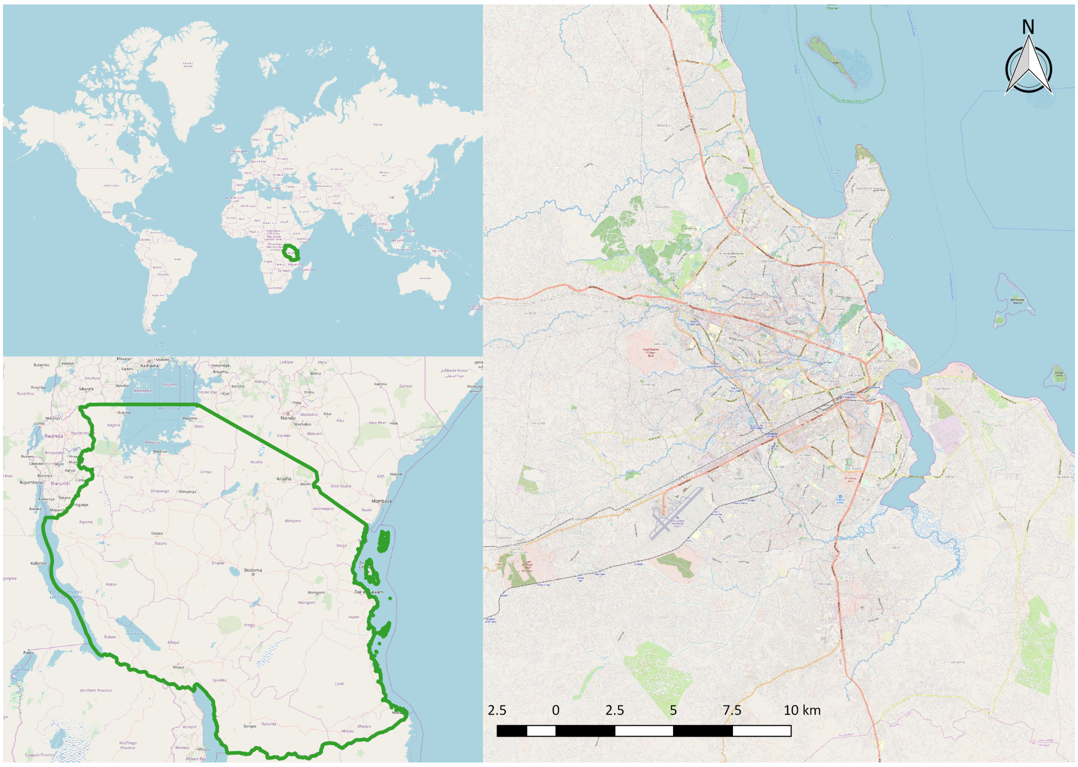


Figure 1.4: Map of the research area in Tanzania. Upper left is the world, the bigger country in green is Tanzania. Lower left is Tanzania with the blue dot the location of Dar es Salaam. On the right is a zoomed-in map of Dar es Salaam.

According to Hanson at all [25] and the World Bank [41] [40], the population in Dar es Salaam is the largest in all of East Africa with 6.400.000 inhabitants. The land area of the city is 1.393km^2, making the population density 4.600$persons\ per\ km^2$ in spring 2019. It is the third fastest growing city in Africa and the ninth worldwide, and further growth can only be expected for the coming years. Dar es Salaam is expected to have a population of 76 million by 2100, making it the second largest city in the world. As regards the 'height profile', this is strongly determined by the 'wealth level', which varies in the city. There are buildings which are more than ten stories high and surrounded by gardens. These are mainly located in the centre and on the peninsula. In the outskirts the characteristic slums can be found, with houses made of corrugated iron. In general, it can be said that the further away from the centre, the buildings become lower but the density of the buildings increases. Figure 1.5 shows a few examples of buildings in Dar es Salaam.

Figure 1.5: Photos of the city of Dar es Salaam.

1.7. Scope

In order to steer the research in the right direction, a scope has been drawn up;

- Work with a u-blox ZED-F9P dual-frequency receiver and a u-blox GNSS Multi-band antenna ANN-MB-00
- Research is only carried out in Delft and Dar es Salaam.
- The financial aspects of the implementation of the receiver in Dar Ramani Huria have not been considered in this study. However, the financial situation of Ramani Huria was kept in mind at the conclusion and recommendations.
- Low-cost has been defined as a maximum amount of 300 USD, this includes the purchase of an antenna but excludes the necessary cables and laptop.
- The focus was on the Dar Ramani Huria project, but there has been a sideways look at other projects.

1.8. Outline of the report

To provide the reader with a structured overview of all the steps taken and the solutions to problems, the report is subdivided into two parts; performance study and case study. both consisting of a short introduction, literature review, methodology, results and discussion. Where the part that contains the performance study focuses on the technical aspect of the research and the case study on the application in Dar es Salaam at Dar Ramani Huria. In order to ensure that all the concepts of the performance study are properly understood, an additional chapter has been introduced setting out the concepts of GNSS.
At the end of the report, the conclusion are presented, combining the performance and case study and providing answers to the research questions. Followed by the recommendations and the appendices. There are three appendices included focussing on; equipment, experiment explanation in details and community-mapping aspects.

I

Performance study

Introduction

In order to comply with the overall performance study aim, to investigate the vertical and horizontal performance of the GNSS receiver, there are two different parts that need to be addressed in this part of the study. One part can simply be described as "receiver performance", and the following research question needs to be answered;

What is the horizontal and vertical positioning performance of the receiver, what factor influences this performance? And what are the differences in these aspects between Delft and Dar es Salaam?

Research into positioning performance goes hand in hand with setting up a network, for which the following question applies;

Where to establish the reference stations and how to design the infrastructure of a network, taking into account the key performance indicators that need to be established and the rapidly changing situation in Dar es Salaam. What is the most suitable method of communication between the rovers, the reference station and other components?

This part consists of a theoretical framework, after which the concept of GNSS is explained in detail. This is followed by the chapters on methodology and results, and this part is closed with a discussion. The conclusion and recommendations are combined with the case study and can be found at the end of the report.

2
Concept of Global Navigation Satellite System positioning

In this chapter the necessary background information is presented in such a way that the methodology, results, conclusion and discussion in this research can be comprehensively understood. The first part of the literature research consists of an explanation of how GNSS positioning works, after which it becomes increasingly focused on this particular study. A section of the chapter focuses on the possible errors that can occur in positioning, after which different solutions are presented. The different positioning modes will be introduced with a focus on the RTK and PPK modes. Finally there is a section dedicated to reference frames, so that the position determination can be put in perspective with the rest of the world. The information provided here comes mainly from the GNSS Handbook [57], GPS Theory, Algorithms and Applications [65], in addition, the course GEOG862 of PennState College of Earth and Mineral Sciences; Department of Geography [5], was also consulted in order to get a first impression of the subject in question, as it provides a very simplified explanation.

2.1. Global Navigation Satellite Systems; an introduction

Global Navigation Satellite System (GNSS) refers to a concept whereby the position of an antenna is determined, based on a constellation of satellites that transmit ranging data, position- and time- data to the antenna. The GNSS receivers use this data to determine the user's position on Earth. GNSS has many applications, but one of the best known is the use of a car-navigation device in a car. This navigation-instrument converts the received satellite signals to a position. Based on this position, it is possible to determine where the user is located and how the route can be followed.

For a very long time, mankind has been interested in where he is in the world; his location. Over the course of time, many ways have been devised to determine positions. People have been able to determine their position for hundreds of years on the basis of observations of distant objects, like a mountaintop. Navigation based on observations of the sun and stars, referred to as Celestial navigation, is also used for centuries. It was only when the space-age began that satellites were used to determine the position with better accuracy. The applications of GNSS have been extended over time, and in addition to Location Based Services (LBS) of various users, there are also applications for surveying, mapping and Geo-information Systems (GIS). The use of GNSS techniques in geodesy has changed the use of geodetic measurements. An increasing number of governments, authorities and regional organisations are using GNSS measurements as the basis for a geodetic network and map development. In addition to these applications, GNSS can also be used for research into, for example, the atmosphere and the precise orbit of a satellite.

GNSS is a generic name that refers to any global system of satellites used for navigation purposes. In addition to the American system, GPS, Europe has also developed a system, Galileo. Russia and China also have a constellation of satellites with GNSS purposes; respectively Glonass and BeiDou. In addition to these four main systems another system is in use; the Quasi-Zenith Satellite System, developed by the Japanese government.

2.2. Concept of GNSS positioning

Simply put, the position is determined by measuring the distance between the receiver and several satellites and trilateration. Before this concept can be discussed in detail, it is important to know which segments there are and how position and time data is transmitted by satellite signals.

2.2.1. GNSS segments

In order for a GNSS system to work optimally, there are several segments that need to work together.

- *Space segment.* The GPS space segment consist of 24 satellites that transmit signals to users. The satellites are located in medium Earth orbit, at an altitude of approximately 20,200km above the surface of the Earth. Each satellite circles the Earth in 12$hour$.
- *User segment.* This segment consist of a receiver, which tracks at least four different GNSS satellites in the same epoch, and computes its position in three dimensions and determines its time.
- *Control Segment.* The control segment consist of a global network of ground facilities. In these facilities they track the different satellite constellations, monitor their transmissions, and send commands and data to the satellites.

2.2.2. GNSS coverage

The coverage of the different satellite constellations can be displayed with so-called ground tracks. The path taken by the satellite is indicated on the world map, but the satellite is then about 20,000km above the earth. The height at which the satellite is located depends on the constellation, and influences the time it takes to circulate around the earth. Figure 2.1 shows the ground tracks of different constellations; the coloured line represents one satellite, moving from West (left) to East (right), over a 24$hour$ period. The endpoints are represented by a filled circle. For this research the ground tracks of Glonass, Galileo, BeiDou and GPS are important, the yellow, orange and white lines can be ignored.

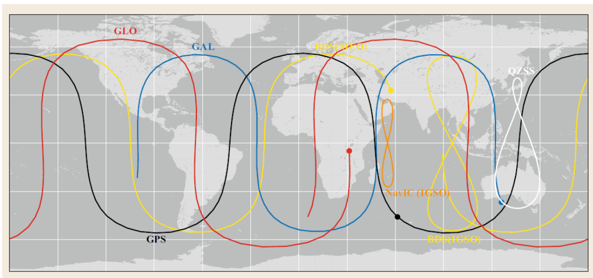
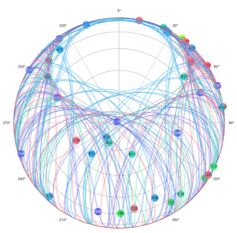
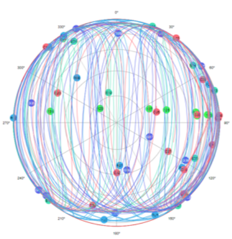


Figure 2.1: Ground track of one satellite that navigates around the earth in 24h, for different satellite constellations. The red line represents the Glonass, blue Galileo, yellow BeiDou and black is GPS. The white, orange and the eight-shaped yellow line are not relevant for this study.

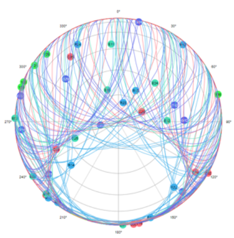
It can be deduced from this figure that there is worldwide coverage with the various constellations of satellites. At any time of the day, there are a number of satellites in sight at every location. This can be visualized by means of a skyplot, which shows how many satellites are at what angle to the receiver. There are several online tools with which the theoretical visibility can be determined. Figure 2.2 shows three examples, all taken on 1 August 2019, starting at 12AM, with a duration of almost 24 hours.



(a) Delft, at the Northern hemisphere.



(b) Dar es Salaam, round the equator.



(c) El Quique, most southern part of Latin America.

Figure 2.2: Skyplots, at three different locations [39].

2.2.3. GNSS signals

GNSS satellites transmit electromagnetic waves is all directions, and the signals propagate with the speed of light. The signals are in the L-band (1 to $2GHz$ range) of the radio frequency spectrum. This range of frequencies have been chosen because they make it possible to perform measurement with adequate precision, where reasonable simple equipment is sufficient for the user, and the signal is not affected by attenuations in the atmosphere under common weather conditions. The GNSS signal is composed of three different components; a carrier wave, spreading code, and a navigation data message. Both the spreading code and navigation message are phase-modulated on the carrier wave, through a technique called Binary Phase Shift Keying (BPSK). The carrier wave has a wavelength of $19cm$, on which each satellite modulates its own unique Pseudo Random Noise (PRN) spreading code with a wavelength of $300m$. At a low rate, the satellite orbit and clock information is built in the navigation data. The PRN code is basically a binary code which seems random, but has been thoughtfully engineered and serves a unique fingerprint for the satellite. In Figure 2.3 an overview of the three different signals and the modulated signal are given.

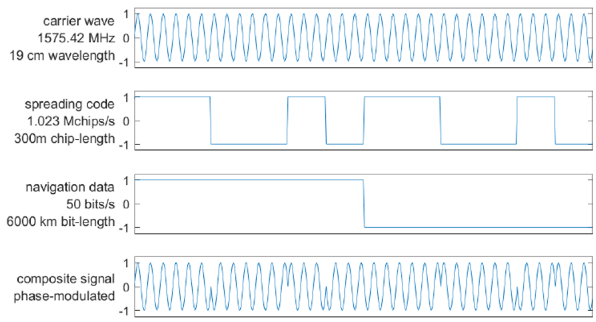


Figure 2.3: The upper wave is the carrier wave, represented by $f(t)$. The second component is the PRN code, shown with $C(t)$. Below that is the navigation message, displayed with $D(t)$. The lower wave is a combination of the top three signals. This shows that the direction of the signal is reversed when changing the PRN code. Source image; [2]

GNSS satellites transmit the phase-modulated signal in all directions and the wave arrives at the receiver with an unknown delay, and , due to the relative velocity of the GNSS satellites with respect to the receiver, with an unknown Doppler frequency shift. These receivers typically consist of so-called channels, and will allocate each of these channels to a specific GNSS satellite. The receiver will search for a particular satellite on each of its channels, by scanning for the corresponding PRN codes at different Doppler offsets and time delays. If there is a match between a channel and the satellite, this combination is stored until the satellite is out of sight or the signal is disturbed.
Within the receiver, a replica is made of the PRN code, which is continuously aligned and compared with the signal received from the satellite. By autocorrelation the original and the copied signal it is possible for the receiver to "lock" into the PRN code, after which the travel time of the signal over the distance between the satellite and the receiver is obtained. This time difference cannot be determined directly, but is approximated by means of PRN code and Doppler frequency measurements, which are basically the shift in time and the shift in frequency that are required to maintain the tracking lock. This process is called the pseudorange code measurement and is shown in Figure 2.4.

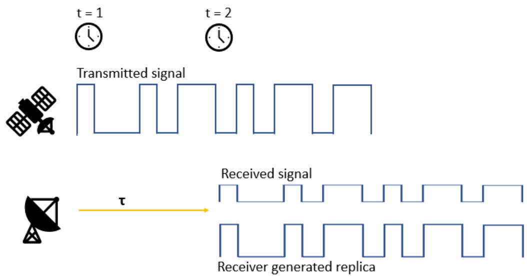


Figure 2.4: Basic principle of the pseudorange code measurements; the time τ is the time it takes for a GNSS signal to propagate from satellite to receiver.

2.2.4. Range positioning

Through the shift in time of the PRN code, in other words the pseudorange code measurements, the travel-time of the signal between the satellite and the receiver can be determined. The travel time τ is calculated by;

$$\tau_r^s = t_r - t^s \tag{2.1}$$

The t_r is the time the signal arrived at the receiver and the t^s is the time the satellite transmitted the signal. It should be noted that both the clock in the satellite and in the receiver may deviate from the true time and may be subject to errors. These errors, among others, are further discussed in Section 2.3. The calculated travel-time is converted into the range distance by a multiplication with the speed of light. The range distance is determined by Equation 2.2;

$$\rho_r^s(t) = c \cdot \tau_r^s \tag{2.2}$$

This presented formula is a very simplified version of the actual situation, where more aspects than just travel-time play a role. The assumptions that have been made are that the clocks in the satellite and the receiver are exactly synchronized, that there is no signal delay due to the ionosphere or troposphere and lastly that there is no measurement noise present. Under these ideal circumstance, the Equation 2.2 can also be written in vector-form, as shown in Equation 2.3:

$$\begin{aligned} \rho_r^s(t) &= ||r_r(t) - r^s(t-\tau)|| \\ \rho_r^s(t) &= [(x_r(t) - x^s(t-\tau))^2 + (y_r(t) - y^s(t-\tau))^2 + (z_r(t) - z^s(t-\tau))^2]^{1/2} \end{aligned} \tag{2.3}$$

The unknown position vector of the receiver is $r_r = (x_r, y_r, z_r)$ and $r^s = (x^s, y^s, z^s)$ is the satellite's position vector, and is known from the navigation message transmitted by the satellite. Note that both the position of the receiver and the satellite are supposed to be in the same reference frame, the Earth Centred, Earth Fixed (ECEF) frame is generally used.

The measured range is equal to the radius of the sphere, centred on a satellite; resulting in an infinite number of possible positions of the receiver that satisfy the measurement. However, this principle is not implemented on a single satellite, but up to two satellites are added to the equation, in a situation where the time component is not taken into account. There are two points where all three satellite circles meet. One of these two points can immediately be dismissed, as it is in space, the other is the location on earth. This principle is illustrated in Figure 2.5.

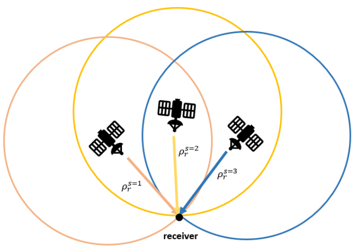


Figure 2.5: The simultaneous measurement of the ranges to three satellites is sufficient to determine a receiver's position in three dimensions.

The solution of position determination of the receiver $r_r = (x_r, y_r, z_r)$ is achieved by an iterative linearisation process. Equation 2.4 present the non-linear observation equations for satellite 1, 2, and 3.

$$\begin{aligned} \rho_r^1(t) &= [(x_r(t) - x^1(t-\tau))^2 + (y_r(t) - y^1(t-\tau))^2 + (z_r(t) - z^1(t-\tau))^2]^{1/2} \\ \rho_r^2(t) &= [(x_r(t) - x^2(t-\tau))^2 + (y_r(t) - y^2(t-\tau))^2 + (z_r(t) - z^2(t-\tau))^2]^{1/2} \\ \rho_r^3(t) &= [(x_r(t) - x^3(t-\tau))^2 + (y_r(t) - y^3(t-\tau))^2 + (z_r(t) - z^3(t-\tau))^2]^{1/2} \end{aligned} \tag{2.4}$$

2.2.5. Pseudorange positioning

So far, the assumption has been made that the clocks in the satellite and in the receiver are perfectly synchronized. However, this assumption is too good to be true . The range measurements, as discussed in the previous section, are subject to unknown clock errors, called dt_r and dt^s. If these clock biases are included in the comparison of the range positioning, it is called pseudorange positioning, or code-measuring. The equation of the pseudorange is;

$$p_r^s = \rho_r^s + c(dt_r - dt^s) \tag{2.5}$$

The GNSS operators, as described in a previous paragraph, monitor the clocks in the satellites and possibly correct for the offset (dt^s) that has arisen in relation to the system time. The information about the clock bias is sent to the satellites, which communicate it to the GNSS receiver using the navigation messages. The receiver uses this offset information to correct the measured pseudorange measurements, allowing for a more accurate positioning. The receiver bias (dt_r) equally impacts the distance measurements to all satellites, represented by the radii of the coloured circles in Figure 2.6. This figure is a two-dimensional depiction of a three-dimensional situation, therefore there are two satellites necessary to determine the location in the (x,y) space. Since the offset of the receiver bias is unknown, it is unclear which colour represents the correct radius of the sphere. Every coloured circle has two intersection points with a circle in the same colour of the other satellite, thus the receiver position in therefore still unknown. However, three circles only intersect each other at a single point for one time offset (the green circles). That shows that the time-offset can be determined as well as the position. In three-dimensions, measurements of at least four satellites are necessary to determine the 3D position of the receiver and the receiver clock bias.

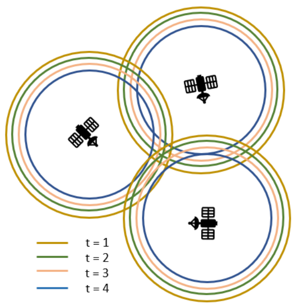


Figure 2.6: Determining the clock offset in the receiver and user position, based on the intersection of the coloured circles that are centred on the satellites.

In practice, as one typically observed more satellites than the minimum of four, GPS positioning does not actually involve drawing circles or shares, but works on the principle of least squares estimation. First the observation model is defined, which links the observations to the unknown parameters in a matrix equation. Since the GPS model is non-linear, this step involves a linearisation around an approximate position. A least squares algorithm is then used to solve this matrix equation, which can contain more observations than unknown parameters; while minimizing the uncertainty of the solution. Similar to the position coordinate computation form the pseudorange measurements, the 3D velocity vector of the receiver can be computed from the Doppler-shift measurements.

Until now, the range positioning has been discussed, which is based on the ideal situation. Then the pseudorange positioning was discussed with the clock errors, however this is still a rather simplified version of the actual distance comparisons. There are more errors that need to be taken into account and included in the pseudorange equation. Consider the following errors; the troposphere propagation delay T_r^s, the ionospheric propagation delay I_r^s, and un-modelled errors including noise and multipath, represented by e_r^s. All these errors are further discussed in Section 2.3. Taking these errors into account results in the following equation:

$$p_r^s = \rho_r^s(t) + c(dt_r + dt^s) + T_r^s + I_r^s + e_r^s \tag{2.6}$$

2.2.6. Carrier-phase measurements

The basic principle of carrier-phase measurements is almost the same as that of the pseudorange measurement; the distance between the satellite and the receiver is determined, but now with the help of the carrier-wave. The range between the satellite and the user is indicated in units of cycles of the carrier-wave. The carrier wave has a frequency of 1.6 GHz. All points on this wave are defined with phase angles, expressed in degrees, where one wavelength consists of 360 °. Similar to pseudorange measurement, the satellite transmits the carrier-wave, and the receiver generates a copy of the incoming signal. By autocorrelation the phase shift between the incoming and the copied signal is determined, as visualized in Figure 2.7.

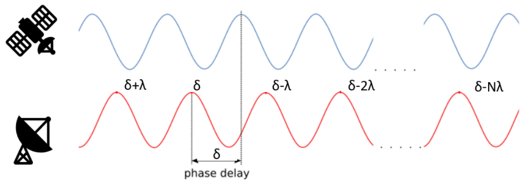


Figure 2.7: Phase delay, δ in the carrier-phase measurements, with N as the integer amount of cycles.

The distance between the source and the receiver of the signal can be determined with ρ in meters, as shown in this simplified formula;

$$\rho = N \cdot \lambda + \delta \tag{2.7}$$

where N the unknown number of full wavelengths the signal has completed, δ is the fractional part of a wavelength that completes distance and λ the wavelength in meters. The receiver compares his carrier wave with the one received from the satellite, and it simply does not know which cycle to compare to, as shown in Figure 2.7. Because the carrier-wave has a much higher frequency than the PRN (see Figure 2.3), the carrier-phase measurement positioning is very accurate. On the other hand, the number of integer cycles between the satellite and the user cannot be measured, as each cycle is the same as the previous one. Determining the amount of integer cycles N is known as the integer ambiguity resolution. To solve this problem, the PRN solution is first examined, after which the carrier frequency is used to improve the accuracy of the positioning from a few meters to a millimetre. As soon the distance-vector between the satellite and the antenna changes, the receiver counts all full phase-cycles and as a result provides a more accurate measurement. In other words, there is in principle only one unknown ambiguity for a whole time series of carrier-phase measurement to a certain satellite, namely at the start of signal tracking.
Since the same principle is used, the formula of the carrier-phase measurements is very similar to that of the pseudorange measurements (Equation 2.6), as can be seen in Equation 2.8.

$$\phi_r^s = \rho_r^s(t) + c(dt_r + dt^s) + T_r^s - I_r^s + \epsilon_r^s + \lambda N_r^s \tag{2.8}$$

The λ is the carrier wavelength and the integer carrier-phase ambiguity N_r^s (in cycles). The representation of the un-modelled phase errors is ϵ, and is the replacement of e_r^s in the pseudorange observation equation.
A discontinuity in a receiver's continuous phase lock on a satellite's signal is called a cycle slip. This can be caused by a low signal-to-noise ratio, a receiver or software failure, a power loss, a defective satellite etc. Most common, however, is that tall buildings and trees obstruct the signal. Under these circumstances, the signal is disturbed, the measurement is no longer continuous, but as soon as it is possible, the signal is restored. In pseudo-range measurements, cycle slips cannot occur, but carrier-phase measurements are affected if the slips are not detected and corrected for. With a cycle sludge the carrier-phase ambiguity (N) is no longer known, so it needs to be solved again for a "correct" position, also referred to as re-initialization.

2.3. GNSS errors sources

In this section, GNSS error sources are discussed, as well as the possible consequences and scale on which the error affects. The errors will be categorized in three different parts, based on the nature of the error. The clock-related errors include the errors related to the timing in both the satellite and the receiver. The atmospheric errors, multipath errors and the effect of the relative motion between the receiver and the satellite are grouped as signal propagation errors. The category system errors includes the receiver noise and the errors involved by sending the navigation massage. The information provided in the following paragraphs is is largely derived from a study by M. Karaim [33].

2.3.1. Clock related errors

The basis of the position determination of the receiver is the time it takes for the signal to propagate from the satellite to the receiver. To be able to measure this time very precisely, GNSS satellites are equipped with very precise clocks, hence expensive. Despite their accuracy, the clocks in the satellite still have a slight offset from the satellite time. The clock in the receivers is most of the time less expensive and less precise, which results in a larger bias.

Satellite clock related errors

There are three different factors that possible affect the GNSS satellite clocks; stability, relativistic effect and timing group delay (TGD). The so-called stability of a satellite is estimated at 8.64 to 17.28ns a day, which results in a range error of about 2.59 to 5.18m.

Both the general and the special relativity theorem will affect a clock aboard a satellite. This means that the clock in the satellite goes faster, than exactly the same clock that stays on Earth by approximately 38.4μs, which result in a range error of about 11.512m. This effect is compensated for by a offset that is introduced to the satellite clock rate before the satellite is launched.

The control segment send navigation messages to the satellite, including a satellite clock correction. The satellite sends these correction, through the navigation message, to the receiver.

Receiver clock related errors

Most of the receivers have clocks that have a low accuracy, compared to satellite clocks; as a result, the error occurring in the receiver is larger. The error is however receiver-type dependent, and the offset (in meters) can therefore be very different. One of the two possible solutions to this problem is the use of the so-called atomic clocks, but for many users they are unaffordable. The other, more common, solution is to approach the error as an extra unknown in the pseudorange observation equation, as discussed in Section 2.2. If the receiver clock bias is added to the equation of unknowns, a fourth satellite is needed to make the equation valid. However, there are limitations to the clock bias, as the clock in the receiver is used to add a time tag to the output of the receiver. This tag is used for time synchronization between the different GNSS systems, and has to have a certain accuracy.

Intersystem clock biases

To ensure that the availability and accuracy of a GNSS receiver is maximised, of combination of different GNSS systems is often used. Each constellation has its own system time, which means that inter-system clock biases must be considered when using multiple GNS systems. These biases are determined by introducing another new unknown in the pseudorange-equation of unknowns, which represent the time difference between the different GNSS constellations. The receiver clock bias can now be calculated by the summation of the internal and inter-system clock bias, as presented in Equation 2.9.

$$dt_r = dt_{r,intern} + dt_{r,intersystem} \tag{2.9}$$

2.3.2. Signal propagation errors

There are four types of errors that belong to the category of signal propagation errors; sagnac errors, ionospheric errors, tropospheric errors and multipath errors.

Sagnac errors

If the location of the receiver is determined by GNSS, it is important that the position of the satellite and the user are in the same reference frame; Earth Centered, Earth Fixed (ECEF) reference is generally used, for more information please refer to Section 2.7. However, the effect of the rotation of the Earth during signal transit time, and therefore the ECEF reference frame, must be accounted for. It is referred to as Earth rotation corrector or sagnac correction. The effect is illustrated in Figure 2.8

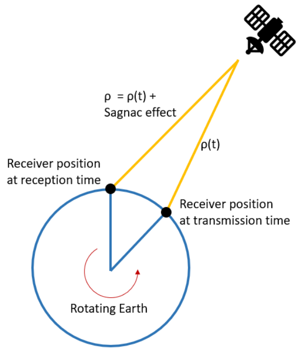


Figure 2.8: Effect of the rotation of the Earth in the signals transit time; sagnac error. The satellite position is at the time of transmission.

If the sagnac effect correction is taken into account, the pseudorange is calculated as the difference between the position of the receiver and the satellite and by adding the sagnac correction.

Ionospheric error
As the signal moves between the satellite and the Earth's surface, it passes through the atmosphere. The atmosphere has different layers, two of which have an sufficient effect on the electromagnetic signal; ionosphere and troposphere.
At an altitude of 100 to 1000km above the surface of the earth is the ionosphere, it consists mainly of charged ions and free electrons. These charged particles refract the signal, resulting in a change in direction and a decrease in speed. A decrease in speed makes it look as if the distance travelled is longer, so that the user seems to be at a bigger distance from the satellite. A major influence on the condition of the ionosphere is the intensity of the solar activity, the condition is therefore dependent on daily and monthly fluctuations. The distribution of electrons in the ionosphere varies throughout the day; in the afternoon the effect is maximal, the sun's radiation has created the largest amount of electrons. The minimal effect is during the night, when the same electrons attach themselves to the positive ions. There are also fluctuations during the seasons, as the amount of sunlight is not constant over a whole year. If the earth and the sun are positioned closer together, as in November, the delay is more than when the sun and the earth are further apart, as in July. In addition to changes over time, the delay also differs by region of the earth. Ionospheric disturbances are most severe in the area of the Earth that lies between 30°North and 30°South of the magnetic equator. The effect on a GNSS signal depends on the time it takes for the signal to pass through the shell of free electrons. If the signal comes from a satellite directly above the receiver, the path to be covered is the crust, so the error would be the smallest. In others, the longer the signal in the ionosphere is, the more significant is the effect of the delay.
The radius of the Earth is 6379km, so the thickness of the ionosphere (approximated at 900km) is quite thin compared with the size of the Earth, therefore the ionosphere is often modelled as a two-dimensional thin shell at a height of 350km. The ionospheric delay is computed by a receiver, using the Klobuchar model for GPS. The error is reduced by about 50% by this model, which uses the receiver's position, satellite's elevation, azimuth and time as input. This model is not suitable for the whole world. In areas further away from the equator, the thin-shell model is sufficient, but in areas around the equator, the ionosphere is thicker and cannot be simplified to a thin-shell model.
The ionosphere is dispersive; the delay caused depends on the frequency of the signal. The PRN, and the navigation message are slowed down, known as the group delay, but the carrier wave appears to accelerate. By working with dual-frequency receivers, an ionosphere free linear combination can be calculated, which can compensate for the delay of the ionosphere. For more information about dual-frequency, please refer to Section 2.4.

Tropospheric error
After the signal has passed the ionosphere, it has to pass through the troposphere. The troposphere is the lowest part of the atmosphere and reaches from the Earth's surface up to $20 km$ above sea level. Although the troposphere is electrically neutral, it influences the signal through dry gases and water vapours. The wet component is difficult to predict and put in a model, but it accounts for only 10% of the delay. On the other hand, the dry component is responsible for the rest of the delay, fortunately this is easier to model. Due to a difference in density with the layers above, there is an angular deviation, but this is of limited influence. The GNSS signal that travels the shortest distance between the satellite and the receiver loses the least energy to the atmosphere by "friction", so it has the least delay.
The atmosphere is subject to a constant change, with the temperature having a major impact. The temperature in the troposphere, on the surface of the earth and at various altitudes, varies according to latitude, season, time of the day, regional weather, etc. In general, one can see that if the temperature is higher, there are more wet components present thus the delay is larger.

Multipath error
If the satellite's signal has gone though the ionosphere and troposphere, it's almost at the receiver. However, there may still be an error, because the signal does not reach the receiver directly. It is possible that the signal is reflected by surrounding structures or the ground. This phenomenon is shown in Figure 2.9. The antenna is the first to receive the signal that goes directly, i.e. the Direct Line-Of-Sight (DLOS) signal, after which the reflected signals arrive. The multipath effect can have an adverse effect on the accuracy with which the position is determined, and strongly depends on the environment in which the antenna is located; tall buildings or structures have the most effect. The multipath error can partly be solved by placing the antenna at a high point, thinking of a tower of rooftop. Since this is not always feasible, there is another possible solution: the use of a choke ring antenna.

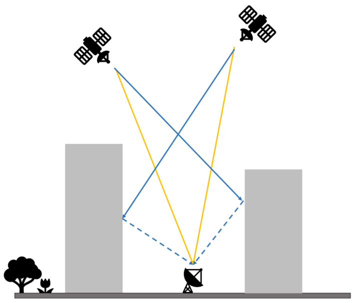


Figure 2.9: The effect of multipath, the yellow lines represents the DLOS and the blue lines the signals reflected by tall buildings near the antenna.

2.3.3. System errors
Some of the errors occurring in the GNSS system are form the overall nature of the system; here the shape of the orbit and the receiver structure will be discussed.

Satellite orbit errors
The position of the antenna is determined by the distance between the satellite and the receiver, but this requires the location of the satellite. This position can be approximated using advantages mathematical models, however in most cases this is not accurate enough. The residual error can be corrected if global or locate network corrections are available.

Receiver noise
When using electronics, including an antenna and receiver, the so-called white noise often occurs. It is a complex error that is generated, and can never be completely prevented. However, if more advanced technology is used, the error can be minimized however it will never completely disappear.

2.3.4. Human based errors

During practical work there are many types of human based errors that can occur. The rule of thumb is that if the process consists of more complex steps, the risk of human errors is higher. Some incorrect actions, however, have more effect than others, in this section the most essential and common errors are discussed. One of the most frequent problems is the incorrect setting of the measuring instruments; the positioning of the antenna, the incorrect configuration of the receiver and the incomplete construction of the setup. The users can choose to position the antenna in the wrong or unfavourable way, after which the location determination is subject to e.g. multipath. Once the antenna is in place, the next step is to properly configure the receiver with the help of various software packages, which can contain -sloppiness- errors. In some cases the receiver will not work at all, or it will give incorrect measurements. The last category is setting up the setup incorrectly, for example for forgetting the ground plate that has to be placed under the antenna, or not connecting the antenna properly to the receiver. In addition to these set-up errors, there are also errors that are based on stress, fatigue or inaccuracy. Due to these factors, it is possible that hasty and ill-considered decisions are made, causing the measurement to fail. In addition to the human based errors described above, it is very important that the right equipment is purchased and taken into the field.

2.3.5. Summary of the errors

In the paragraphs above several GNSS error sources are discussed, these are divided into different categories; clock-related, signal propagation, system and human based errors. The consequences of these errors are shown in Table 2.1, which shows the consequences of the error.

Table 2.1: Summary of the described errors.

Error category	RMS range error [m]	"Solution"
Clock error	3	Relative and simultaneous measurements
Signal propagation	5	Modelling, dual-frequency, relative positioning, placing antenna
System errors	2	Precise orbit models, More high-end equipment
Human errors	Depends	Manuals

2.4. GNSS frequency bands

As mentioned before, GNSS satellites broadcast signals, where the carrier wave has a frequency of 1 to $2GHz$, this range is called the L-band. In the L-band several sub-frequency bands are defined by the International Telecommunications Union (ITU) .
Two different domains in the L-band spectrum have been defined for satellite navigation; the upper L-band (1559 - 1610MHz) and the lower L-band (1164 - 1300MHz). This part of the spectrum is also called the Radio Navigation Satellite Service (RNSS) band. There is also the Aeronautical Radio Navigation Service (ARNS), the purpose of which is navigation by safety-critical application in which interference may not occur. Each satellite constellation uses slightly different frequency ranges, this is shown in Figure 2.10.

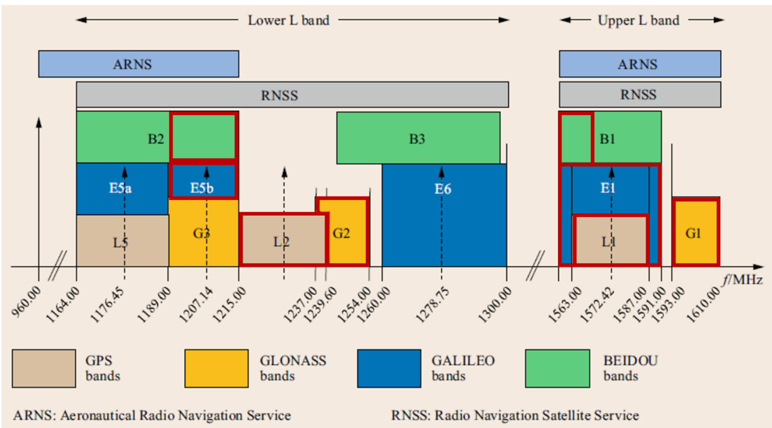


Figure 2.10: According to the GNSS Handbook [57]; frequency bands used by different satellite constellations for GNSS applications. The blocks with a red outline are used in the receiver used for this study.

2.4.1. Multi-frequency

As the signal moves between the satellite and the receiver on the Earth's surface, it passes through the ionosphere. The ionosphere consist of mainly charged ions and free electrons that refract the signal, resulting in a change in direction and a decrease in speed. For more information about the ionospheric delay and the errors that are occur in the positioning due to this delay, please refer to Section 2.3. The ionosphere is dispersive; the delay caused depends on the frequency of the signal. The time delay for a higher frequency wave is less than it is for a lower frequency wave, That means that L1 (1575.42MHz) is less affected than L2 (1227.60MHz) and L5 (1176.45MHz). The differences between the L1 and L2, L1 and L5 and even L2 and L5 are sufficiently large to help with the estimation of the ionospheric group delay. Therefore, by tracking all the the carrier waves, a multi-frequency receiver can determine by modelling a significant part of the ionospheric error. There are several possible combinations for dual-frequency instead of multi-frequency; L1/L2, L1/L5 and L2/L5 for the GPS satellite constellation. For Galileo, Glonass and BeiDou the way of operating is essentially the same, the bands that are used for the low-cost receiver of interest in this research are shown in Table 2.2

Table 2.2: Overview of the dual-frequency pairs.

Signal	GPS	Galileo	Glonass	BeiDou
Single frequency	L1	E1	L1	B1
Dual-frequency	L1 and L2	E1 and E5	L1 and L2	B1 and B2

The so-called Ionospheric Free (IF) combination for GPS with the L1 and L2 frequencies is expressed for the pseudo-range;

$$\begin{aligned} \rho_{IF} &= \frac{f_{L1}^2}{f_{L1}^2 - f_{L2}^2} \cdot \rho_{L1} - \frac{f_{L2}^2}{f_{L1}^2 - f_{L2}^2} \cdot \rho_{L2} \\ \rho_{IL} &\approx 2.546 \cdot \rho_{L1} - 1.546 \cdot \rho_{L2} \end{aligned} \tag{2.10}$$

where the p_{IF} the ionosphere-free pseudorange measurement is, and the f_{L1} and f_{L2} the frequency for respectively the $L1$ and $L2$ band. This ratio of frequencies is multiplied with ρ_{L1} and ρ_{L2} that is the "original" pseudorange measurements for the $L1$ and $L2$ band. The pseudo-range equation, as presented in Equation 2.6, can be adjusted for the ionospheric free combination and results in a new equation of the pseudo-range measurements;

$$p_{IF}^s = \rho_r^s(t) + c(dt_r + dt^s) + T_r^s + e_r^s \tag{2.11}$$

In addition to the pseudo-range, carrier-wave measurements can be used, which applies to the GPS signals L1 and L2;

$$\begin{aligned} \phi_{IF} &= \frac{f_{L1}^2}{f_{L1}^2 - f_{L2}^2} \cdot \phi_{L1} - \frac{f_{L2}^2}{f_{L1}^2 - f_{L2}^2} \cdot \phi_{L2} \\ \phi_{IF} &\approx 2.546 \cdot \phi_{L1} - 1.546 \cdot \phi_{L2} \end{aligned} \tag{2.12}$$

where the ϕ_{IF} the ionosphere-free carrier-wave measurement is, the f's are the same as in Equation 2.10, but instead of a multiplication with the pseudorange measurement, the "original" carrier-wave measurements are used. The previous presented carrier-wave equation, Equation 2.8, can be modified to remove the atmospheric biases;

$$\phi_{IF}^s = \rho_r^s(t) + c(dt_r + dt^s) + \epsilon_r^s + \lambda M_r^s \tag{2.13}$$

2.5. Differential GNSS

One of the ways to improve position accuracy is to use Differential GNSS (DGNSS), also called Relative GNSS (RGNSS); it combines information from one (or more) reference stations with another station, called the rover. Observations to the same satellite are differenced between receivers (single difference), and then single differences are differenced between pairs of satellites (double difference). On the condition that all data is collected in the same epoch. This step-by-step approach eliminates satellite and receiver clock errors and reduces the effects of the satellite orbit and ionospheric and tropospheric delay errors. This is applicable for the relative position between the two receivers. In principle, a corresponding approach could be using pseudorange, resulting in a lower accuracy.

2.5.1. Single Differencing

There are two types of single difference, the so-called between-receiver and the between-satellite differencing. For both of the situations is it of importance that both receivers track the same satellites simultaneous. In the situation of the between-receiver, there is one satellite with two different receivers placed on the Earth's surface, as can be seen in Figure 2.11a. Since this arrangement is used, the clock error can be removed from the carrier-phase measurements formula; this bias is the same for both measurements on the receivers, while all the other parameters are different. How this is established is explained using the formulas below:

$$\begin{aligned} \phi_{r1}^{s1} &= \rho_{r1}^{s1}(t) + c(dt_{r1} + dt^{s1}) + T_{r1}^{s1} - I_{r1}^{s1} + \epsilon_{r1}^{s1} + \lambda M_{r1}^{s1} \\ \phi_{r2}^{s1} &= \rho_{r2}^{s1}(t) + c(dt_{r2} + dt^{s1}) + T_{r2}^{s1} - I_{r2}^{s1} + \epsilon_{r2}^{s1} + \lambda M_{r2}^{s1} \end{aligned} \tag{2.14}$$

By subtracting the observations of both receivers, the difference between the two receivers is revealed, this is presented in Equation 2.15 and is visualized in Figure 2.11c.

$$\begin{aligned} \phi_{r1,r2}^{s1} &= \phi_{r2}^{s1} - \phi_{r2}^{s1} \\ \phi_{r1,r2}^{s1} &= \rho_{r1,r2}^{s1}(t) + c(dt_{r1,r2}) + T_{r1,r2}^{s1} - I_{r1,r2}^{s1} + \epsilon_{r1,r2}^{s1} + \lambda M_{r1,r2}^{s1} \end{aligned} \tag{2.15}$$

If the setup is such that the distance between the two receivers is less than $10km$, then it can be assumed that there is no difference in atmospheric delay between the two carrier-phase measurements (ϕ_r^s), i.e. the $T_{r1,r2}^{s1}$ and the $I_{r1,r2}^{s}$ can be removed from the equation, both this delay are approximately zero meter;

$$\begin{aligned} \phi_{r1,r2}^{s1} &= \phi_{r1}^{s1} - \phi_{r2}^{s1} \\ \phi_{r1,r2}^{s1} &= \rho_{r1,r2}^{s1}(t) + c(dt_{r1,r2}) + \epsilon_{r1,r2}^{s1} + \lambda M_{r1,r2}^{s1} \end{aligned} \tag{2.16}$$

were $M_{r1,r2}^{s1}$ the carrier-phase ambiguity represents, this is a real number. If further calculations are made using the above formula, the carrier-phase ambiguity M_r^s can be written as;

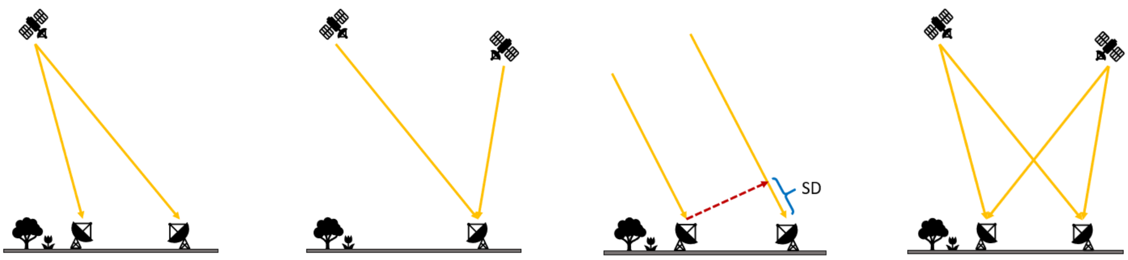
$$\begin{aligned} M_{r1}^{s1} &= \phi_{r1} - f \cdot \delta t_{r1} + N_{r1}^{s1} \\ M_{r2}^{s1} &= \phi_{r2} - f \cdot \delta t_{r2} + N_{r2}^{s1} \end{aligned} \tag{2.17}$$

where δt_{r1} and δt_{r2} represents respectively the clock error at receiver $r1$ and $r2$. The integer ambiguity is written as N_r^s per receiver. By subtracting the ambiguity of $r1$ and $r2$ from each other, this results in the single difference ambiguity;

$$\begin{aligned} M_{r1,r2}^{s1} &= M_{r1}^{s1} - M_{r2}^{s1} \\ M_{r1,r2}^{s1} &= \phi_{r1,r2} - f \cdot \delta t_{r1,r2} + N_{r1,r2}^{s1} \end{aligned} \tag{2.18}$$

Here, seeing that the single difference ambiguity consists of an integer ambiguity N, plus a factor with real numbers, this results in a real valued parameter. In the second situation, between-satellite, there is one receiver, with two different satellites, as shown in Figure 2.11b. Because one receiver is used, the receiver clock error can be extracted from the formula of the carrier-phase measurements, as presented in Equation 2.19. For the between-satellite situation, the comparison of the carrier-phase measurement applies;

$$\begin{aligned} \phi_{r1}^{s1,s2} &= \phi_{r1}^{s1,s2} - \phi_{r1}^{s1,s2} \\ \phi_{r1}^{s1,s2} &= \rho_{r1}^{s1,s2}(t) + c(dt^{s1,s2}) + T_{r1}^{s1,s2} - I_{r1}^{s1,s2} + \epsilon_{r1}^{s1,s2} + \lambda M_{r1}^{s1,s2} \end{aligned} \tag{2.19}$$



(a) Single difference; between-receiver.

(b) Single difference; between-satellite.

(c) Single Difference, between-receiver; difference between the two receivers.

(d) Double difference.

Figure 2.11: Single- and double- difference of the carrier-phase measurements.

2.5.2. Double differencing

If the between-satellite and the between-receiver single difference are combined, the double-difference is obtained. The setup consists of two receivers ($r1$ and $r2$) and two satellites ($s1$ and $s2$), as shown in Figure 2.11d. This combination eliminates both the receiver clock error, dt_r and the satellite clock error, dt^s. The formula of the non-differenced carrier-phase measurement is then;

$$\begin{aligned}\phi^{s1}_{r1,r2} &= \rho^{s1}_{r1,r2}(t) + c(dt_{r1,r2} + dt^{s1}) + T^{s1}_{r1,r2} - I^{s1}_{r1,r2} + \epsilon^{s1}_{r1,r2} + \lambda M^{s1}_{r1,r2} \\ \phi^{s2}_{r1,r2} &= \rho^{s2}_{r1,r2}(t) + c(dt_{r1,r2} + dt^{s1}) + T^{s2}_{r1,r2} - I^{s2}_{r1,r2} + \epsilon^{s2}_{r1,r2} + \lambda M^{s2}_{r1,r2}\end{aligned} \tag{2.20}$$

This way, the satellite and receiver error will cancel. However, both receivers must track the same satellites at the same time. If there are K of satellites; subtract the single difference observation of one reference satellite from all other single difference observations. One unknown (single difference) receiver clock error) cancelled out, but there is also one observation less.

$$\begin{aligned}\phi^{s1,s2}_{r1,r2} &= \phi^{s1}_{r1,r2} - \phi^{s2}_{r1,r2} \\ \phi^{s1,s2}_{r1,r2} &= \rho^{s1,s2}_{r1,r2}(t) + T^{s1,s2}_{r1,r2} - I^{s1,s2}_{r1,r2} + \epsilon^{s1,s2}_{r1,r2} + \lambda N^{s1,s2}_{r1,r2}\end{aligned} \tag{2.21}$$

where $\phi^{s1,s2}_{r1,r2} = \phi^{s1,s2}_{r2} - \phi^{s1,s2}_{r1} = \phi^{s2}_{r1,r2} - \phi^{s1}_{r1,r2}$ and besides, the real-valued parameter $M^{s1,s2}_{r1,r2}$ has been changed to the integer parameter $N^{s1,s2}_{r1,r2}$, also called the double-difference phase ambiguity. This can be written in formula form;

$$N^{s1,s2}_{r1,r2} = M^{s2}_{r1,r2} - M^{s1}_{r1,r2} \tag{2.22}$$

In order to be able to determine a correct position, this N value must be solved, next to the double-differencing geometric range, -tropospheric delay, and the -ionospheric effect (which can be neglected in case of sufficiently short baselines of max $10km$), as before $I^s_{r1,r2} \approx 0$ and $T^s_{r1,r2} \approx 0$

2.5.3. Summarized step-by-step approach of ambiguity resolution

It is now clear how the single differencing and double differencing work; here is a brief summary of how to solve the ambiguity resolution, according to the step-by-step plan visualized in Figure 2.12.

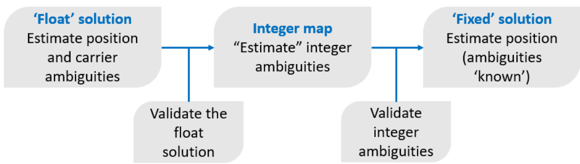
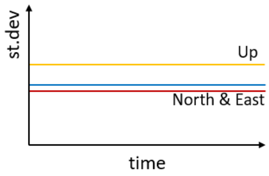


Figure 2.12: Step-by-step approach of resolving the ambiguity resolution, starting with the float solution and via an integer mapping process to the float solution.

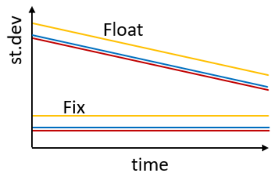
The integer ambiguities $N^{s1,s2}_{r1,r2}$ -for all satellites during an observation- are determined as estimators, collectively with the coordinates of the receiver and (possibly) the tropospheric delay error. The ambiguities are first estimated, using least square or a Kalman filter, as floating-point numbers, this solution is called the float-solution. There are several ways to improve the accuracy of the position determination, for example with LAMBDA. The ambiguities are then fixed, resulting in a integer value for the ambiguities value of N; the resulting solution is called the fixed-solution. If the ambiguity is fixed, the phase measurement has actually become a pseudo-range measurement, but one that is more precise. Resulting in a more precise position determination. Successful ambiguity resolution is depended on different factors, among other factors the length of the baseline (smaller distance is better), the number of satellites that are traceable (more satellites gives a better result), continuous tracking of satellites, amount of multipath (less is better), the number of frequencies observed (two is better than one) and the duration of the observation session (the longer the better the result).

The float solution becomes more accurate after a long time (think of a measurement of at least 1 hour); comparable with the results of the fix solution. This can be seen in the simplification of the real situation in Figure 2.13, where the carrier-phase measurements can be seen on the right side in Figure 2.13b. On the left side one can see the standard deviation of the position determination of pseudorange measurements for comparison.

For more information about these graphs, please refer to the CIE4522 GPS course [2] at the faculty of Civil Engineering at the TU Delft.



(a) Pseudorange standard deviation.



(b) Standard deviation of the carrier-phase measurements. Difference between fix- and float solutions over time.

Figure 2.13: A simplified visualisation of the standard deviation of the position determination with pseudorange and carrier-phase measurements compared. In carrier-phase the difference between the fixed and the float solution can be seen. In both graphs the yellow line is the Up-, red and blue the North- and East- component. The time is logarithmically indicated here and only two epochs are shown.

In addition to the fact that a longer observation time improves the result, this also happens when the frequency of observations is increased in this period of time. More observations will always help for a more accurate result, but in this situation it is also important that the geometry of the satellite constellations in relation to the receivers changes. Therefore it is too hasty to say that if there are 5 measurements per second instead of 1, the ambiguity resolution will also be found 5 times faster.

2.5.4. Dual-frequency for ambiguity resolution

Until now, the general principle of ambiguity resolution has been explained; this resolution depends on the signal. The solution can be determined faster and more accurately if dual-frequency is used. When looking for the integer to convert the float solution into a fix solution, two signals must be taken into account in the case of dual-frequency. The number of integers on one frequency must correspond to a number of integers on the other frequency. There are substantially fewer possibilities for this, which increases the speed of solution finding. It is important to note that the second frequency is then not used for the ionospheric delay determination, in practice it is assumed that the ionospheric delay in receiver 1 and 2 are the same and can therefore be neglected.

2.6. Positioning modes

There is a wide diversity of GNSS positioning modes, with a difference in precision, accuracy but also in complexity. In general, as complexity increases, so does the accuracy of the results. The different positioning modes can be divided into three categories; precise point positioning, code differential positioning and carrier-phase differential positioning.

2.6.1. Precise positioning modes

Single Point Positioning

Single Point Positioning (SPP) is the foundation of GNSS positioning. The technique is founded on pseudorange measurements of at least four different satellites. In the previous paragraphs, where the workings of GNSS were explained, the focus was on SPP. There are several variants of positioning based on this method.

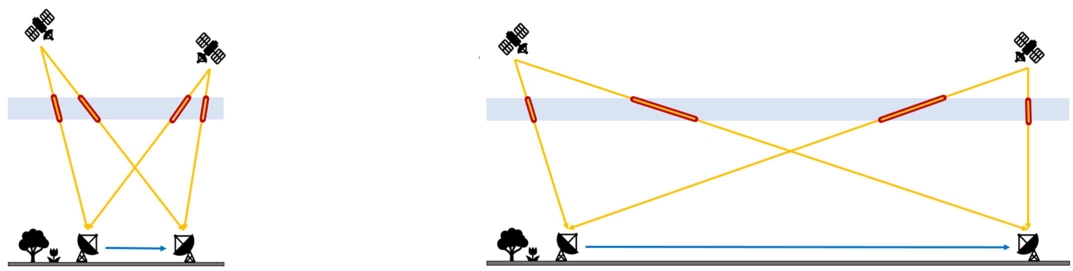
Precise Point Positioning

An more advanced version of the SPP technique is the Precise Point Positioning (PPP), it is a positioning procedure that performs precise position determination using a single GPS receiver. To accomplish a high level of position accuracy the PPP technique models GNSS system errors and possibly removes them. The accuracy of positioning is improved by using dual-frequency receivers, which provides a solution for the atmospheric delay to which the signal is subject. The position determination also depends on the satellite clock- and orbit- corrections; after the rectifications are determined, they are sent to the end-users via satellite or via the Internet. One of the organisations that provides this service is the International GNSS service (IGS). The corrections are put in use by the receiver, resulting in decimetre-level positioning with only one GNSS receiver required. Delicate effects, such as Earth- and ocean tides, offsets in the satellite and receiver antenna are also modelled and the observations can be corrected for these effects. The time it takes to capture the receiver signal and convert it into a solution can take up to 30 minutes under normal conditions, and with the most advanced techniques it can take up to 20 minutes .

Real-time kinematic and post-processed kinematic positioning
In Real-Time Kinematic (RTK) positioning and Post-Processed Kinematic (PPK) is a DGNSS technique; a reference station is set up at a known location, which transmits carrier-phase and pseudorange data over a communication link to a (moving) GNSS receiver, called the rover. The vector between the reference station and the rover is called the baseline. This set-up is visualized in Figure 2.14, where the receiver on the left side represents the reference station and the one on the right side the rover. Single- or dual-frequency GNSS receivers can be used for this purpose, in which the dual-frequency can generally arrives at a fixed solution in a shorter time, with a higher accuracy in position determination. RTK is based on the idea that, with the important exception of multipath and receiver noise, GNSS error sources are similar for the reference station and the rover station. In other words, if the rover is close to the reference station, the more errors are similar.

The reference station is positioned at a known location; it is able to calculate corrections, this is done in real-time. These corrections are based on the difference between the known location and the location that is calculated from the satellite constellations that are in view and can be tracked at that moment. The corrections can then be sent to the rover in different ways. The difference between RTK and PPK lies in the fact that the corrections are not sent in real-time in PPK, but are dealt with by post-processing.

There is a substantial difference between RTK/PPK with long-baselines and with short-baselines, where a maximum distance of about $20km$ is considered for short-baselines and from $50km$ for long-baselines. Because the distance between the rover and the reference station is so small that it can be assumed that the atmospheric delay for both receivers is the same. The correction coming from the reference station therefore contains the atmospheric biases, so that the rover naturally considers them when determining its position. This makes single frequency sufficient, however if dual-frequency is available both frequencies can be used as separate observations to assist in the ambiguity resolution. For long baselines, it is necessary to use precise orbits, e.g. from IGS. To handle the ionospheric delay, dual-frequency receivers are required. It can be used to determine the ionospheric free measurements, as described in Section 2.3, in consequence the ambiguity resolution is more difficult. The difference between short-baselines and long-baselines can be seen in Figure 2.14. On the left side one can see the short-baseline (Figure 2.14a), where the red parts of the signal indicate where the signal passes through the ionosphere. As one can see, the distance (and therefore the time) that the signal passes through the ionosphere is about the same for short-baselines. With long-baselines (Figure 2.14b) there is a more substantial difference, so it would be too much of a simplification if it were said that the delay is the same.
Both for short and long baselines the coordinates of the reference point should be in the same reference system and of the same quality as the satellite orbits, long baselines makes use of precise orbits and therefore this implies that the coordinates of the reference station should be with centimetre precision.



(a) RTK and PPK for short-baseline situation.

(b) RTK and PPK for long-baseline situation.

Figure 2.14: Differences in short- and long-baselines for RTK and PPK positioning modes.

RTK positioning is a procedure used by an RTK-enabled GNSS receiver to acquire position estimations by using data from a reference station. The data is transmitted over the internet, radio or due to post-processing. The NTRIP protocol (Networked Transport of RTCM via Internet Protocol) (Appendix B) enables the rover to access data from the RTK reference station over an online connection to attain, in theory, $1cm$ accuracy. The reference station receiver is arranged to the known position of this point during equipment arrangement. The receiver placed at the reference station continuously observes the satellites in view and estimates positions that are transmitted to the rover, called base data.

2.6.2. Summary of Positioning modes

Different positioning methods have now been explained, but now the question remains how they relate to each other. The difference can be found in the type of measurements that are made; RTK and PPK are carrier phase methods and are significantly more accurate than DGNSS, a code-based method. This creates a general tendency to use RTK or PPK. However, the advantage of DGNSS is that it is more suitable for longer baselines. An overview between these two methods in which the possible accuracy can be weighted against the length of the baselines is shown in Figure 2.15.

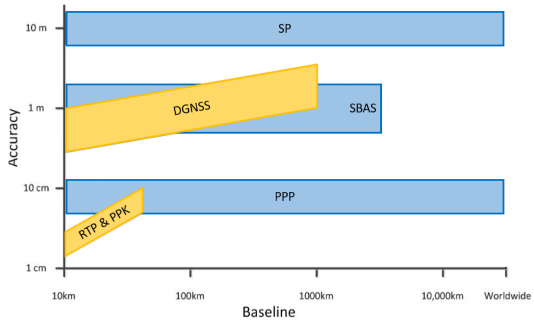


Figure 2.15: Comparison between different GNSS positioning modes, focus on difference between DGNSS and RTK. Based on a figure from Novatel [26]

2.7. Reference systems

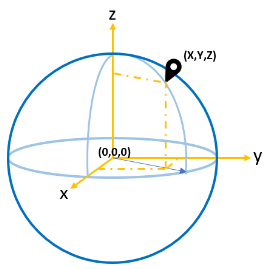
To describe the position of points a (mathematical) framework is needed, consisting of a coordinate reference system. There are many coordinate reference systems, with each their own application, so only a few evident systems are discussed in the following paragraphs. The height always plays a special role in reference systems, and is closely associated with the flow of water.

2.7.1. Horizontal reference systems

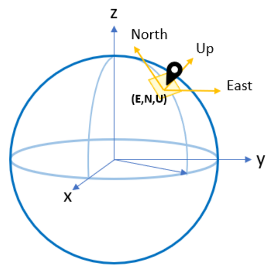
Cartesian coordinate systems

One of the most straight forward methods to give the position of an object in 3D space is by three coordinates X, Y and Z in a Cartesian coordinate system. The coordinates are defined with respect to reference point (0,0,0). For the Earth Centered, Earth Fixed (ECEF) reference system the origin is chosen as the centre of the Earth. Instead of a global terrestrial system, also a local 3D topocentric Cartesian reference system can be defined; East-North-Up (ENU) reference system. The Y-axis is pointing in the North direction, the X-axis in the East direction and the Z-axis in the Up direction. The origin is somewhere on the surface of the Earth; and can be moved at any time. For the coordinates it is common to use the letters E for East, N for North and U for Up.

Figure 2.16 gives an overview of the two types of Cartesian coordinates that are described here; ECEF and ENU.



(a) Earth Centered Earth Fixed Cartesian coordinate system.



(b) East-North-Up Cartesian coordinate system.

Figure 2.16: Cartesian coordinate systems.

Spherical and ellipsoidal coordinate systems
Although straightforward , Cartesian coordinates are not very convenient for representing positions on the (curved) surface of the Earth. For this purpose it is more convenient to use curvilinear coordinates defined on a sphere or ellipsoid.
Geocentric spherical coordinates take as their starting point a sphere with radius R approximating the mean radius of the Earth ($6371km$). The coordinates ψ, λ and r can be used to represent positions on a sphere. In this case the Earth is simplified as a sphere, with ψ the geocentric latitude and λ the longitude of the point. The radius of the Earth (R) and the height above the reference sphere (h') combined define the vertical component r. The sphere is not a very convincing approximation of the surface of the Earth and the heights defined with respect to the sphere are in most cases meaningless. Closely related to the spherical coordinates are the ellipsoidal coordinates. The position of an object with respect to an ellipsoid is given in terms of geographic or geodetic latitude ψ, longitude λ and height h above the ellipsoid. In Figure 2.17 the spherical and ellipsoidal coordinates are visualized.

(a) Spherical coordinates with radial distance (R), polar angle (θ) and azimuth angle (ϕ).

(b) Ellipsoidal coordinates with in blue the longitude (λ) and in green the latitude (θ).

Figure 2.17: Spherical and ellipsoidal coordinates.

2.7.2. Vertical reference systems

A point on the surface of the earth is not only defined by its horizontal positioning. In this context, there is a third component; its height. Traditionally, surveyors refer to this segment of a position as the elevation. One of the classical methods to determine the elevation is with the use of levelling. A level, correctly located on the surface of the earth, defines a line parallel to the geoid at that particular point. The elevation is then orthometric; it is defined by the vertical distance between the point of interest and the geoid as it would be measured along a plumb line. These elevation estimations are not directly available from the geocentric position vectors derived from GPS measurements.

Ellipsoidal heights
Modern geodetic datums are based on the surfaces of geocentric ellipsoids to approach the surface/shape of the Earth. Since there is a ever-changing topography on the earth surface the actual surface of the Earth does not coincide with the approximations. The distance depicted by a coordinate on the reference ellipsoid to the point on the Earth's surface is calculated along a line perpendicular to the ellipsoid. This distance is called the ellipsoidal height and also know as the geodetic height, usually h is the corresponding symbol. Ellipsoidal heights are not generally directly related to elevation; it is not determined in the more-conventional sense of up or down. The ellipsoidal height is visualized in Figure 2.19.
The ellipsoidal height of a point can be determined using a GNSS receiver. It is within the capabilities of GNSS to measure the distance between the Earth's geo-centre and any point on the Earth's surface, or even above.
The GNSS satellites orbit around the centre or mass, but the concept of where the surface of the Earth is, is unknown to them. The surface-based receiver, determines the position in the horizontal plane. If the GNSS has the parametrisation of the reference ellipsoid included in its software, the vertical position of the receiver can be estimated. However, the ellipsoidal height depends on which model of the reference ellipsoid is used. The curvature of the ellipsoid and its origin can be different for each model; as the datum changes, the ellipsoidal height changes.

Geoid height
Another approach to determine the elevation is to use the earth's gravitational field. Every object on or around the earth contains potential energy derived from gravity in the the direction of the Earth's center. Quantifying

this energy is a method to determine the elevation, because the amount of potential energy of an object depends on the gravity that depends on the distance between the centre of mass and the object. When points with the same potential energy are connected to each other, this is called equipotential surfaces. There are an infinite number of these surfaces, where the geoid is the most important and best known. It is defined in such a way that it best matches the Mean Sea Level (MSL). MSL is not an equipotential surface, because more forces than gravity have an effect on the sea level. It is not a smooth surface, as gravity is not coherent across the surface of the earth. At each point gravity has a size and a direction, which can be described with a vector. Due to differences in topography and composition of the earth, these vectors have different values and directions. Some parts of the earth are denser than others; where there is high density there is more gravity [55]. Figure 2.18 shows a map with the geoid shown in different colours. On the right and left hand side one can see the Netherlands and Tanzania respectively. Important note is that the scales are different in the maps. The change in geoid, over the depicted red lines, is determined; in both the Netherlands and Tanzania is the gradient 0.02 m/km. However, as can be seen on the map, there has been more change in the region of Dar es Salaam. The geoid has a change of 10 meters, over a distance of 140 km, resulting in a gradient of 0.07 m/km.

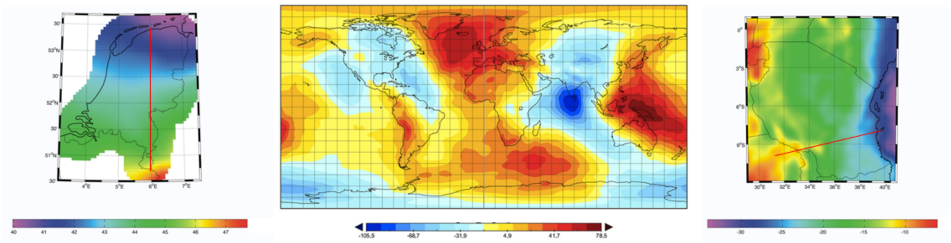


Figure 2.18: Comparison of the geoid in Tanzania and The Netherlands, with in the middle a worldwide overview. The scales are different, but all in meters. [55] [20]

The geoid height is the distance measured along a line perpendicular between the ellipsoid of reference to the geoid. These heights are negative if the geoid is below the reference ellipsoid and positive if the geoid is higher, and is usually symbolized by N. In Figure 2.19 one can see how the geoid height relates to the geoid, reference ellipse and Earth's surface.

Height conversion
The conversion between the different heights, ellipsoidal- (h) and geoid height (N), is made to determine the geodetic reference height (H). This conversion is done based on the formula:

$$H = h - H - N_0 \tag{2.23}$$

A constant offset (N_0) needs to be determined between the geoid and the vertical datum, it can reach several decimetres in value. The zero-point, also called date point, for the vertical component of a position depends on the potential for the chosen reference equipotential surface. This point is usually defined on title-page data in such a way that it is as close as possible to the MSL. This sounds easier than it is; different tide-gauges effects are measured in different countries, as the tide effects differ from one sea to another. In addition, some countries, such as Belgium, did not use the MSL before the height date, but the low water spring. In Figure 2.19 the relationship between heights with respect to this vertical datum is visualized.

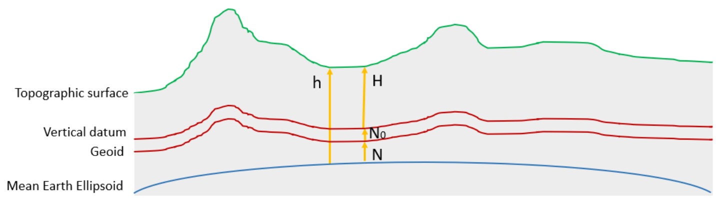


Figure 2.19: The different vertical heights visualized in one figure.

GNSS can only acquire the height of a point of interest with respect to a reference ellipsoid from its positioning observations. For computation of the ellipsoidal height to MSL, a record of precomputed geoid slopes can be

used within a GNSS receiver. For this purpose, models are used, all of which are an indication of reality. In the Netherlands, which is a topographically flat country, the model is a much better approach than is to be expected in Tanzania. The differences in topography, plus the low geoid height in the Indian Ocean, cause the model to give a poorer estimation.
It is very intuitive to say that water flows from a high point to a low point. However, the definition of high and low in this case is not sufficiently clear and should be commented upon. Since water bodies (large or small) have a mass, they are subject to gravity and have a certain potential energy. To determine how the water flows it can be said that it goes from high potential energy to low potential energy, or from a high to low geoid height. In a ellipsoidal height system, it is possible that water flows from a point with low 'height' to a high 'height'.

3

Literature review and performance indicators

This chapter provides the necessary review of literature, mainly comparing it with studies that preceded this thesis. In the first section, these studies are compared, starting with single frequency, followed by dual-frequency GNSS receivers. After a short summary, the focus is shifted to the different key performance indicators used in different studies to quantify the performance of the GNSS receiver. Finally, it is concluded which key performance indicators will be used in this thesis.

3.1. Comparative studies

This thesis follows in a long line of low-cost GNSS performance studies, but it is one of the first to focus on this specific low-cost, dual-frequency GNSS receiver. In the next few paragraphs, some of these studies will be introduced, giving a brief summary of the positioning method and equipment used, and the results obtained. The focus is first on studies that have taken place with low-cost single-frequency GNSS Receivers, using mainly Android smartphones. Subsequently, attention is paid to the Xiaomi smartphone, which is the first smartphone with an internal dual-frequency GNSS receiver.

Centimetre level accurate positioning, based on GNSS observations, can now be achieved by using relative or absolute positioning techniques using low-cost equipment. Until a few years ago, the only way to achieve this level of performance was by using high-cost geodetic quality GNSS receivers and antennas, capable of receiving and processing dual-frequency data. More recently, it has been shown that similar positioning performance can be achieved with low-cost, single-frequency RTK receivers when data from different satellite constellations are used [1] [2]. Precise positioning using low-cost equipment is especially important for developing countries, where there are no opportunities to purchase high-end equipment but people often do have a smartphone at their disposal [1].

3.1.1. Single-frequency positioning performance

When the Google's Application Programming Interface (API) was released in 2016, it became possible to extract raw GNSS single frequency data from Android devices, with the observations made by the internal GNSS receiver [19]. This achievement ensured that research was conducted into the positioning capabilities of low-cost Android smartphones (approximately 100USD), as an alternative to high-end receivers that are many times more expensive (several hundreds and thousand USD) [48].

In the same year that Google's API was released, the first performance studies started. The research by Banville and van Digglen [8] shows that centimetre-level precision is possible when using single frequency pseudorange, carrier-phase, and Doppler measurements collected from a Samsung Galaxy S7 smartphone. It takes three minutes before the position is determined with the PPP positioning mode, provided that information about the ionospheric delays is available a priori and a approximation of all measurement error sources can be provided.
In addition to the research into the performance of the raw GNSS observations of the Samsung smartphone,

Raelini et al [51] has done research on the Google/HTC Nexus 9 tablet. This tablet also has an internal GNSS receiver, where the raw measurements can be extracted. In this study, the positioning was performed by means of L1 phase double-differences observations, using the open source goGPS software, over baselines ranging from approximately $10m$ to $8km$. In this study, the same positioning procedure was applied to a u-blox receiver, in order to be able to display the differences in performance between the tablet and a low-cost single-frequency receiver. The result shows that with the Nexus 9 tablet decimetre-level accuracy can be achieved, even if no phase ambiguity resolution can be achieved. The u-blox receiver showed similar results, but the root-mean-square was twice as low in the Up component. It is expected that sub-centimetre level accuracy could be achieved, as the conservative GNSS receiver shows, provided that integer phase ambiguities could be solved.

The performance of the Nexus 9 tablet was further investigated in Gill et al [23], this time with a different approach; instead of just pseudo-range measurements, the carrier-phase is also included in this study. Gill's study uses static PPP positioning mode, again with single-frequency. Observations are made for ninety minutes, and for the best positioning result combined with orbit and clock information from the International GNSS Service [17]. To make the positioning even more accurate, a global ionospheric map is used to trace the ionospheric delays. Because there were no ground-truth coordinates, the authors were unable to draw a conclusive conclusion regarding the positioning accuracy. However, it could be shown that with this setup a solution can be achieved with a repeatability of 25, 28 and $51cm$ along perspectively the East, North and Up components.

A successor to the aforementioned Samsung Galaxy S7; the Samsung Galaxy S8+ was used together with the Huawei P10+ smartphone in a performance study by Dabove at al [15]. In this study, the RTK positioning mode was chosen and use was made of a 15-minute single frequency measurement in which both GPS and Glonass satellite constellations are traced by the receiver. The baseline length between the reference station and the rover was $50km$, with the corresponding solution having an accuracy of 0.6 and $1.5m$ for the Samsung and the Huawei smartphone respectively. As a possible cause of this accuracy difference it is suggested that the ionospheric error is different for the reference station and the rover, because the baseline length of $50km$ is too large. In addition, the incorrect placement of the smartphone is seen as a possible error-source. Resulting in a uncertainty about the location of the Huawei phone, what plays an important role in the accuracy determination.

The study by Odolinski and Teunissen 2016 [44] analyse low-cost single frequency RTK receivers that are able to perform and process BeiDou observations in addition to GPS. Both studies prove that the millimetre accuracy positioning performance is comparable to that of dual-frequency GPS RTK receivers, of which the accuracy is known to be millimetre-level achievable. In the paper published by Odolinski and Teunissen 2019 [46] two different types of low-cost RTK receivers, which can track L1 GPS, B1 BDS, E1 Galileo and L1 QZSS or any combinations thereof, for a location in Dunedin, New Zealand, are examined for the first time. The best performing low-cost single-frequency RTK receiver, the u-blox with L1+L1+B1+E1 frequencies, is compared with a double-frequency GNSS receiver afterwards. The low-cost single frequency achieves similar results as the double-frequency receiver, except that the single-frequency receiver takes longer to achieve a fix solution. The results are in all cases, provided that only the fix solutions are considered, $2cm$ accurate.

3.1.2. Dual-frequency positioning performance

So far the focus has been mainly on single frequency receivers, sometimes as a separate receiver, sometimes integrated in a smartphone. In June 2018 the Xiaomi Mi 8 was released, this is the first dual-frequency capable smartphone, capable of tracking L5/E5a and L1/E1 frequencies [24]. This not only aims to improve positioning performance by being able to track ionospheric delays, but will also allow for he assessment of multipath [21].

Fortunato et al [21] has performed an analysis of the PPP and RTK performance of the Xiaomi dual-frequency measurements, in a sub-urban environment. It appears that both the PPP and RTK had a positioning accuracy that fell within a range of a few meters and has a very low repeatability. As a possible cause, the very-small sample of observations is mentioned. With this research in mind, Wu et al [64] conducted further research, but now with PPP static and kinematic positioning mode. The result shows that the root-mean-square-error for the East-, North- and Up- components are respectively 4.1, 21.8 and $11.0cm$ for a 6-hour static measure-

ment. The best result achieved in kinematic mode was low; at meter level.
The study conducted by Psychat et al [50] examines for the first time the raw measures of the Xiaomi smartphone, which draws a comparison between the SPP and the PPP positioning modes. It was found that the GPS and Galileo code measurements are allowed to vary within a bound of ±5.5 and ±4.9m for 99.7% of the time.

3.1.3. Summarized similarities and differences in previous studies

The main similarity between all these studies is that they have all experimented with low-cost GNSS receivers, analysing the raw observation data. Initially, research was mainly conducted into the performance of single-frequency receivers, after which the focus was shifted to dual-frequency. However, there are also some differences between the studies, in which not only the equipment used but also the positioning mode can be different. Most of the studies used the PPP setup, where measurements were made of 15, 90 minutes or 6 hours. In addition to PPP, an RTK set-up was also used. Theoretically, the result of the RTK would be better than that of PPP if it concerns a short measurement at a short baseline length, but this is not clearly shown in the research of Fortunate et al [21]. In recent years, research has also been done into the performance of the GNSS receivers if one or more satellite constellations are included in the position determination. In general, it can be noted that if more satellite constellations are included, the result is of a higher quality.

If all the results of previous studies presented above are compared, there is a difference between an accuracy of a few meters to a few centimetres. These are promising results, but the ideal solution for Dar Ramani Huria has not yet been found. In addition to previous studies, this thesis focuses on a GNSS receiver that has only recently been launched on the market. Performance tests have already been carried out by several hobbyists and experts, but not yet on a scientific level and with the associated accuracy analyses. Mainly the person behind the website *rtklibexporer.com* has tried a lot with this particular receiver, where the results are promising. He did an experiment where he sat in his car and drove a circle in his neighbourhood, where the antenna was installed on the roof of the car. He did the analysis of the observations in the freely available software RTKLIB. The results have been compared to those of a u-blox M8T receiver, with the ZED-F9P variant giving a better result.

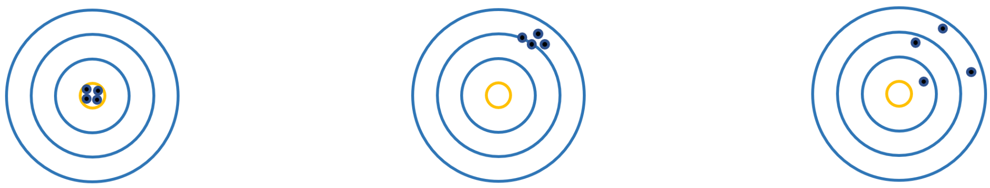
In addition to being a newly launched GNSS receiver that still needs to be researched, this thesis compares for the first time the performance in Delft and Dar es Salaam, working with the same positioning mode and GNSS satellite constellations.

3.2. Key-performance indicators

In Section 3.1 several scientific researches were presented, in which attention was paid to the results obtained during the various studies. The methods by which the results can be presented and quantified are called the key performance indicators. Literature research has shown that these different indicators can be relevant for this thesis as they give an indication of the differences and similarities in performance between Delft and Dar es Salaam. In addition, these indicators are also used in the research presented above, so that a comparison can be made between this research and previous studies. In the foregoing studies, the emphasis is on the performance indicators; positioning over time and the scatter, whereby the RMSE and the PDOP are also mentioned. How these indicators work, are determined, their importance and significance will be presented in the next paragraphs, with a short summary at the end.

3.2.1. Accuracy and precision

There are two common terms when it comes to the performance of a measurement; accuracy and precision. As a rough approximation it can be said that the accuracy consists of the precision plus the bias. Accuracy is defined as the extent to which the correctness of the measurement can be indicated. If an experiment is repeated, the results may differ. The spread in the results of a repeated experiment is called the repeatability; the degree to which repeated measurements, under unchanged conditions, show the same results. The formal approach to repeatability is the precision. The differences between accuracy and precision can best be made graphically clear, as done in Figure 3.1.



(a) Accurate and precise. (b) Not accurate, but precise. (c) Not accurate and not precise.

Figure 3.1: Difference between accuracy and precision.

Precision can be expressed using the Dilution of Precision (DOP); it is the square root of the sum of estimate variances in the East, North and Up direction. The geometric DOP (GDOP) is shown in Equation 3.1

$$GDOP = \sqrt{\sigma_E^s + \sigma_N^2 + \sigma_U^t + \sigma_{dt}^2} \tag{3.1}$$

The GDOP becomes the position DOP (PDOP) is the contribution of the receiver clock (σ_{dt}) is left out, and it is further reduced to the horizontal DOP (HDOP) is the vertical opponent is removed from the equation. In a likewise manner once can obtain the vertical DOP (VDOP) and the time DOP (TDOP). Relevant for this research is the PDOP, with extra consideration to the VDOP and HDOP.

The accuracy is the 3D root mean square error (RMSE) of the position estimates in the East, North and Up direction. It is calculated according to Equation 3.2;

$$RMSE_{3D} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\Delta E_r^2 + \Delta N_r^2 + \Delta U_r^2)} \tag{3.2}$$

It is important to realise that the RMSE error is calculated in relation to a ground truth, a point whose position is accurately and reliably known. RMSE is generally used to measure the error of prediction, i.e. how much the predictions that is made differ from the predicted data. If the mean is used as the prediction for all the cases, then RMSE and standard deviation will be the same.

Importance and significance

The RMSE and the PDOP are expressed in a single number, which summarises the performance in a concise manner. The disadvantage of this, however, is that a nuance is lost, three directional components in which a difference in performance can be expected are condensed into a single number. Therefore the choice was made to extract the standard deviation (or RMSE with the average value of all solutions as ground truth) from the .pos file and to plot it against time, together with the PDOP values that can be calculated from it. This is based on the so called formal standard devations. In this way the course of the measurement can be made visible. It is expected that at the beginning of the measurement larger values for the RMS and PDOP will apply, but as soon as the fix solution is reached it will remain reasonably constant.

3.2.2. Number of satellites, skyplot and elevation angles

The amount of satellites in view gives a first indication whether the results will be successful. Another, more detailed way of displaying the amount of satellites in view is the skyplot and the plot with the elevation angles over time. The skyplot shows the location of the satellite during the experiment. In addition, there is a skyplot that indicates in which direction it can be expected that the GNSS receiver will not be able to track satellites, for example due to an obstruction. These obstruction-skyplots are, by hand, made on location and give an indication of how successful the measurement would be. The graph with the elevation angles over time shows whether the satellite is on the horizon or directly above the receiver.

Importance and significance
It is important that a sufficient number of satellites can be traced by the receiver; more observations results in a improvement of the precision. In other words; more observations ensure that the errors play a smaller role in determining the position because the averaging involves a larger dataset. In addition, it is of importance that the distribution of the satellites in the sky is proportional, as is represented by the skyplots. Why an even distribution is important, can best be explained using Figure 3.2. Here one can see a part of the circle of the signal coming from the satellite. In the leftmost picture there is only one satellite, where the real range is the blue line. The noise and errors indicate a "widening" of the range, which is the yellow area around the blue line. If there are two or three satellites, the probability is 95% that the observed position will be in the dark yellow area. As one can see, in some constellations the dark yellow surface is smaller than in others.

Figure 3.2: Difference in geometry, there is a 95% probabilit that observed position will be in the dark yellow area.

In addition to the amount of satellites and the spatial distribution of the satellites, the elevation angle is also of importance. When the satellite is on the horizon of the receiver, the distance that the signal has to travel due to the atmosphere is longer, so that the signal is more subject to errors. This will be discussed further in the section dealing with the residuals.

3.2.3. Scatter plot

The scatter plot is an intuitive indicator that can provide a lot of information. The North and East components of all position-solutions made during a measurement are plotted against each other, after which the horizontal distribution of the solutions can be studied. The first step is to look at the fix and float solutions, after which the analysis quickly focuses on the fix solutions. The (float and) fix solutions can be used to create a probability density function (PDF) histogram, in which the shape and spread of the data are displayed. This data combined with the visual aspects of the scatter plot on the horizontal plane can make possible outliers stand out. As in the literature it was decided to remove outliers of more than 3σ, after which a 95% confidence ellipse can be calculated from this data, how this calculation works is described on the website of ResearchGate [6].

Importance and significance
Creating a scatter plot gives a good first impression of the distribution of solutions in the horizontal plane. The distinction between fix and float can be visualized and the extreme values in the East and North direction can easily be read. In general, it gives a good picture of the distribution of solutions. However, the visual aspect is not sufficient to be able to draw a conclusive conclusion, which is why the choice was made to work with a histogram. In these histograms, the distribution of solutions per directional component is indicated with

the help of the spread. One can use the PDF histogram to determine the underlying probability distribution of the data by comparing it against a known probability density function. It is to be expected that if there is a float solution, the spacing of the points is wider than if there is only a fix solution. As soon as the outliers have been removed, it is to be expected that the result will improve further. Finally, the data outside the confidence ellipse is removed, resulting in probably the best result.
In addition, it is important that the percentage of fix solutions is kept in the gate, whereby a higher percentage of fix solutions is most likely to give a better result.

3.2.4. Positioning over time and Time To Fix Ambiguity

In addition to the scatter plot, the positioning over time is also reasonably intuitive. The solutions that are determined during an epoch are plotted against time, in which - in all probability - first the float solution can be seen, over time the ambiguity resolution is solved and a fix solution is reached. The time it takes between the beginning of the measurement and the moment that the single-point fix solution is reached is known as the time to first fix (TTFF). In addition, there is also the time to fix ambiguity (TTFA), which is defined as the time it takes to resolve the ambiguity. In much literature, TTFA is classified as TTFF, however, in this study a distinction has been made and the TTFF has been disregarded form the scope of the research.

Importance and significance

In the same way as the scatter plot on the horizontal plane, the positioning over time gives an idea of the performance of the GNSS receiver over time. The interpretation of this key indicator consists of two aspects; float and fix solutions. Where in the fix solutions a distinction can be made with the solutions that fall within the 95% confidence ellipse or not. Initially, if the float solution is still included, a greater fluctuation in position determination can be expected. As seen as the fix solution is reached, it is optimal if there are no cycle slips and the position determination is constant over time. The average of these fix solutions can be determined, as well as the PDOP. Again, it is important to keep the percentage of fix solution in mind. A short TTFA means that the receiver is able to reach a fix solution faster, which ensures that the measurements can be done faster. A short time is desired, so that the receiver can quickly retrieve the tracing and fixing of the solution after the signal has been interrupted.

3.2.5. Signal strength

The next indicator is the strength of the signal; this can be done by looking at the so-called carrier-to-noise density ratio(C/N_0, usually expressed in $dB-Hz$). It refers to the ratio of carrier- and noise power (dB) per unit bandwidth (Hz). The latter is very important; since two frequencies are used, this ratio can be calculated for the L1 and L2 signal.

Importance and significance

The C/N_0 determines whether a receiver can lock on to the carrier wave of a certain satellite if view, and if the information encoded in the signal can be retrieved. If there is too much noise, the information can not be retrieved.
Two different GNSS receivers with the same antenna and tracking the same GNSS satellites at the same time can have a different C/N_0 output. Assuming that the position is calculated correctly, the differences can be attributed to receiver properties. One can think of the noise figure of the front-end and/or the bandlimiting. The C/N_0 gives an indication of the quality of the signal and is independent of the algorithms used to track the satellites. In addition, this ratio also depends on the setup; for example, if a long cable is used between the antenna and the receiver, the noise increases substantially. The values to be expected in an outdoor experiment are between 30 and $50 dB-Hz$ [GPS course at the TU Delft]. If the value is below that there is too much noise, and the signal is not strong enough to be able to determine a valid solution. If the values are above this $55 dB-Hz$, then the situation is unrealistically optimal.

3.2.6. Ambiguity ratio test

The ambiguity ratio test is a test to decide whether or not to accept the estimated integer ambiguity vector. The ambiguity ratio factor is the ratio between the best solution and the second best solution. The ratio test in fact tests the closeness of the float solution to its nearest integer vector. If the ambiguity ratio exceed a set threshold, then the fixed solution is used, otherwise the float solution is used.

Importance and significance

In general one can say; the larger this number, more confidence there is in the fixed solution. Normally the threshold value of 3.0 is chosen, this is maintained during this study. This key-indicator can be used to determine the TTFA, where a faster TTFA is seen as positive because signal tracking, can be interrupted and then quickly restored.

3.3. Extra performance indicators

There are three more performance indicators; residuals, atmospheric delay and multipath. They are not key-performance indicators, but analysis variables to support the conclusions and explanations.

3.3.1. Residuals over time and elevation

Residuals are impacted by various sources of errors; multipath, atmospheric delay and internal receiver errors. With internal receiver errors one can think of the noise associated with the use of electronic equipment. The multipath and the atmospheric delay can be distinguished from each other, however in both cases the internal receiver error is still included in these sources of error.

Importance and significance

It goes without saying that all residuals should be as small as possible in order to be able to determine the best possible position.

3.3.2. Atmospheric delay

The calculation and determination of the atmospheric delay consists of several steps, using dual-frequency measurements. These steps and the corresponding formulas are discussed step-by-step in this section. The first step is to use the code-measurements (ρ) to determine the ionospheric delay ($\hat{I}$), after which the phase-measurements (ϕ) are used to calculate the ionospheric delay ($\hat{I}'$). This parameter only indicates the course in ionospheric delay. In order to make these comparisons one need information about the two different frequencies, the f_1 and f_2 are respectively $1.5754GHz$ and $1.2276GHz$. The wavelengths are calculated from the frequency divided by the speed of light, resulting in λ_1 is equal to $0.1903m$ and λ_2 is $0.2442m$ for GPS. All these parameters together calculate the ionospheric delay on phase-frequency L1 according to Equation 3.3;

$$\begin{aligned} \hat{I} &= \frac{f_2^2}{f_1^2 - f_2^2} \cdot (\rho_2 - \rho_1) \\ \hat{I}' &= \frac{f_2^2}{f_1^2 - f_2^2} \cdot (\lambda_1 \cdot \phi_1 - \lambda_2 \cdot \phi_2) \end{aligned} \tag{3.3}$$

To study the variation in ionosphere delay the differences and divided differences over time are used, for the code-code and the phase-phase measurements. Both the I' en I should be aligned to see the ambiguities. Outliers greater than 2σ are removed, this is only necessary for the phase-phase difference plots due to carrier-phase ambiguities.

Code-code and phase-phase measurements mean the use of both code-observations and phase-observations respectively.

Importance and significance

differences in performance in Delft and Dar es Salaam. As described in Section 1.6, the ionospheric delay depends on the amount of solar radiation energy that is released into the atmosphere. There is a difference between the Netherlands and Tanzania, where it is expected that in Dar es Salaam the results show a poorer performance.

In order to give an indication of the atmospheric delay, only GPS signals have been used, and Glonass and Galileo are not taken into account.

3.3.3. Multipath

Multipath is included in the residuals and depends on the location of the GNSS antenna. The next step is the computation of the pseudo-range errors (from the multipath linear combination) for the satellites. The multipath combinations are shown in Equation 3.4. The multipath of ρ_1 is displayed with $m_{1,2}$ and of ρ_2 with

$m_{2,1}$. These equations are derived from the course CIE4522 at the TU Delft.

$$
\begin{aligned}
m_{1,2} &= \rho_1 + (-\frac{f_1^2 + f_2^2}{f_1^2 - f_2^2}) \cdot \lambda_1 \cdot \phi_1 + (2 \cdot \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2}) \cdot \lambda_2 \cdot \phi_2 \\
m_{2,1} &= \rho_2 + (-\frac{f_1^2 + f_2^2}{f_1^2 - f_2^2}) \cdot \lambda_2 \cdot \phi_2 + (2 \cdot \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2}) \cdot \lambda_1 \cdot \phi_1
\end{aligned}
\tag{3.4}
$$

Importance and significance
During this research little attention is paid to the multipath combinations, but in general it is possible to check by means of the multipath whether the antenna is positioned at a suitable location.

3.3.4. Conclusion of the indicators used

In the previous section, several performance indicators have been reviewed, explaining how they work and explaining why some of them are relevant. Not all these indicators are required in order to reach a well-founded conclusion. In this thesis, the emphasis is on the scatter plot in the horizontal plane and the positioning over time for the three separate directional components; East, North and Up. The main reason is that these indicators are used in similar studies, allowing the results of the GNSS receiver of interest to be compared with other equipment. These two intuitive indicators provide sufficient information to test the performance of the GNSS receiver, with keeping Dar Ramani Huria's project in mind. In addition, it is important to investigate the differences in performance between Delft and Dar es Salaam, where the expectation can be expressed that it is dependent on the atmospheric delay, and the necessary attention is paid to this. In order to get an indication of whether the experiment will be of sufficient quality, the number of satellites in view and the signal strength are examined. If these indicators are indeed of satisfactory level of quality, it is relevant to further analyse the other indicators.

4
Methodology

As already explained in the chapter regarding the literature review, there are many similarities between earlier performance studies and this thesis. In this study, experiments are also performed to determine the performance of the GNSS receiver. The first section is dedicated to how the PPK network is built, with a reference and rover station. Then it is discussed how the implementation of the installation of the different stations was done. From Section 4.3 on, the experiments will be discussed, including an explanation of how the experiments are structured and which variables are used.

4.1. Design of positioning

The first step in achieving accurate, precise and fast measurement results, in a mapping survey context, is to determine the GNSS positioning mode. In Chapter 2, the different modes are explained in detail. When comparing these methods, the local DGNSS, RTK and PPK methods appear to be the best ones to use for Dar Ramani Huria's project. For an overview of this comparison, please refer to Figure 4.1. When considering the accuracy over the baseline length, the choice is made to use PPK. The difference between these two positioning modes is that PPK involves post-processing, which provides greater flexibility, and is therefore the starting point. What the positioning design looks like is shown in Figure 4.1, where the baseline, reference and rover station is shown. At each station, the GNSS receiver is connected to the laptop, after which the experiments can take place. The raw measurements of both stations are combined on the computer, as shown in the middle of the figure. Appendix B discusses in detail how to assemble the setup, and elaborates on the choices that have been made when setting up the PPK network.

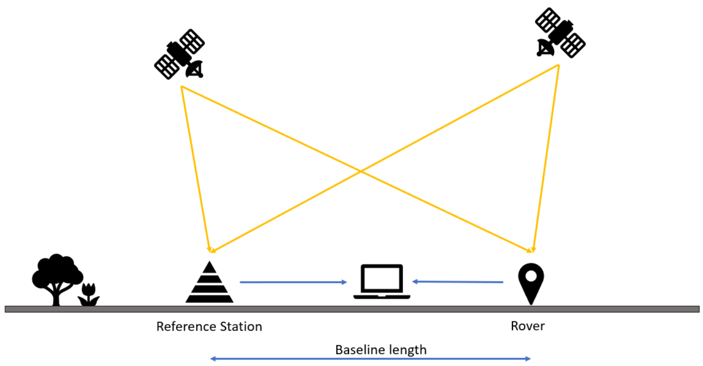


Figure 4.1: Design of the positioning mode

4.2. Implementation of the installation of the stations

As shown in Figure 4.1, the PPK network consists of a rover and a reference station, which have to be placed somewhere. The method to determine these locations is discussed in the following paragraphs.

4.2.1. Placing rover stations

Before each experiment can begin, a location must be chosen where the experiment will take place. In order to build a well-functioning PPK network, there are some requirements that a station has to met, they are listed below;

- *Distinction of station.* Each station must be distinguishable, so that it is clear which experiment is being conducted and so that it is clear to which location the surveyor should go. The easiest way is to give each station a distinctive name.
- *Stable arrangement.* Since some measurements can take a longer time, sometimes up to several hours, it is important that the station is located exactly where it should be. For static experiments, this means that the station must not move during the entire experiment. For kinematic experiments this means that the antenna is exactly where one want it to be.
- *Recognizable.* It is important that the point at which the station is placed can be found again at a later time. The process of making the station recognizable is also called monumentation. There's a wide variation in the kind of monumentation that is set for a GPS project. One of the most important methods to be able to find the location of the station is to sketch the surroundings and to take extensive photographs in which it is clear which way the station is to be looked at.
- *Clear view of sky.* This requirement is the most important, especially for placing the reference station. If the sky is well visible, there are several satellites from which the signal can be received, which reduces the errors. Another advantage is that the chance of multipath is substantially smaller if there are no obstructions in the vicinity of the station.

The item "Clear view of sky" requires some extra attention, particularly with static control surveys. It is often impossible to have a totally clear view of sky, especially in a densely built city like Dar es Salaam and to a lesser extent Delft, so compromises have to be made. Once the best possible location has been chosen, a visibility sky-plot can be created. This round map shows the direction and height of the obstacle. With this information, two things can be done, either the elevation mask of the measurements can be adjusted or another location for the antenna is found.

4.2.2. Placing reference station

Setting up a PPK network starts with determining the position of the reference station. In Delft a high-end antenna was partly used, which is located on the roof of the NMi tower. This antenna is firmly mounted in a fitting location, and the data is available online for PPK, so it is well suited for this research. In addition, a self-assembled reference station was used that was placed at a location that is already known and the information about the station is provided on the GNSS data server at the TU Delft [bron], a few meters away from the high-end antenna. In Dar es Salaam the reference station itself has to be set up. In order to be able to set up the reference station, the above mentioned requirements must be met;

- *Clear view of sky.* In order to have a clear view of sky, it was decided to place the reference station on the roof of HOT's office. It is located high up, so there are few obstructions in the area.
- *Recognizable and distinction of the station.* There is no other reference station nearby, so this does not pose a challenge.
- *Stable construction.* An advantage of placing the reference station on the roof is that few people have access to it.

To make sure that the setup is stable, and the equipment is not affected by the elements, a shelter has been built, as can be seen in Appendix B.

The position determination of the reference station is done with PPP positioning mode. The duration of the experiment was 24, and an observation was made every 30 seconds. During these 24 hours, all GPS satellites were passed twice, and all satellites of other constellations at least once. The raw measurement file was converted into a RINEX file using RTKLIB CONV after which it was processed using the Canadian $NRCAN$ website [13]. An extensive manual can be found on this website, as well as how to avoid common mistakes.

The PPP post-processing can be done in static and kinematic mode, where this experiment was chosen to select static. The result, in International Terrestial Reference Frame, of the PPP for the reference station in Dar es Salaam is:

- X = 4904285.61984
- Y = 4008272.37238
- Z = -747305.33480

As these results are necessary information to perform the tests described below, it has been decided to already mention the results here instead of in the results chapter.

4.3. Structure of the experiments

To understand impacts on receiver performance, several experiments were conducted. The key-indicators are used to analyse and compare these experiments. There are a number of variables among the experiments, which are listed below:

- *Location.* Delft and Dar es Salaam.
- *Quality of antenna.* High-end antenna or low-end antenna.
- *Movability.* Static and kinematic experiments.
- *Programs.* RTKLIB and u-center.
- *Baselines.* Different baseline lengths are used.

It is -unfortunately- too time-consuming to carry out all experiments in such a way that only one variable changes at a time, but all possible combinations are nevertheless made. In order to be able to come to a well-founded conclusion, a selection was made; this combination of variables is shown in Table 4.1, where on the top row the different variables are presented. There is one experiment that serves as a basis, called the Starting Point Experiment (SP experiment), of which a variable is changed for subsequent experiments.

Table 4.1: Overview of all the experiments performed during this research.

Location	Antenna	Movability	Programs	Baseline	Extra	Name
Dar es Salaam	Low-end	Static	RTKLIB	cm		Darcm
				m		Darm
				4km		Dar4km
				6km		Dar6km
				9km		Dar9km
		Kinematic	RTKLIB	drive	Drive with bajaj	DarK1
				4km		DarK2
				6km		DarK3
				9km		Dark4
Delft	Low-end	Static	RTKLIB	m		Delftm
				6km		SP experiment
				14km		Delft14km
			U-center	cm		DelftUm
				6km		DelftU6km
		Kinematic	RTKLIB	6km		DelftK
	High-end	Static	RTKLIB	6km		DelftH
	Low-end	Static	RTKLIB	m	Disrupt signal	DelftHoodm
				6km		DelftHoodkm

In the following paragraphs, attention will be paid to the *SP experiment*, after which the variables will be explained in more detail.

4.3.1. Starting point experiment

As mentioned above, the performance of the system and the receiver were determined by means of various experiments. The *SP experiment*, with the default settings, is presented here. The location of the reference station is discussed in the previous paragraph, and so the focus is now on the rover. The subsequent experiments are all a variant of this, and only the changes are discussed. The starting position is summarized and shown in Table 4.2;

Table 4.2: Starting point of experiments - rover.

Experiment	Location	Antenna	Movability	Baseline	Program	Duration
Starting point experiment	Delft	Low-end	Static	6km	RTKLIB	1h during day

For a detailed guide on how to perform this experiment, please refer to Appendix B. This process is visualized in Figure 4.2. In order to carry out the experiment, the rover and the reference station each need the following equipment: GNSS receiver, antenna, charged laptop, data micro-usb cable and extras like a field-book, pen, charged smartphone (with sufficient internet credit).

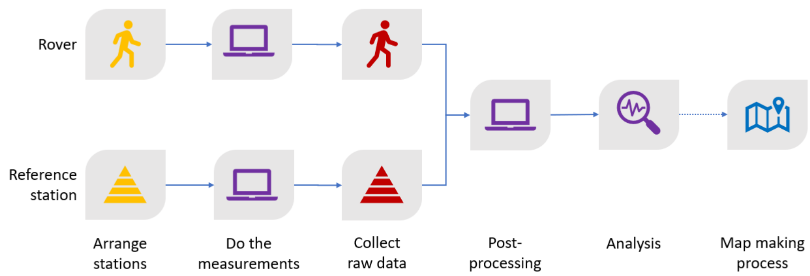


Figure 4.2: Visualization of the experiment process, these steps form the starting point of every experiments done in this study.

4.3.2. Experiments in Dar es Salaam and Delft

The experiments were carried out at two different locations: Delft and Dar es Salaam. Bearing in mind the atmospheric irregularities, it is expected that the results in Dar es Salaam show a poorer performance. In both cases, the rover's antenna is located on several baseline lengths, for more information please refer to the variable "Baseline variations". Figure 4.3 shows a few examples of static experiments in Dar es Salaam.

Figure 4.3: Impression of the static experiments in Dar es Salaam. The pictures on the left side show respectively the $4km$ and $6km$ baseline experiments. The two picture on the right side show the measurement done on the wall surrounding HOT's office.

4.3.3. Kinematic experiments

The kinematic experiments in Dar es Salaam were performed using a bajaj (local name for a tricycle). The antenna is placed on top of the roof, at a constant height of 1.70m above the road. The kinematic experiment consisted of making a measurement during the route that was taken between the HOT office and the location of the static experiment. In addition, a route has been taken in the vicinity of the HOT office, and it has been decided to drive past several typical places of Dar es Salaam. The choice has been made for a road along the beach, a residential area with large, expensive houses and a typical middle class neighbourhood. For security reasons it was decided not to drive through slumps, the equipment was too clearly visible in the bajaj and the laptops could easily be stolen. In Figure 4.4 an impression of the kinematic experiment in Dar es Salaam is shown.

In the Netherlands it was decided to walk through the centre of Delft, the so-called "block around". A route has been chosen that is accessible for everyone and is a appropriate representation of the centre of Delft, with some interesting "obstacles". The route contains a typical Delft bridge, after which a small alley was entered, followed by a part alongside canal houses to a small park. During this experiment, the antenna was kept at a constant height, and an assistant carried the computer.

Figure 4.4: Impression of the kinematic experiment in Dar es Salaam. The picture on the left side shows the bajaj, the picture in the middle and on the right shows the antenna on the roof of the bajaj.

4.3.4. High-end antenna experiment

The high-end antenna positioned on the tower of the NMi is a *Trimble NETR9* that has been placed there since April 2011. Besides the fact that several scientific studies have focused on the performance of this high-end antenna, due to the long period of observation, it can be assumed that the results are of high quality. The low-end antenna is the previous mentioned *u-blox antenna* and is available for a substantially lower price. It is expected that the experiments with the high-end antenna will result in a better performance. In Figure 4.5 the two different antenna's are shown.

Figure 4.5: The three pictures on the left side show the high-end antenna, the other picture depicts the low-end antenna.

4.3.5. Baseline variations

The vector between the reference station and the rover is called the baseline, a larger baseline length worsens -theoretically- the results. To investigate this, an experiment is carried out at different distances. In Dar es Salaam a baseline length of $30cm$, $30m$, $4km$, $6km$ and $9km$ was used. In Delft the baseline distances were almost the same; $3m$, $6km$ and $14km$. The choice to use $14km$ instead of $9km$ was made because the experiment could not be carried out completely safely (and comfortable) at a distance of $9km$. In Figure 4.6 a few pictures of different experiments are shown.

Figure 4.6: Examples of locations where the antenna and receiver are placed in Dar es Salaam and Delft.

4.3.6. U-center experiment

There are two different programs that have been used during this study; u-center and RTKLIB. The difference is that RTKLIB performs positioning calculations on the computer and u-center on the GNSS receiver chip. If RTKLIB is used, u-center must still be used to configure the receiver. How it is done can be found in the manual, provided in Appendix B, and for more detailed reference, please refer to the u-centre's manual [7]. When looking at previously performed and recorded experiments, no difference can be expected between these two software packages.

4.3.7. Re-initialisation experiment

One of the performance indicators is the time to get ambiguity, as described in the key-performance indicator section, for more information please refer to Section 3.2. This can be measured at the beginning of each experiment, but the signal can also be disturbed manually. The actual purpose of the coverage is to store equipment, but by using the heavy material it can also be used to interrupt the satellite signal. The hood is placed over the antenna for 30 seconds, after which it is measured for one minute and it is checked if the signal is picked up again by the receiver. This continues to be repeated for approximately an hour, and was only carried out in Delft on a baseline length of $3m$ and $6km$. The experiments set up is shown in Figure 4.7.

Figure 4.7: Two different methods of disrupting the signal, one is with a above mentioned equipment-cover the other one is a (kitchen) pan. The experiments with the pan are done at the $6km$ baseline in Delft, the other at a meter baseline.

5 Results

This chapter presents the results that belong to the performance study part of this thesis. The chapter starts, like any experiment, with the positioning of the rover. Following this, a summary of all the results achieved is presented, after which the SP experiment is discussed in detail. It explains step-by-step how certain results were obtained, how they should be interpreted and what the consequences are. Afterwards, some experiments that deserve extra attention will be discussed.

5.1. Positioning of the rover

Prior to the completion of the various experiments it is important to choose where the rover stations should be positioned. In order to guide this choice, several requirements have been drawn up, as presented in the Case Study part, Chapter 9. When these requirements and wishes were taken into consideration, locations were chosen in the research areas. The locations with a short baseline are shown on the map in Figure 5.1a and Figure 5.1b for respectively Delft and Dar es Salaam.

(a) Rover stations in Delft.

(b) Rover stations in Dar es Salaam.

Figure 5.1: Location of the rover stations for the sensor performance study, in Delft and Dar es Salaam. The yellow line presents the reference station and the blue line the rover.

In Delft the choice was made to carry out the experiments on the roof of the NMi tower, to provide a clear view of the sky. The left hand side picture in Figure 5.1a shows the location of the rover with a baseline of approximately $3m$. The right hand side picture shows the location of the experiments with a baseline of several meters. In Figure 5.1b the left hand side picture is the location of the rover a few meters away from the reference station, it is placed on top of a stone fence, which is the enclosure of HOT's office property. The right hand side picture shows the location and arrangement of the centimetre baseline experiment. There are two antennas shown of which the right one is the rover-antenna, which is at a distance of approximately $30cm$ from the reference station; this location is on the roof of HOT's office. Closely related to the above results are the locations of the rovers, when the research area is being scaled up to the whole of Delft of Dar es Salaam. When these wishes and requirements were taken into account, locations were chosen in Delft and Dar es Salaam. These locations are indicated in Figure 5.2.

(a) Rover stations in Delft.

(b) Rover stations in Dar es Salaam.

Figure 5.2: Location of the rover stations for the system performance study, in Delft and Dar es Salaam. The yellow line presents the reference station and the blue line the rover.

In Delft the choice was made for a location on the flat roof of the author's house, since here there are no obstructions for the GNSS signal in the area. The house is located in the centre of Delft, on a baseline length of $6km$. This picture is shown on the left side of Figure 5.2a, with the typical Dutch windmill in the background. For the experiment with a baseline length of $14km$ it was decided to position the rover on the Noordereiland in Rotterdam. The measurement was carried out on a friend's roof terrace, which is a horizontal location with not that many obstructions in the surroundings, that can be seen at the bottom right in Figure 5.2a. The last positioning represents the location of the reference station.
In Dar es Salaam experiments have been done at different distances; 4, 6 and $9km$. In the lower left corner, in Figure 5.2b, the $6km$ location is shown, and this spot is in the middle of a soccer field belonging to a primary school. A similar environment was at the $4km$ point, belonging to the picture at the top left. The picture in the top centre is from the $9km$ point, as here the antennas are placed on a permanent tent (comparable to a party tent) that was located on an open, sandy parking lot. The photos on the right are also part of the receiver-performance study; the photo in the lower right corner is the reference station.

5.2. Summary of the experiment results

An analysis was performed of all the conducted experiments, in which certain key indicators were highlighted. In Table 5.1, an overview is made of the results used to draw a conclusion and to answer the research questions. The key indicators presented mainly originate from the positioning over time and the scatter plot. However, the signal strength and the number of satellites traced by the receiver is also presented. This matrix of results is somewhat overwhelming, which is why it is explained column by column, so that all results can be interpreted with greater ease.
The first column contains the name of the experiment, which can be found in the methodology, Section 4.3. The second column indicates whether a range of 30 to $50db-Hz$ has been determined for the experiment in question, if the C/N_0 of the experiment falls within this range, then "yes" is placed in this column. The next column contains the seconds it takes to resolve the ambiguity; the TTFA . Followed by how many satellites are in view on average during the entire measurement. The next four columns contain information about the fixed solutions, without removing any outliers. The percentage of the fix solutions in relation to all solutions is indicated, followed by the RMS in the East, North and Up direction. The next five columns contain the values of the fix solutions located in the confidence ellipse, with the percentage of fix expressing how many fix solutions there are compared to all the solutions determined. In addition, it is important to note that all experiments have been carried out with an elevation angle of 15%. There is one additional point that deserves attention: the kinematic experiments. During the experiments, a route was taken, where observations were made throughout the whole time. In these experiments the deviations in the East, North or Up directions are irrelevant and therefore not presented in the matrix. The column with the experiment names contains some asterisks. Of the other experiments, the positioning over time and the scatter plot are presented in Appendix A.

Table 5.1: Summary of static experiments in Delft and Dar es Salaam.

	General			Fix solutions (mm)				Fix solutions inside confidence ellipse (mm)				
Experiment	Signal Strength	TTFA (s)	# Sat	% Fix	RMS East	RMS North	RMS Up	% Fix	RMS East	RMS North	RMS Up	PDOP
SP experiment*	Yes	32	21	98.42	3.58	3.98	8.22	95.79	3.49	3.87	7.56	0.92
Dar6k*	Yes	2827	24	11.68	10.53	9.56	12.86	11.56	10.46	9.41	12.85	1.91
Darcm	Yes	28	23	99.54	6.31	4.53	7.94	93.42	3.57	2.96	7.79	0.91
Darm	Yes	98	22	83.10	5.90	3.88	9.23	80.07	5.84	3.51	8.85	1.12
Dar4km	Yes	144	24	26.49	4.63	4.94	15.09	25.10	4.08	4.66	14.57	1.58
Dar9km*	Yes	194	26	8.99	9.58	16.78	33.90	8.93	9.42	16.83	34.02	3.91
Delftm	Yes	25	20	99.85	4.93	2.17	3.93	96.88	4.86	2.00	3.74	0.64
Delft14km	Yes	308	14	39.91	35.12	78.08	78.04	37.13	4.08	6.94	18.89	2.53
DelftUm	Yes	57	22	56.13	1.33	1.84	3.67	51.75	1.13	1.42	3.56	0.40
DelftUkm	Yes	24	21	99.32	3.44	7.28	6.11	95.39	3.31	6.64	6.10	0.96
DelftHkm*	Yes	34	19	98.65	2.49	3.57	3.75	94.09	2.44	3.42	3.75	0.56

5.3. Starting point experiment

The first step is to discuss the results achieved during the *SP experiment*, with a step-by-step review of the results. Before starting, it is briefly repeated which variables were set and how they were set during the experiment, as presented in Table 5.2.

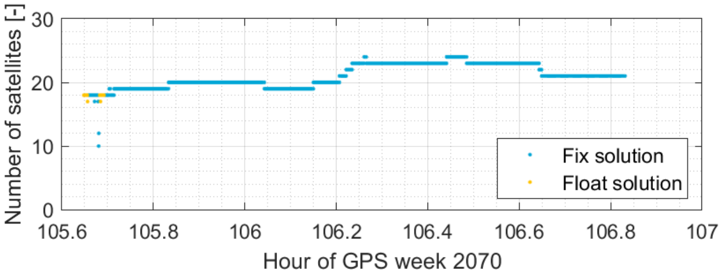
Table 5.2: Starting point of experiments - rover.

Experiment	Location	Mode	Movability	Baseline	Program
Starting point experiment	Delft	PPK	Static	6km	RTKLIB

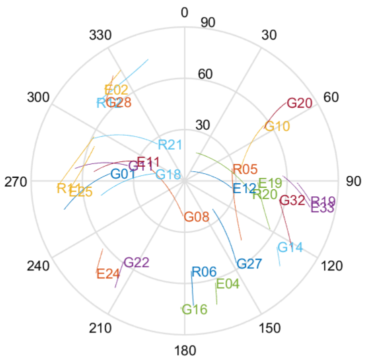
This experiment was performed on the flat roof of the author's house during a sunny day, and lasted over an hour. During this experiment 4253 solutions were determined, with a frequency of $1Hz$. The elevation angle is set to 15 degrees.
In the following paragraphs the number of satellites, skyplot and elevation angles will be discussed first, after which the scatter plot and the positioning over time will be presented. Subsequently, the signal strength, residuals and atmospheric delay are presented.

5.3.1. Number of satellites, skyplot and elevation angles

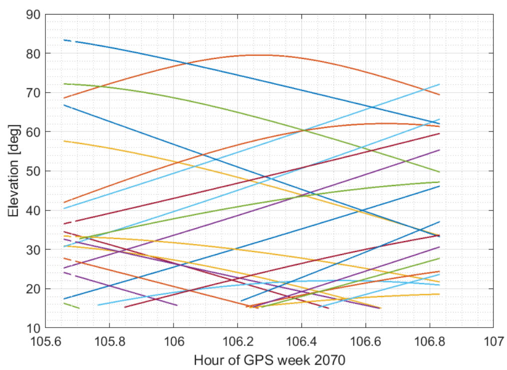
The first step in the analysis process is to determine the quantity and location of the satellites, for which the skyplot is used. In Figure 5.3b this skyplot is shown, where each colour represents a different satellite. The results can be compared with the elevation angles, as shown in Figure 5.3c. The total amount of satellites in view are shown in Figure 5.3a, where a distinction is made between the fix and float solutions.



(a) Number of satellites in view.



(b) Skyplot of the satellites in view.



(c) Elevation angles of the satellites in view.

Figure 5.3: Satellite Tracking for starting point experiment.

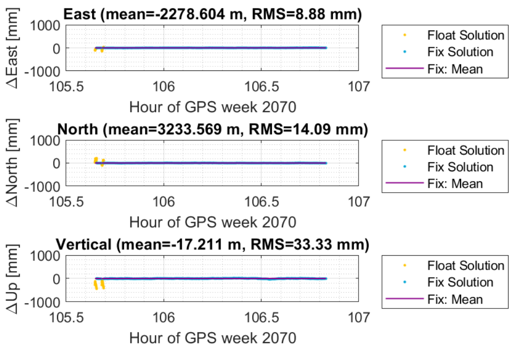
It can be seen in all three figures that there are more than enough satellites traceable by the receiver at any moment of the experiment; the minimum number of satellites in view is 10 and the average of all solutions is 21. A sufficient number of satellites ensure that positioning can be carried out with more accuracy, where a proportional distribution of satellites across the sky provides a geometric advantage.

5.3.2. Scatter and positioning over time

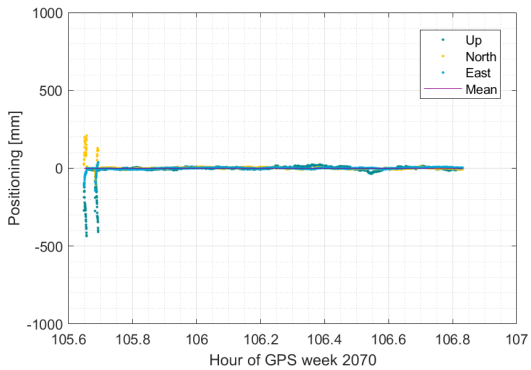
The follow-up step in the analysis of the SP experimt is studying the positioning over time and scattering on the horizontal plane. The starting point is the float and fix solutions; these solutions over time are presented in Figure 5.4. Then the focus is shifted to the fix-solutions, as shown in Figure 5.6, the next step is to remove outliers that are larger than a threshold value of three times the standard deviation, or 3σ, as shown in Figure 5.7. The last step is to look at the 95% confidence ellipse and perform the analysis on it, as shown in Figure 5.8.

Fix and float solutions

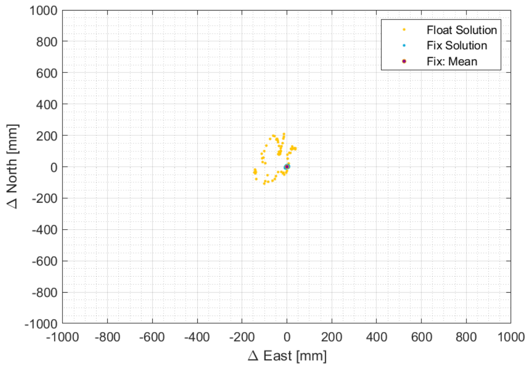
The first review concerns the fix and float solutions, as shown in Figure 5.4. Figure 5.4a shows how the measurement over time fluctuates around the zero point, where the float solutions are shown in yellow and the fixed solutions in blue. The choice was made to center all solutions around the zero point in the ΔE,ΔN and ΔU direction, so that the maximum and minimum deviations become clearly visible and a comparison between the results of the different experiments can be made more easily. Centring around the zero point is done by subtracting the average of the entire measurement from all solutions, the average is now on the zero line and is displayed with the purple line. The title still contains the original average value of all three directional components. Figure 5.4b is a similar graph, in which the East-, North- and Up- components are displayed in one graph, in order to be able to see the differences at a single glance. The solutions in the horizontal plane are shown in Figure 5.4c, showing the maximum divergence of the East and North directions is the same as that of the positioning over time. The statistical distribution of the solutions is shown in Figure 5.5, where the purple line is the PDF function as calculated from the mean and the standard deviation.



(a) Positioning over time, where the three directional components are shown separately.



(b) Positioning over time, where the three directional components are shown together.



(c) Scatter plot of the East and North components.

Figure 5.4: Positioning over time and scatter plot of the fix and float solutions of the *SP experiment*.

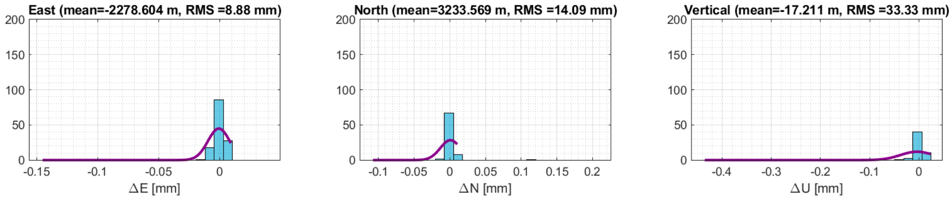


Figure 5.5: Histogram of the fix and float solutions together.

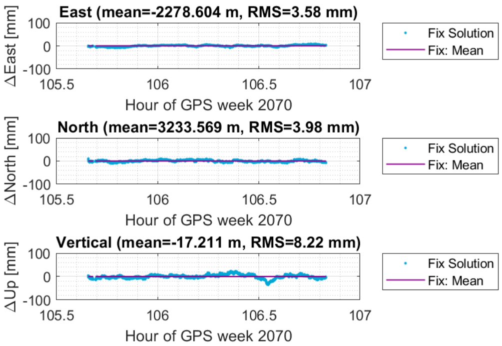
Now that the positioning over time and the scatter plot of the fix and float solutions are displayed next to the relevant histogram, a comparison between the directional components can be made. Two different aspects are examined; the difference between the fix and the float solutions and the difference between the directional components.

In the figures above, the float solutions are shown in yellow, revealing that the first solutions are in float mode and show more fluctuation around the centred point. This is entirely in line with expectations; in the fixed solutions the ambiguity is solved, it takes a few seconds to perform the corresponding calculations. The histogram visualizes these are also located, the shape of the PDF is not as desired and there are too few bars visible. The RMS of all solutions is quite high, so the hypothesis that float solutions do not improve performance can be confirmed.

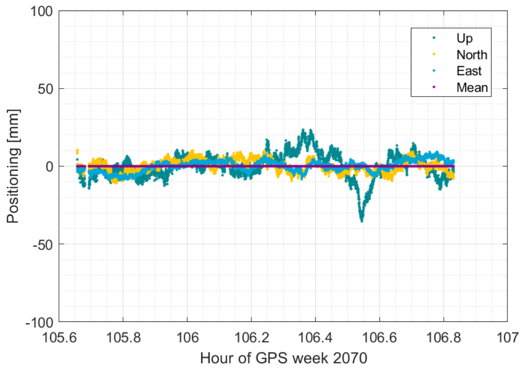
The other interesting point is the difference between the directional components. The East and North components show the best results, in the graphs the solutions fluctuate the least, the RMS error is the lowest and the shape of the histogram is the best, but still unsatisfactory. The Up component shows the poorest performance, the RMS of 33mm is even twice as high as that of the East component.

Fix

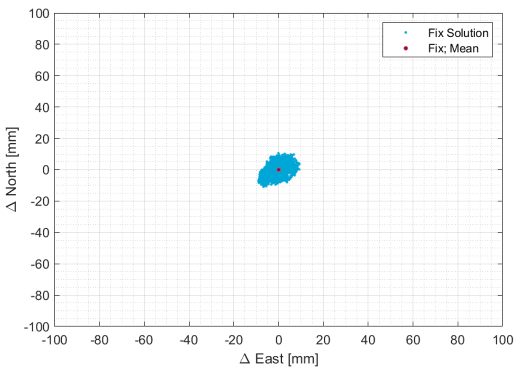
The focus is shifted to the fix solutions, shown in Figure 5.6. Figure 5.6a displays the positioning over time, where the float solutions are no longer visible. The similar Figure 5.4b, where the three components are shown on top of each other, shows the same. Figure 5.6c shows the scatter plot on the horizontal plane. All these results are visualized in the histograms of Figure 5.6d in a static way. For all these figures the mean and the RMS are based on the fix solutions.



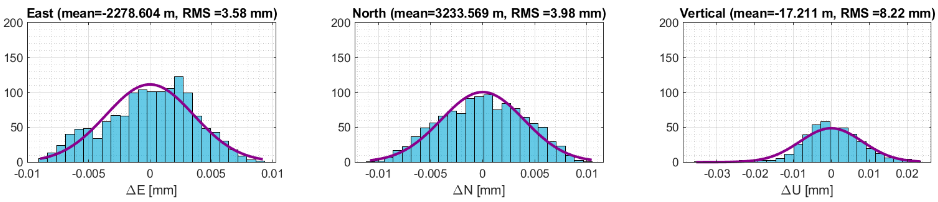
(a) Positioning over time, where the three directional components are shown separate.



(b) Positioning over time, where the three directional components are shown together.



(c) Scatter plot of the East and North components.

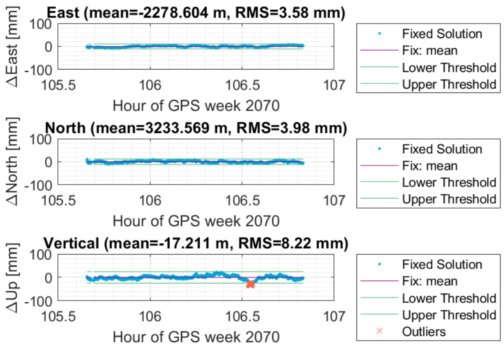


(d) Histogram of the fix solutions.

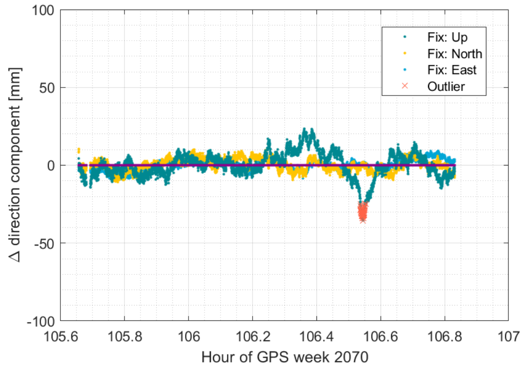
Figure 5.6: Positioning over time and scatter plot of the fix solutions of the *SP experiment*.

Comparing Figure 5.4 with these figures, Figure 5.6, reveals that if only the fix solutions are taken into account, the performance improves. This is in line with expectations, because the float solutions drastically deteriorate the positioning. This improvement in results can be distinguished in three different ways; the maximum deviation, the RMS and the shape of the histogram. First, the maximum deviation is reduced; this is mainly reflected in Figure 5.6a where it becomes visible that the first few highly fluctuating float solutions are missing. This is also reflected in the RMS, as written above the figures, where a decrease can be seen in relation to the fix and float solutions together. Again the RMS values of the East- and North- component are the lowest, but the difference with the Up component is reduced. To conclude, the shape of the PDF function has been substantially improved, and more bars can be displayed.

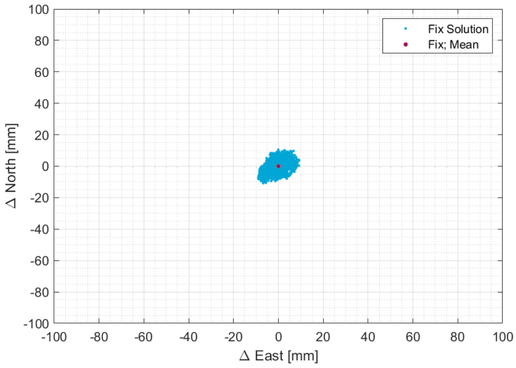
Fix minus outliers
The performance of the fix solutions is beginning to resemble a optimal performance, but it is still insufficient to draw a convincing conclusion. The next step is to remove outliers that are more than three times the standard deviation. In this way, faulty-fixes and incorrectly determined fix solutions can be removed from the dataset. The determined outliers are visualised in Figure 5.7 with a red cross. The left figures, Figure 5.7a and Figure 5.7b, show the positioning over time. The scatter plot is shown in Figure 5.7c. The histogram of Figure 5.7d gives a visual analysis of the results shown above.



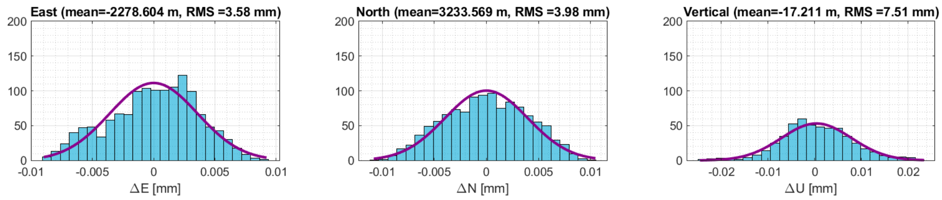
(a) Positioning over time, where the three directional components are shown separate and outliers removed.



(b) Positioning over time, where the three directional components are shown together and outliers removed.



(c) Scatter plot, where the outliers are removed.



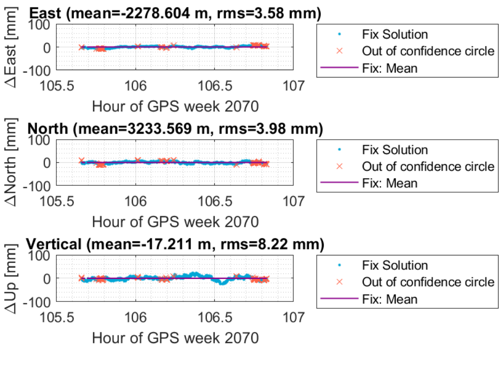
(d) Histogram, where the three directional components are shown separate and outliers are removed.

Figure 5.7: Positioning over time and scatter plot of the fix solutions of the *SP experiment* were the outliers are removed.

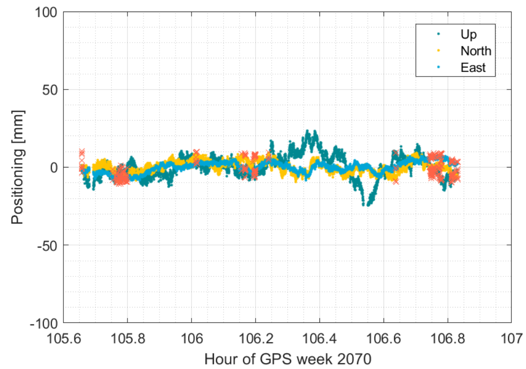
Studying the figures above, compared to Figure 5.6, again draws attention to three points: maximum dilation, RMS and the histogram. However, differences between the horizontal and vertical directional components can be distinguished. In the East- and North- direction no outliers were detected that had to be removed. The maximum deviation, RMS and the shape of the histogram are entirely comparable. For the Up component it is a different story; some outliers were detected, this is reflected in the positioning over time graphs, RMS and the histogram. There are only a few outliers that have been removed, so the change in all these aspects is not very big. But the change does mean an improvement in the performance results.

Fix inside circle

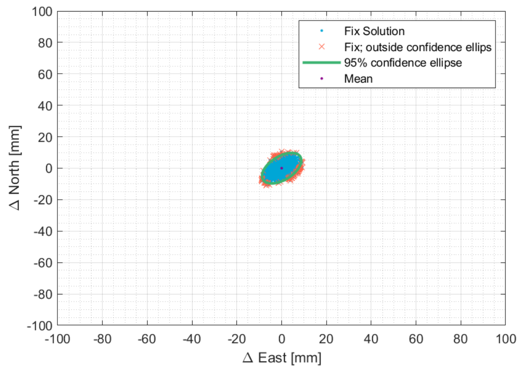
After the outliers, of more than three times the standard deviation, have been removed, focus is shifted to the solutions in the confidence ellipse. In Figure 5.8 these solutions are indicated with a blue dot, the solutions outside the ellipse are indicated with a red cross.
It should be noted that the vertical component is not dependent on the confidence ellipse, this concerns only the solutions in the horizontal plane. The initial decision was to identify which solutions in the East or North direction fall outside the ellipse, these have been completely removed from the measurement. In this way, the Up components are also dependent on the confidence ellipse.



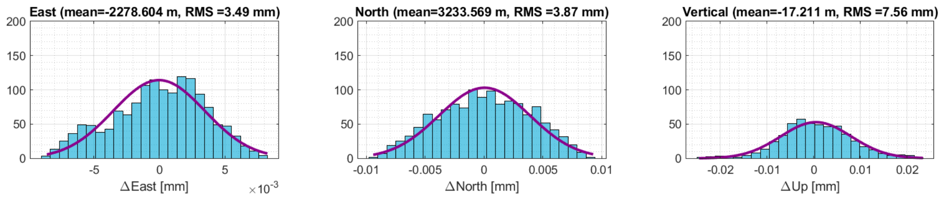
(a) Positioning over time with the confidence ellipse, where the three directional components are shown separate and outliers removed.



(b) Positioning over time with the confidence ellipse, where the three directional components are shown together and outliers removed.



(c) Scatter plot with the confidence ellipse, where the outliers are removed.



(d) Histogram with the solutions inside the confidence ellipse taken into account.

Figure 5.8: Positioning over time and scatter plot of the fix solutions inside the confidence ellipse of the *SP experiment* were the outliers are removed.

In the figures it appears that there are quite a few solutions outside the confidence ellipse. An improvement can be seen for both directions, this is mainly visible in the RMS. In the previous graph this was slightly higher than the 3.49mm and 3.87mm for the East and North direction respectively. The shape of the histogram is similar to previous results, a change was not expected with such a small difference in RMS. For the vertical component the situation is slightly different. There is a small increase in RMS,studying Figure 5.8b shows that when removing the solutions that fell outside the confidence ellipse, the Up components also changed. The outliers, such as around 106.5 hours, remain in the dataset, which increases the RMS. The small difference in RMS is not visible in a change in the histogram.

5.3.3. Signal strength

Once the positioning over time and the scatter plots have been discussed, the signal length is now reviewed. In Figure 5.9 the carrier-to-noise density is shown in $dB-Hz$ for the L1 and L2 signal from the GPS, Galileo and Glonass satellites where the solution has the fixed status. It should be noted that with Galileo and Glonass the names of the signals are not L1 and L2, but this way the frequency range in which the signals belong is indicated. For more information about the signals, please refer to Section 2.4. In these images each satellite has its own colour, which satellite belongs to which signal-strength value is not relevant.

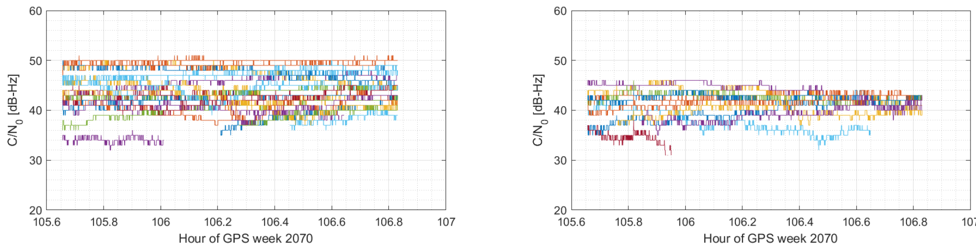


Figure 5.9: Carrier-to-noise density over time for all GPS, Galileo and Glonass satellites in view.

The values of the C/N_0 should be between 30 and $50 db-Hz$ for outdoor experiments. For all satellites, for the L1 and L2 signals, this is the case. This makes it possible to conclude that this measurement -theoretically- would be valid. In the graph with the L1 signal a purple line can be seen in the lower left corner, which shows lower values and is rapidly coming to an end. The satellite belonging to this signal went at the moment 106 below the elevation level of 15%, so it is no longer included in the measurement. This is also the case when looking at the overview with the elevation angels, as shown in Figure 5.3c.
In addition, in the right Figure there is a red line that stops a little before that, it belongs to the same satellite. The explanation that the L2 signal comes to an end earlier than the L1 signal is in short because the L2 signal is weaker, but the full explanation is beyond the scope of this investigation.

5.3.4. PDOP over time

In Figure 5.10 the change of PDOP over the time of the fix solutions is shown in purple and the standard deviations of the East, North and Up direction in blue, yellow and green respectively. The standard deviations over time are taken from the RINEX file. It has been mentioned before, the solutions in this ellipse can be seen as the best results, it has been decided to use these solutions to determine the PDOP and the standard deviation over time.

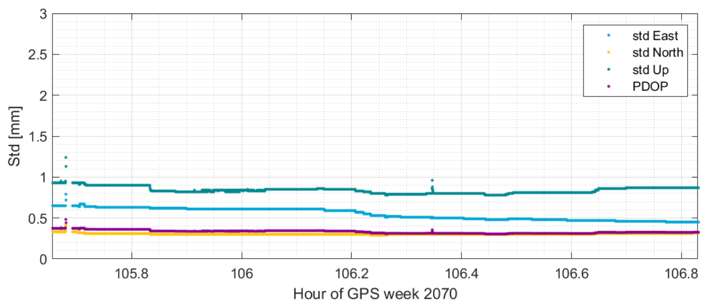
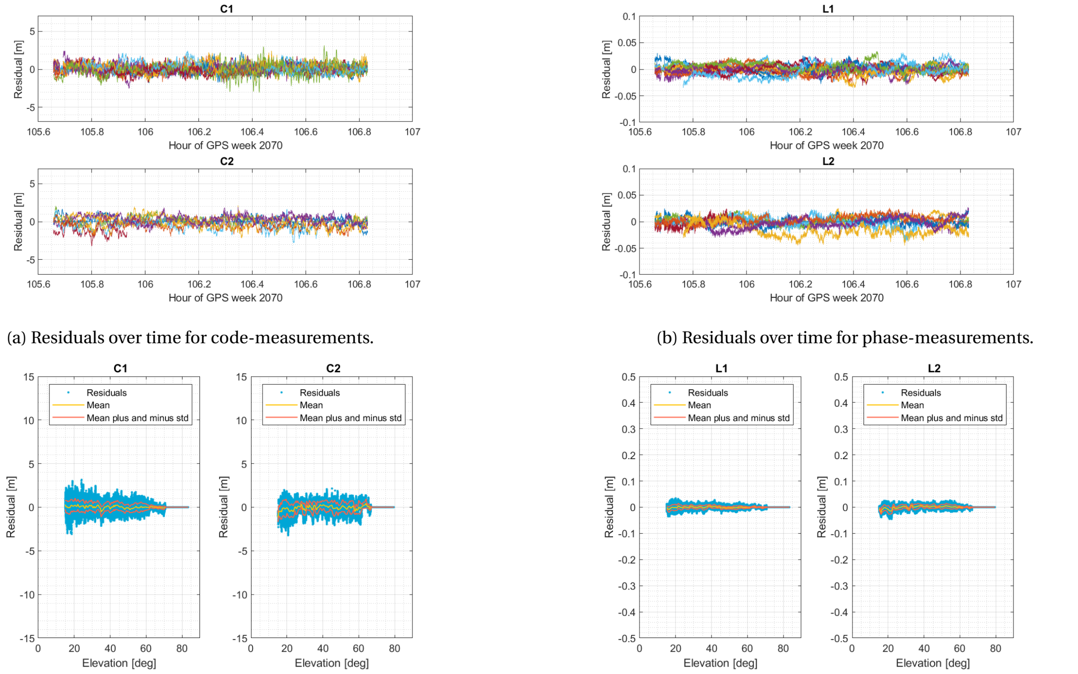


Figure 5.10: PDOP for all fixed solutions inside confidence ellipse

This Figure shows that the standard deviation of the three different directional components is slightly different. The deviation of the North component is around $0.4mm$ and the East component around $0.6mm$. The up component has a higher standard deviation, which is in line with expectations since the vertical component often has a poorer performance. The PDOP is calculated based on these three standard deviations, and its value is often between 0 and $2mm$ [29], as shown in the graph.

5.3.5. Residuals

In Chapter 3 it was mentioned that the residuals are influenced by the errors caused by multipath, instrumental errors and the atmospheric delay. The residuals can be displayed in two different ways; over time or over the elevation of the satellite. In Figure 5.11 both variations are shown, for both code- and phase-measurements where only the fixed solutions are taken into account.



(a) Residuals over time for code-measurements.

(b) Residuals over time for phase-measurements.

(c) Residuals over elevation angle for code-measurements.

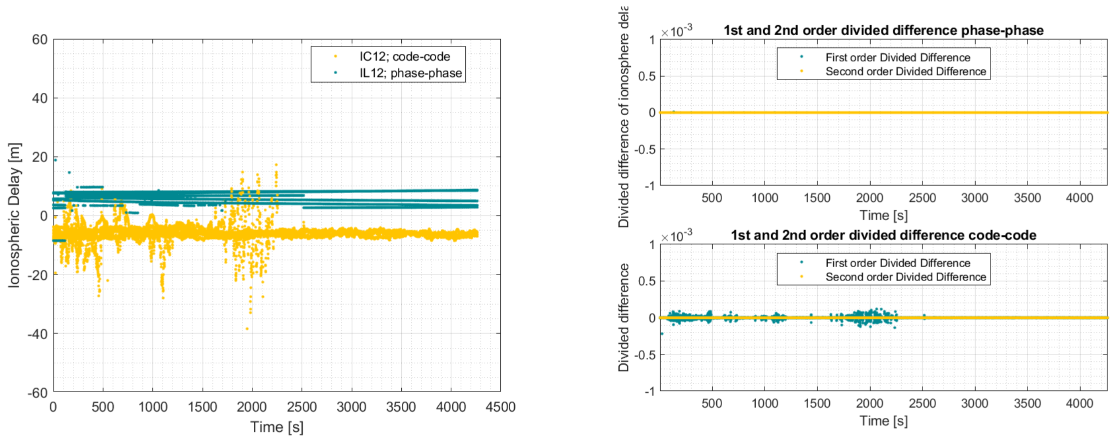
(d) Residuals over elevation angle for phase-measurements.

Figure 5.11: Residuals for both the code- and phase-measurements.

In Figure 5.11a and Figure 5.11b no outliers are visible, and this is a very stable measurement. In Figure 5.11c and Figure 5.11d, when the satellite is right above the receiver, the residuals are smaller. This is to be expected, as the distance between the satellite and the user is then the smallest, making the atmospheric delay the smallest.

5.3.6. Atmospheric Delay

After discussing the general residuals it is now time to review the atmospheric delay. In Figure 5.12a this delay is shown in a graph where the time in seconds of the measurement is shown on the x-axis. In addition, Figure 5.12b shows the first and second order difference for the code code and phase-phase measurements. Outliers larger than 2σ are removed from the results, this is only necessary for the phase-phase difference plots due to carrier-phase ambiguities.



(a) Ionospheric delay over time.

(b) First and second order differencing over time

Figure 5.12: Atmospheric delay of the experiment in Delft with a baseline of $6km$

The linear combinations are not unbiased estimators in Figure 5.12a, this can be concluded from the fact that the estimated delays are sometimes negative, which is in reality not possible. This is due to the fact that using phase-measurements introduces a phase-ambiguity. Using code-measurements introduces an instrumental bias, so the code-code linear combination is also biased (if this instrumental biases has not yet been corrected). Carrier phase-measurements are more precise than code-measurement, this explains the more noisy linear combination of the code-code linear combination. Using only phase-measurements leads to the least noisy combination, due to the more precise measurements.
The first divided difference for the phase-phase combinations in Figure 5.12b shows a semi-clear signal. For the code-code combination the noise is larger than the signal in the data, such that the spread in the data points is somewhat larger for the phase-combination and the signal cannot be seen. The highest variations in divided differences are visible at the beginning and the middle of the experiment, this corresponds to a period of time that many satellites have a too low elevation, as can be seen in Figure 5.3c. At lowest elevation angles, the signal travels the longest path through the ionosphere, which corresponds to the largest ionospheric gradients.

5.4. Highlighted experiments

The *SP experiment* has been discussed in detail, but more experiments were conducted. The performance research was carried out with Dar Ramani Huria's community mapping project in mind, so it is interesting to continue with an experiment that took place in Dar es Salaam. In order to make a comparison between Delft and Dar es Salaam it was decided to discuss the $6km$ baseline experiment in Tanzania in more detail. Dar Ramani Huria will benefit from only having to build a reference station once, after which a large part of the city can be mapped. With this in mind it has been decided to also discuss the $9km$ experiment in Dar es Salaam in more detail.
In addition to the static experiments, kinematic experiments were also carried out. It might be interesting for HOT Tanzania to use this method of surveying. The map-making process can be drastically accelerated, which makes it interesting to discuss these results in this thesis. Comparison of the performance also takes place between Delft and Dar es Salaam on this aspect, so two kinematic experiments will be discussed.
Lastly, both of the re-initialisation experiments are presented, where the focus is on the TTFA.

5.4.1. Experiment in Dar es Salaam; 6km baseline

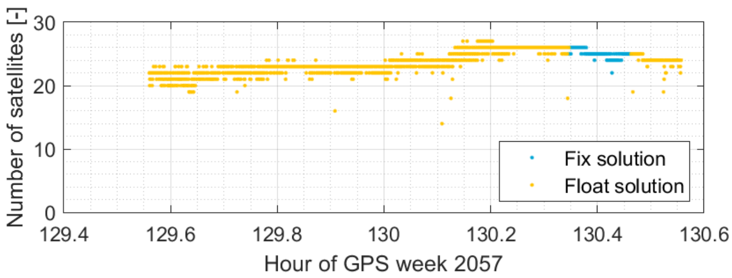
Of all the variables introduced, the location is a very important one, and makes a major impact in researching the implementation of the GNSS receiver in Dar Ramani Huria's project. It has therefore been decided to discuss this experiment in detail in this chapter, but only the fix solutions have been looked at and the float solutions have been left out of consideration. The overview is given in Table 5.3

Table 5.3: Experiment in Dar es Salaam with a baseline length of $6km$.

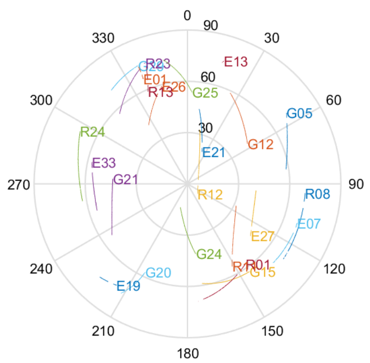
Experiment	Location	Antenna	Movability	Baseline	Program
Dar6km	Dar es Salaam	Low-end	Static	6km	RTKLIB

This experiment was performed on a soccer field next to a primary school during a sunny day, and lasted over an hour. During this experiment 3580 solutions were made, with a frequency of $1Hz$. The elevation angle is set to 15 degrees.

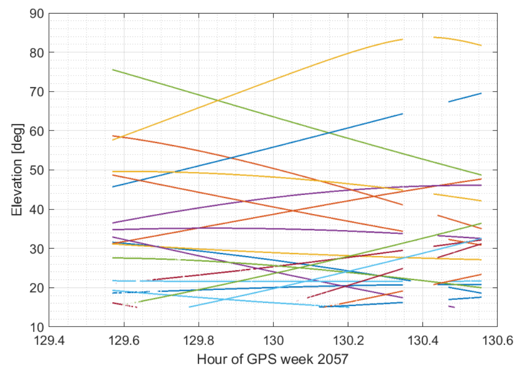
Number of satellites, skyplot and elevation angles
As with the SP experiment, the first step is to look at the number of satellites in view, again using a skyplot, Figure 5.18b, and a graph with the elevation angles, Figure 5.18c.



(a) Number of satellites in view.



(b) Skyplot of the satellites in view.



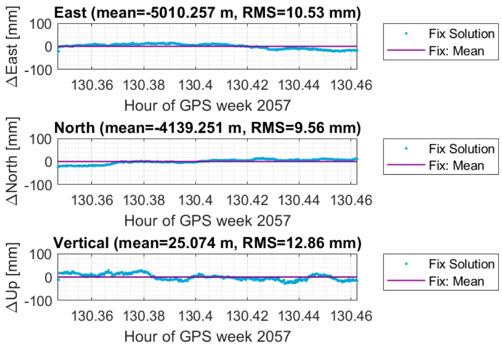
(c) Elevation angles of the satellites in view.

Figure 5.13: Tracking of the experiment in Dar es Salaam with a baseline of $6km$.

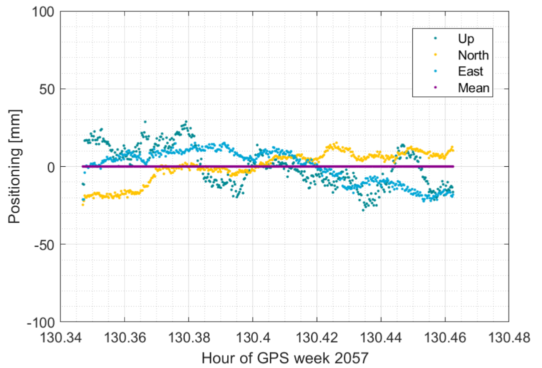
When the above Figure 5.13 is analysed, it appears that there are enough satellites in sight of the receiver. The minimum number of satellites in view during the entire experiment is 12, which is more than sufficient for a -theoretically- successful measurement. When looking at Figure 5.13a, however, it appears that substantially fewer fixed solutions are achieved when compared to the *SP experiment*. Analysing Figure 5.13c shows that around the hour 130.4 there is a period when there are substantially fewer satellites in the picture and so the receiver can trace much fewer satellites. More accurately, when looking at the amount of satellites in Figure 5.13a, this is the period that fix solutions are reached.

Positioning over time and scatter plot

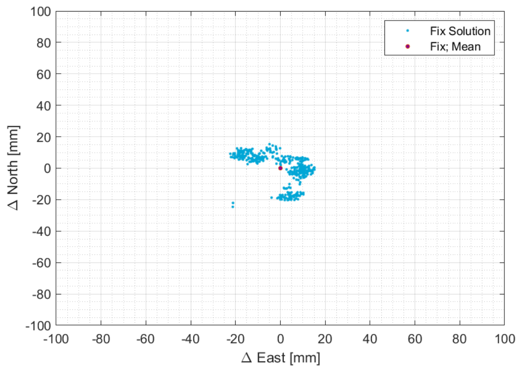
The performance qualification of this highlighted experiment is done in the same way as in the SP experiment. It starts with the positioning over time, scatter plot and the corresponding histogram. The difference is that only the fixed solutions are presented, and the float solutions are not taken into consideration, as can be seen in Figure 5.14.



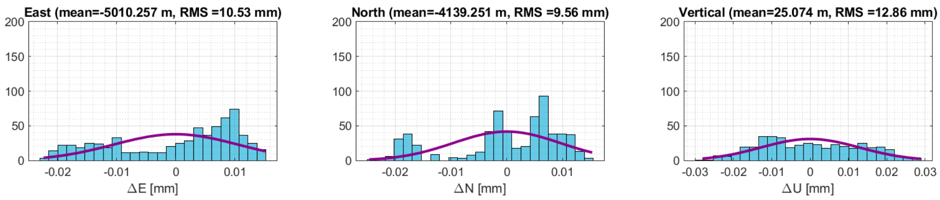
(a) Positioning over time, where the three directional components are shown separate.



(b) Positioning over time, where the three directional components are shown together.



(c) Scatter plot of the East and North components.



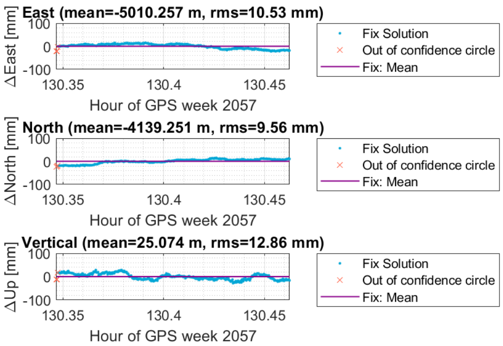
(d) Histogram of the fix solutions.

Figure 5.14: Positioning over time and scatter plot of the fix solutions of the experiment in Dar es Salaam on a baseline length of 6km.

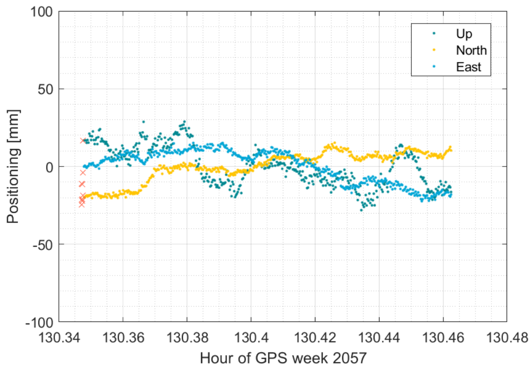
Now that the positioning over time and the scatter plot of the fix and float solutions are displayed next to the relevant histogram, a comparison between the directional components can be made. Two different aspects are examined; the difference difference between the directional components and the difference in RMS between the *SP experiment*.

In the graphs above, the titles contain the RMS of the various directional components. In Figure 5.14a and Figure 5.14b it becomes clear that the RMS of the vertical component is once again the highest, but the differences are not very large, with a maximum of about $3mm$. In the scatter plot, the fluctuation of the horizontal components is shown by means of a scatter plot. It is striking that the solutions make a kind of semi-circle, where there are no solutions in the south-western part of the circle. If the higher RMS and the solutions in a semi-circle are considered together, the histogram should be taken into account. From this it becomes clear that in the East (and North) direction, there are few solutions around the middle point, but mainly to the left and right of it. The vertical component, contains a better fitting PDF, however, this function is very flat and the RMS is the highest.

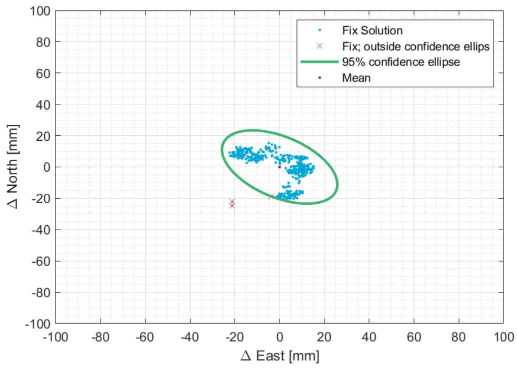
Comparing this experiment with the *SP experiment* shows some differences. If a comparison is made between Figure 5.6 with Figure 5.14 and the values of the RMS it can concluded that this experiment shows a poorer performance. Possible reasons are discussed in Chapter 6.
In order to be able to continue the comparison, the solutions that fall within the 95% confidence ellipse are examined, which is shown in Figure 5.14c in green. All fixed solutions outside of this ellipse are represented by a red cross in Figure 5.15.



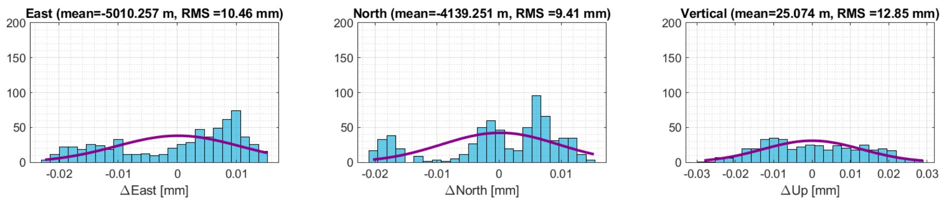
(a) Positioning over time with the confidence ellipse, where the three directional components are shown separate and outliers removed.



(b) Positioning over time with the confidence ellipse, where the three directional components are shown together and outliers removed.



(c) Scatter plot with the confidence ellipse, where the outliers are removed.



(d) Histogram with the solutions inside the confidence ellipse taken into account.

Figure 5.15: Positioning over time and scatter plot of the fix solutions inside the confidence ellipse of the 6km Dar es Salaam experiment were the outliers are removed.

In the figures it appears that there are only a few solutions outside the confidence ellipse. Comparing these final results with earlier results shows almost no improvement. The positioning over time, scatter plot, RMS and histogram for the three different components are discussed, starting with the horizontal components. No significant improvement can be seen for both directions, this is mainly visible in the RMS. The shape of the histogram is similar to previous results, a change was not expected with such a small difference in RMS. The striking division between many results on the eastern and western side of the scatter plot is again reflected in the histogram. For the vertical component the situation is the same; there is a small decrease in RMS and no change in the histogram.
If the results of the *SP experiment* are compared with these results, it can be concluded that the positioning over time, scatter plot, RMS and histogram were better in the *SP experiment*.

PDOP over time

After the positioning over time and the scatter plot, the PDOP values are examined and presented in Figure 5.16. It was decided to only study the PDOP and the standard deviation over time of the fixed solution inside the confidence ellipse; these results are expected to be the best and therefore the most interesting.

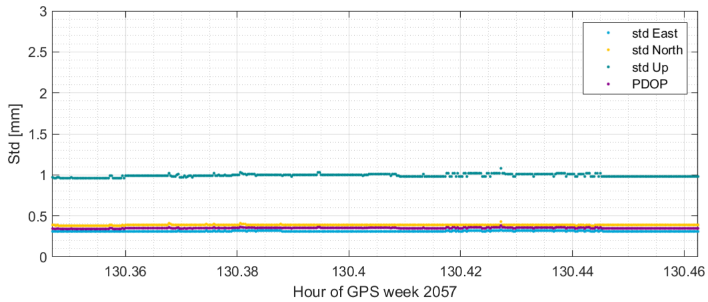
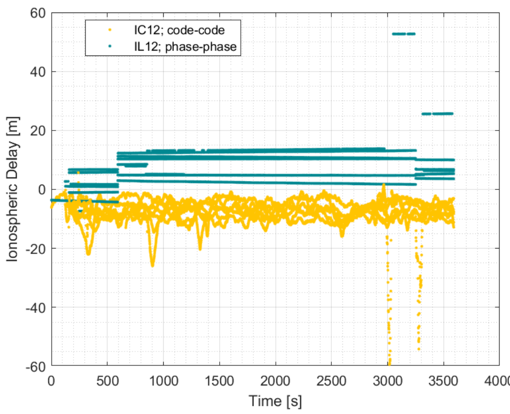


Figure 5.16: PDOP for all fixed solutions inside the confidence ellipse.

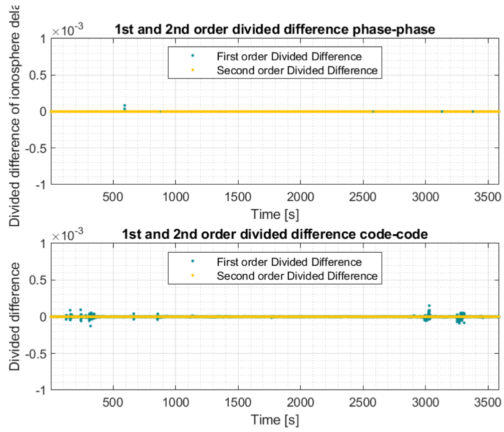
Like with *SP experiment*, the vertical component in Dar es Salaam features the highest standard deviation, also near $1mm$. The standard variations of the North and East component are now much more comparable and are both around the value of $0.4mm$, as well as the PDOP values.

Atmospheric delay

In the Figure 5.17 the ionospheric delay of the code-code and the phase-phase measurements can be studied, where the code-code is indicated in yellow and the phase-phase in dark green. In Figure 5.17b the first and second order differencing is indicated, where the same colours now have a different indication. The green points represent the first order divided difference and the yellow points the second order.



(a) Ionospheric delay over time.



(b) First and second order differencing over time

Figure 5.17: Atmospheric delay of the experiment in Dar es Salaam with a baseline of $6km$

The linear combinations are in this experiment also not unbiased estimators. In Figure 5.17a, this can be concluded due the fact that the estimated delays are sometimes negative, which is in reality not possible. Due to the fact that phase-measurements are used, and a phase-ambiguity is introduced.

The first divided difference for the phase-phase combinations in Figure 5.17b shows a semi-clear signal, with an outlier just after 500 seconds. For the code-code combination the noise is larger than the signal in the data, such that the spread in the data points is somewhat larger for the phase-combination and the signal cannot be seen.

If the comparison is made with the ionospheric delay of the *SP experiment*, there is one aspect that is particularly striking: the dispersion of the results. Looking at Figure 5.12 it can be seen that there is less spread of the code-code and phase-phase measurements compared to the delay presented in Figure 5.17. The explanation and a detailed description can be found in Chapter 2.

5.4.2. Different baseline length in Dar es Salaam

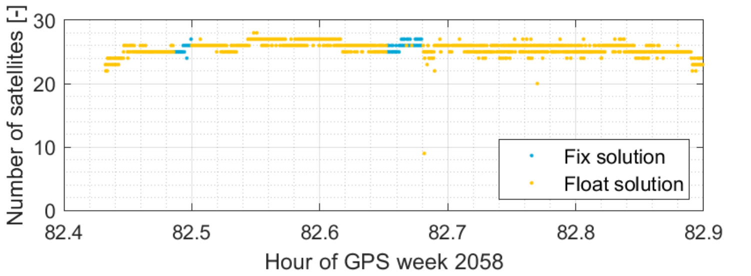
Ideally, with one reference station as much as possible of the city of Dar es Salaam, or any other location, could be mapped. With this in mind, it is interesting to go deeper into the $9km$ experiment that took place in Dar es Salaam. An overview of the experiment, and which variables are used, is shown in Table 5.4;

Table 5.4: Experiment in Dar es Salaam with a baseline length of $9km$

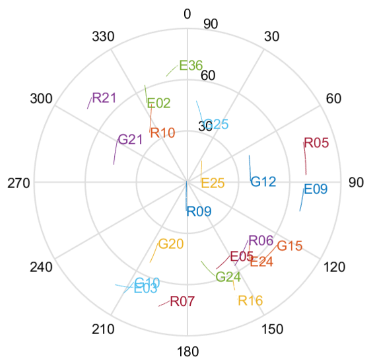
Experiment	Location	Antenna	Movability	Baseline	Program
Dar9km	Dar es Salaam	Low-end	Static	9km	RTKLIB

This experiment was conducted on a sunny day in Dar es Salaam, and the location of the rover station was on a sandy parking lot. The highest point was on a permanently installed construction that resembled the shape of a party tent, where it made a appropriate position to place the antenna. The construction looked solid and permanent enough to be able to carry out the experiment statically, possibly coming back one more time. During this experiment 1679 solutions took place, as after approximately 20 minutes the police interrupted the experiment. As a result, there are fewer measurements to compare the results with other experiments, but still enough solutions to carry out a statistical analysis.
The results of this experiment are discussed using the same key-performance indicators as in the previous experiments; number of satellites, skyplot, elevation angle, positioning over time, scatter plot, histogram and atmospheric delay.

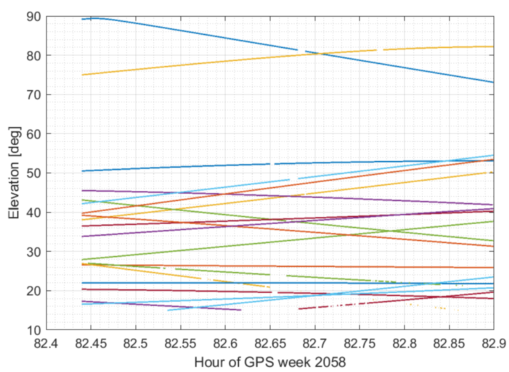
Number of satellites, skyplot and elevation angles
As in the previous experiments, the number of satellites, skyplot and the elevation angle will be examined first. These key performance indicators are shown in Figure 5.18.



(a) Number of satellites in view.



(b) Skyplot of the satellites in view.

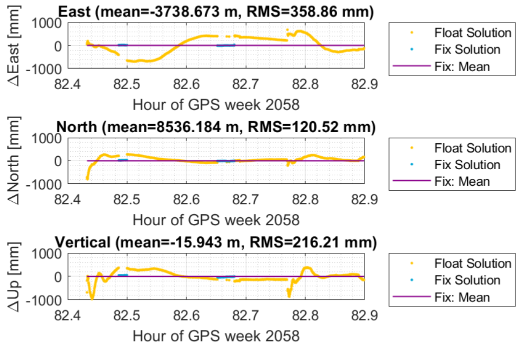


(c) Elevation angles of the satellites in view

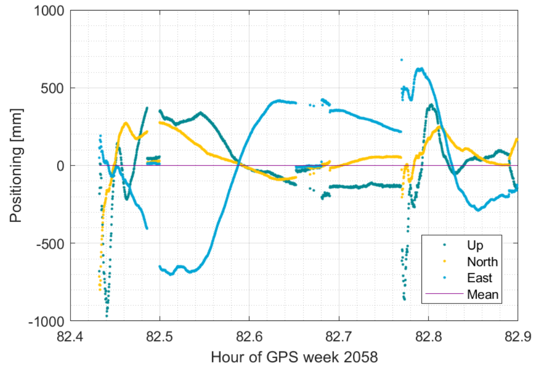
Figure 5.18: Tracking of the experiment in Dar es Salaam with a baseline of $9km$

In the various graphs of Figure 5.18 it soon becomes clear that few fixed solutions have been achieved, and most of the solutions are in float solution. The amount of satellites, as shown in Figure 5.18a and Figure 5.18c, meets the requirements to make it a sufficiently precise solutions. Striking in Figure 5.18b is that there is a less optimal distribution of satellites in view, between 210 and 300 degrees there is only the GPS satellite G21.

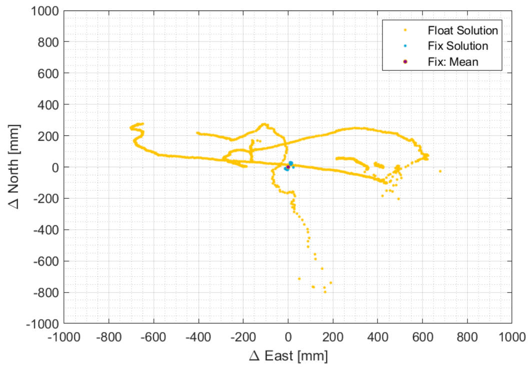
Positioning over time and scatter plot
Since there are so many float solutions in this experiment, the positioning over time and the scatter plot now only focuses on the float and fix solutions, as shown in Figure 5.19.



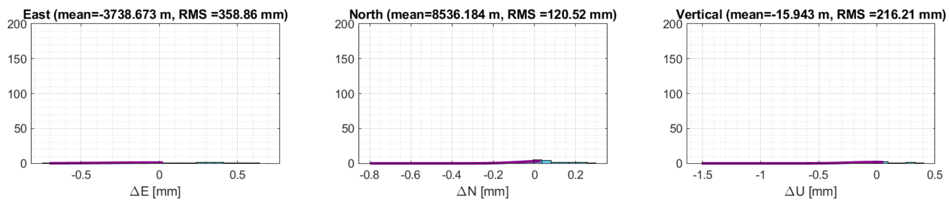
(a) Positioning over time, where the three directional components are shown separately.



(b) Positioning over time, where the three directional components are shown together.



(c) Scatter plot of the East and North components.



(d) Histogram of the fix and float solutions together.

Figure 5.19: Positioning over time and scatter plot of the fix and float solutions of the experiment taking place in Dar es Salaam on a baseline length of 9km.

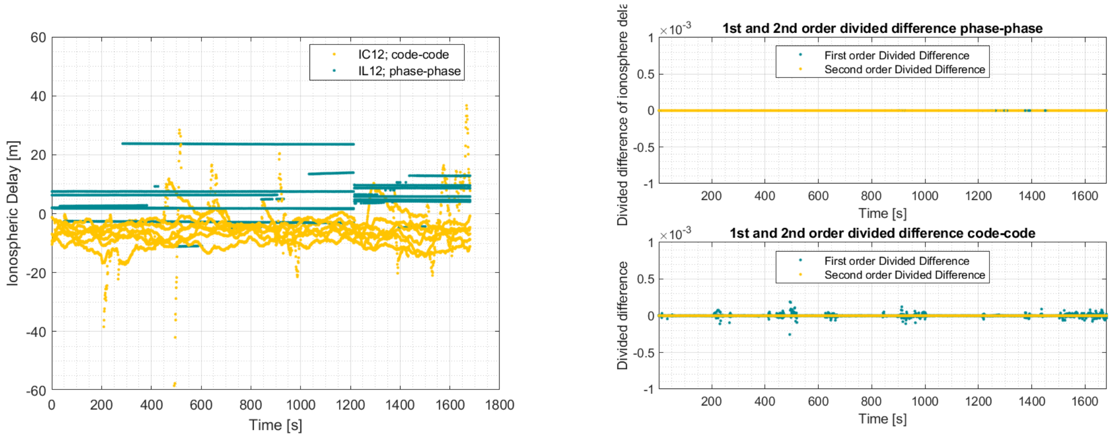
Now that positioning over time and the scatter plot of the fix and float solutions are displayed next to the relevant histogram, a comparison between the directional components can be made. Two different aspects are examined; the difference between the directional components and a comparison with the 6km baseline experiment in Dar es Salaam is made.

The first thing that stands out with respect to the different directional components is that there is more fluctuation in solutions in the East component than in the Up component. This is also shown when comparing the RMS values, where the East component is almost three times as high as the North component, and the Up component only has twice the value of the North component. Of all the obtained solutions histograms were made, as shown in Figure 5.19d, again 25 bars were used. Because the fluctuations are so large, these different bars are not visible.

A glance at the different figures shows that the results of this experiment are not as promising as those of the $6km$ experiment. Part of the explanation could be the difference in atmospheric delay, but on a difference of baseline length of $3km$ this shouldn't have a decent effect. Another explanation could be that either the solutions time of 20 minutes was too little or the placement of the antenna was sub-optimal.

Since only 9% of all solutions are fixed solutions, it was decided not to further elaborate on the results.

Atmospheric delay
In figure 5.20 the ionospheric delay and differencing can be seen. The code-code and phase-phase measurements are visualized in yellow and green dots respectively.



(a) Ionospheric delay over time.

(b) First and second order differencing over time.

Figure 5.20: Atmospheric delay of the experiment in Dar es Salaam with a baseline of $9km$.

These results are interesting to compare with the results of the experiment that took place in Dar es Salaam with a baseline length of $6km$, as presented in Figure 5.17. It can be seen that here the phase-phase measurements show a poorer result, the delay exceeds $20m$ for a longer period than in experiment *Dar6km*. In addition, there are several "jumps" in the data, whereas in the previous experiment the transitions were often smooth. It is worth noting that there are fewer points in the code-code linear estimations of the ionospheric delay. It should be emphasized that this will be caused by the fact that fewer observations have been made for this experiment, instead of more than 60 minutes this experiment lasted only 20 minutes. A second look at the graphs reveals that there are less outliers in these measurements, which cannot be explained by the shortened duration of the measurement. The atmospheric delay is explained in more detail in the discussion, and compared with the other experiments.

5.4.3. Experiment in Delft; high-end antenna

In order to achieve the best results, it is probably a profound decision to use a high-end instead of a low-end. Therefore the next variable that will be further studies is the use of a high-end antenna. Section 4.3 explains the difference between these two antennas, showing some figures to make the difference clearer. An overview of this static experiment is given in Table 5.5.

Table 5.5: High-end antenna experiments - rover

Experiment	Location	Antenna	Movability	Baseline	Program
DelftHkm	High-end	PPK	Static	6km	RTKLIB

The experiment used the high-end antenna and took place on the flat roof of the author's house on a sunny day. To recap; the high-end antenna that is used is located on the tower of the NMi and for the rover the low-end antenna is used. During this measurement 2452 solutions were made, for a little less than an hour. The results obtained are analysed using the following key-performance indicators; number of satellites, skyplot, elevation angles, positioning over time, scatter plot and the atmospheric delay.

Number of satellites, skyplot and elevation angles

The amount of satellites in view is presented in Figure 5.21. In this experiment it is not relevant to present the skyplot and the graph with the elevation angle.

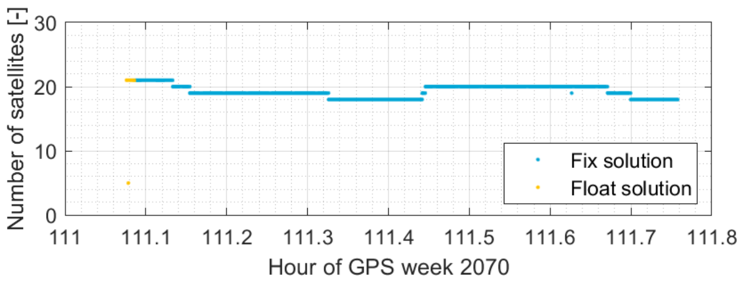
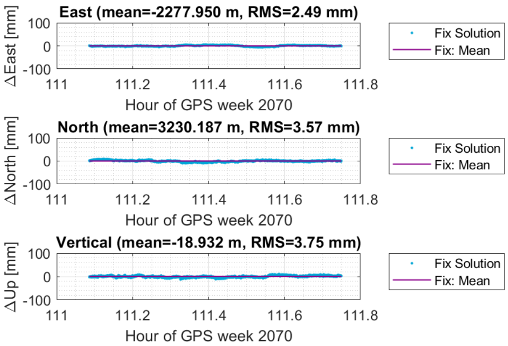


Figure 5.21: Number of satellites in view.

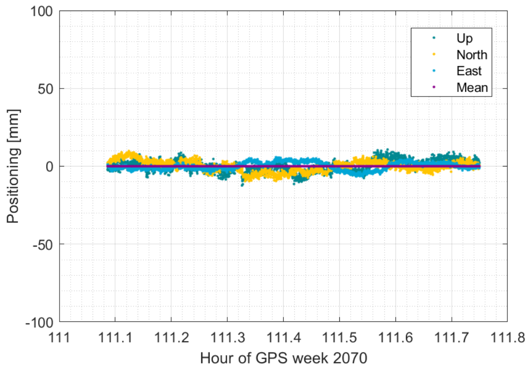
It becomes clear that there are enough satellites in view, with many fixed solutions being achieved. The first solutions are still in float mode, but after half a minute the ambiguity resolution is reached.

Positioning over time and scatter plot

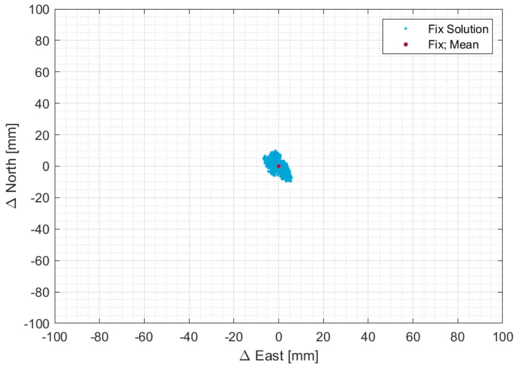
Comparing the high-end with the low-end antenna experiments starts with key performance indicators positioning over time, scatter plot and histograms for each directional component. The results are presented in Figure 5.22



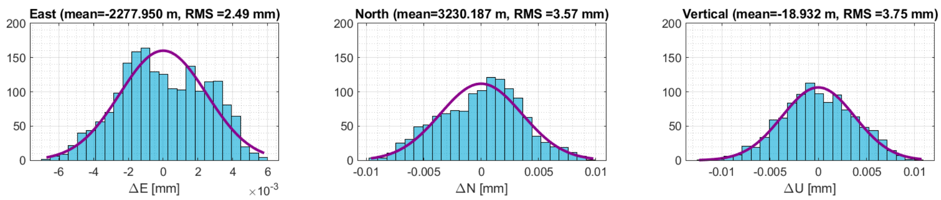
(a) Positioning over time, where the three directional components are shown separate.



(b) Positioning over time, where the three directional components are shown together.



(c) Scatter plot of the East and North components.



(d) Histogram of the fix solutions.

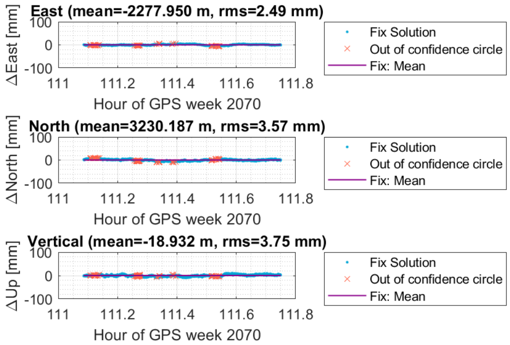
Figure 5.22: Positioning over time and scatter plot of the fix solutions of the high-end antenna experiment.

Positioning over time and the scatter plot of the fix solutions are displayed next to the relevant histogram, a profound comparison between the directional components can be made. Two different aspects are examined; the difference between the directional components and a comparison with the $6km$ baseline experiment in Delft with a low-end antenna.

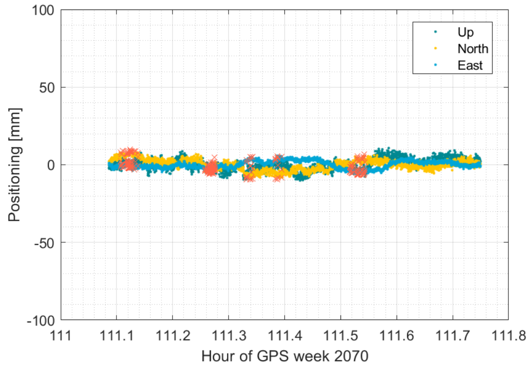
There is little fluctuation in all three directions, as all solutions differ little from the average value. This is reflected in the graphs with the solutions over time, as well as in the scatter plot. These findings are somewhat similar to what is visible in the histograms, but in the East direction there are few values that have the average value. There are more solutions that have a deviation to the west than to the East. To some extent this is also visible for the North component, where there are more solutions that have a deviation in the north direction than in the south direction. For the Up component, the PDF is the best fit. The RMS of the vertical component is again higher than that of the horizontal components, but the difference is fairly small.

Comparing this experiment with the *SP experiment*, using a low-end antenna, shows a clear difference in RMS in the vertical component. During the *SP experiment* the RMS is 8.22mm, while in this experiment it is around 3.75mm. This improved positioning is confirmed in the positioning over time, as it becomes clear that the fluctuations of the East, North and Up components are similar, as is the case with the histograms. However, the distribution of the solutions in the SP experiment for the horizontal components is more in line with the PDF.

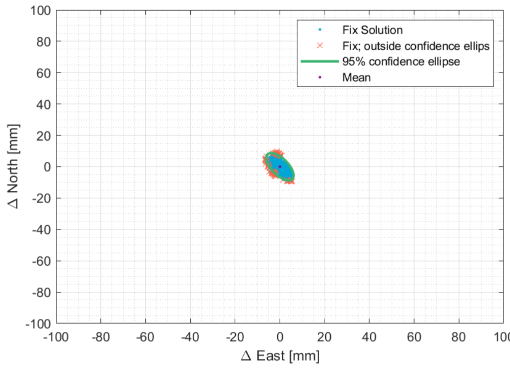
The next step in the analysis process is the fix solutions located in the 95% confidence ellipse, which are shown in Figure 5.23, where all fixed solutions outside of this ellipse are represented by a red cross.



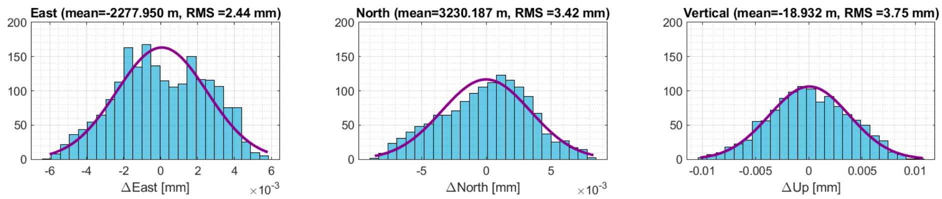
(a) Positioning over time with the confidence ellipse, where the three directional components are shown separate and outliers removed.



(b) Positioning over time with the confidence ellipse, where the three directional components are shown together and outliers removed.



(c) Scatter plot with the confidence ellipse, where the outliers are removed.



(d) Histogram with the solutions inside the confidence ellipse taken into account.

Figure 5.23: Positioning over time and scatter plot of the fix solutions inside the confidence ellipse of the high-end antenna experiment were the outliers are removed.

In line with expectations, the result has now been further improved. When reviewing the RMS of the different directional components, it can be observed that the East component has become smaller, while the North component and the vertical component have remained the same. When the focus is shifted to the histograms, there is little difference in shape in the histograms of Figure 5.22d, the slightly irregular shape has remained in the East and North direction.
Comparing these results with those of the fix solutions in the confidence ellipse of the starting point experiment, Figure 5.8, there is mainly an improvement in the vertical direction component. The RMS in the SP experiment is 7.56mm and in this experiment it is 3.75mm.

PDOP over time
After the positioning over time and the scatter plot, the PDOP values are examined and presented in Figure 5.24. It was decided to only study the PDOP and the standard deviation over time of the fixed solution inside the confidence ellipse. This is because these results are expected to be the best and therefore the most interesting.

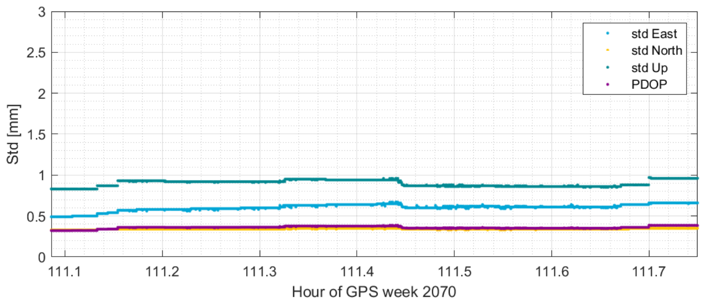


Figure 5.24: PDOP for all fixed solutions inside confidence ellipse

As can be seen in Figure 5.24, the standard deviation of the vertical component is the largest and of the horizontal component the lowest.

5.4.4. Moving PPK experiment in Delft

In the context of Dar Ramani Huria, and considering the size of the city, it might be interesting to do the measurements kinematic. First the kinematic experiment in Delft will be studied, after which the kinematic experiment in Dar es Salaam will be presented in the next section.
In this highlighted experiment a walk through the centre of Delft was made, at a distance of about 6km from the reference station. During this walk, some characteristic pieces of Delft were passed, as indicated on the map of Figure 5.25. All solutions are indicated in orange, as in previous results this means that it is a float solution.

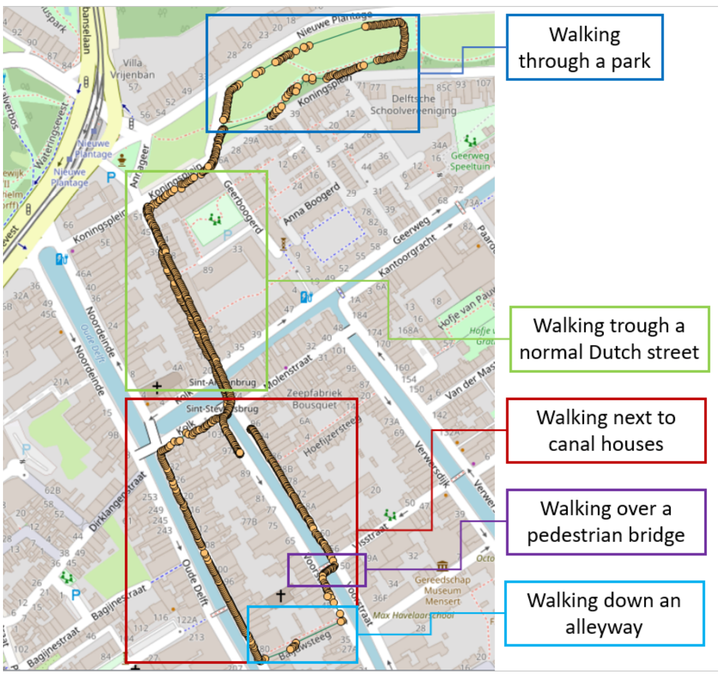


Figure 5.25: Map of the walked route
PPK kinematic experiment in Delft.

If one looks at the map, there are some interesting places to highlight; the alley and the bridge. In Figure 5.26a the solutions taken in the area of the bridge are shown and in Figure 5.26b the solutions taken when walking through the alley.

(a) Area around the bridgde
PPK kinematic experiment in Delft.

(b) Area around the array
PPK kinematic experiment in Delft.

Figure 5.26: Interestingness parts of the walked route in Delft
PPK kinematic experiment in Delft.

First, the results in the vicinity of the bridge, as presented in Figure 5.26a, will be elaborated on. On this map it appears as if the canal has been crossed while swimming, instead of walking over the bridge. There is a difference of $7.20m$ between the walking path and the solutions according to the GNSS receiver. If the comparison is made with parts of the route that run parallel to this bridge, it appears that there is the same discrepancy of $7m$. There are two possible explanations for this constant south-eastern offset; offset in the map and offset in the measurement. The offset of the map means that the map is "shifted" in relation to the actual location and is consequently not a appropriate representation of reality. The map chosen to show is from OpenStreetMap, and will be further clarified in Section 7, the maps of OpenStreetMap are in general very accurate. No literature has been found, but it is very unlikely that the inaccuracy is in the map. So the offset is most likely caused by the GNSS receiver or setting up the RTK network. As the location of the reference station has been an -although accurately worked out- approach, there may have been an error in this. The low-end antenna was positioned a few meters away from the high-end antenna, so a conversion had to be made from the known location of the high-end antenna to the position of the low-end antenna. It can be assumed that the bias of $7m$ can largely be explained by this, besides that there may still be an error in the solutions.

The next interesting part of the measurement is the part where an alley was passed. The route passes between two rows of tall buildings, known as an urban canyon, which interferes with satellite tracking through the receiver. This can be observed when looking at the number of satellites in view; passing the alley has been around the $109.15H$. As can be seen in Figure 5.27 there are few satellites in sight of the antenna at this moment. A decrease in performance due to a reduction in the number of satellites in view is entirely in line with expectations.

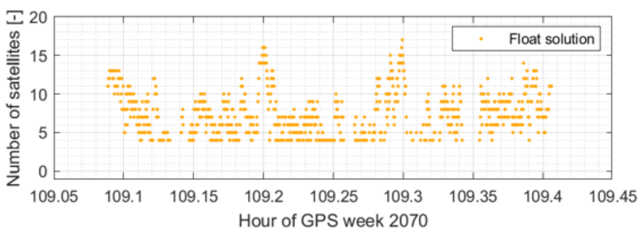


Figure 5.27: Number of satellites for the moving experiment in Delft.

Throughout the experiment, no fix solutions have been reached, and relatively few satellites are in view. The minimum number is four and the maximum is 17 satellites in view. This can be explained by the fact that most houses or buildings obstruct the antenna, and in the park the tall trees disturb the signals.

5.4.5. Moving PPK experiment in Dar es Salaam

In addition to a moving experiment in Delft, a kinematic experiment was conducted in Dar es Salaam. The antenna of the GNSS receiver was placed on the roof of the bajaj, and the receiver with antenna was kept inside the bajaj. To get an impression of how this experiment is done, reference is made to photographs that are presented in Section 4.3. With the bajaj a route was taken that passes characteristic parts of Dar es Salaam, the road is presented in Figure 5.28 where again only floated (so orange) solution points can be seen.

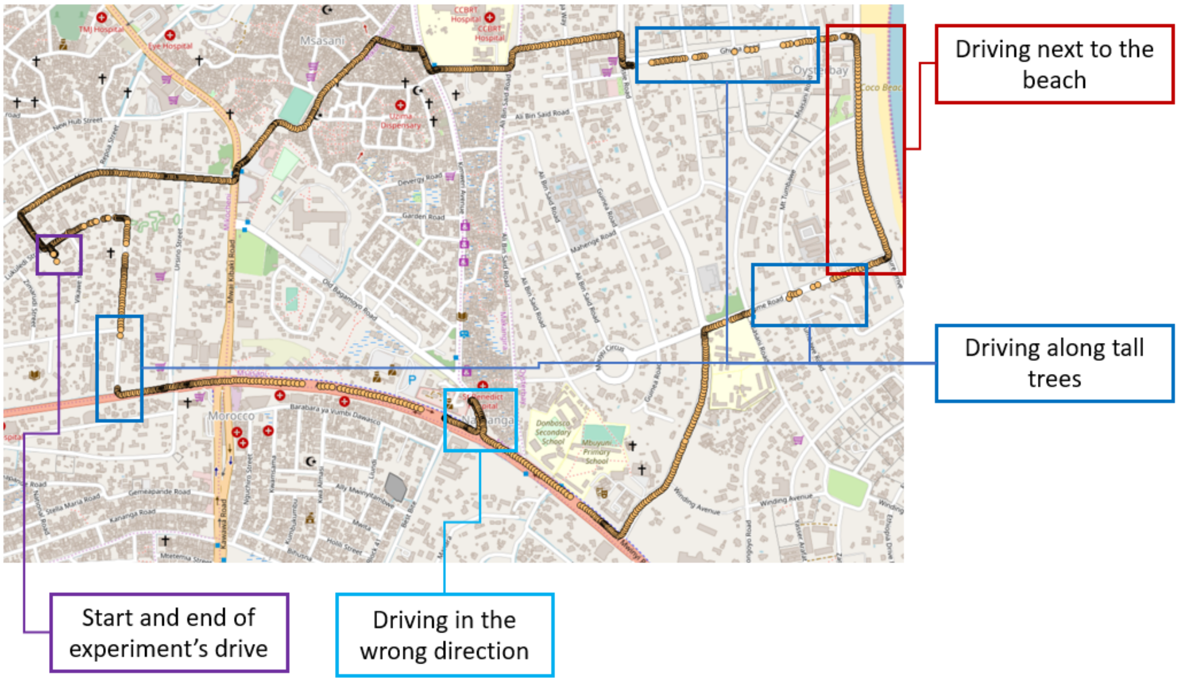


Figure 5.28: Map of driven track
PPK kinematic experiment in Dar.

There are two interesting parts of the route that deserve extra attention; making a wrong turn and riding under high trees. Starting with making the wrong turn, presented in Figure 5.29a. Initially, the bajaj was on the left side of the road, as the legislation in Tanzania requires. At one point the decision was made to turn around. In order to complete the turnaround, the bajaj had to leave the road, it is clearly visible in the figure. During the turn, the solutions are closer together, as the speed is lower. Just before crossing the road, the speed is the lowest, and the density of points is the highest. After the turning point, the vehicle continues to drive on the left side of the road.

One of the segments of the route where few solutions are made ,due to trees that disturb the signal, (the most right one) has been zoomed in. This can be seen in Figure 5.29b. For these figures optical satellite images of google were used to display the trees. It should be noted that bajaj also drove pieces beside the road, as a result of which the trees formed more of an obstruction than if the bajaj had driven in the middle of the road.

(a) Took the wrong turn and drove back
PPK kinematic experiment in Dar es Salaam.

(b) Area around the array
PPK kinematic experiment in Dar es Salaam.

Figure 5.29: Interesting parts of the driven route
PPK kinematic experiment in Dar es Salaam.

5.4.6. Re-initialisation experiment; meter baseline

During the re-initialisation test, the GNSS signal is disturbed for 30 seconds every minute, causing the total loss of contact between the receiver and the satellite. This experiment was performed to analyse the TTFA, i.e. the time it takes for it to reach a fix solution again after the signal has been disturbed. A PPK positioning mode was used in Delft, where the baseline was several meters long, a low-end antenna and the measurement was done in RTKLIB. Figure 5.30 shows how the ambiguity ratio test proceeds over the duration of the experiment, with the yellow float and blue dots representing the fix solutions. In order to be able to show the course of the solutions, a thin, grey line between the solutions was plotted. The purple dots show when after disturbing the signal the ambiguity ratio again has a value of at least 3.

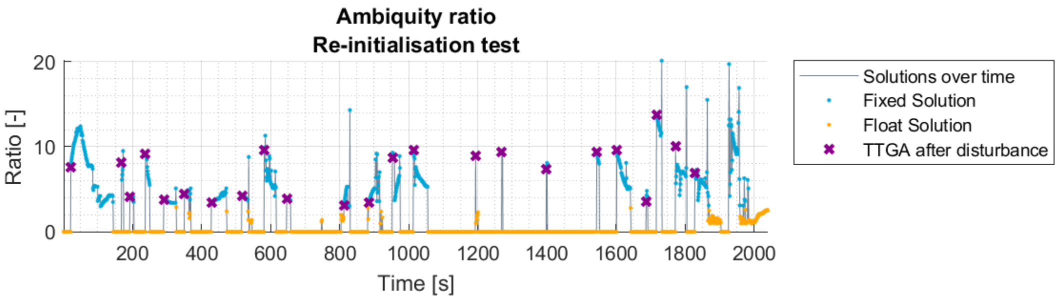


Figure 5.30: Ambiguity ratio test over time, for the experiment at a meter distance from the reference station.

Displaying the TTFA in the form of a graph gives an indication, in order to avoid possible ambiguities, it was also decided to display the TTFA in Table 5.6. If the TTFA is >60s, there are no fixed solutions within a minute. If these values are not taken into account, the average TTFA is 1.33s.

Table 5.6: Re-initialisation experiment in Dar es Salaam with a baseline length of few meter.

Disturbance	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
TTFA (s)	1	1	1	1	1	1	1	1	>60	1	1	>60	9	3	>60
Disturbance	16	17	18	19	20	21	22	23	24	25	26	27			
TTFA (s)	>60	1	1	1	1	1	1	1	1	1	1	1			

5.4.7. Re-initialisation experiment; 6km baseline

The same experiment was carried out at a baseline distance of 6km in Delft. Again every minute the signal is disturbed for 30 seconds and a graph with the TTFA is shown, as shown in Figure 5.31.

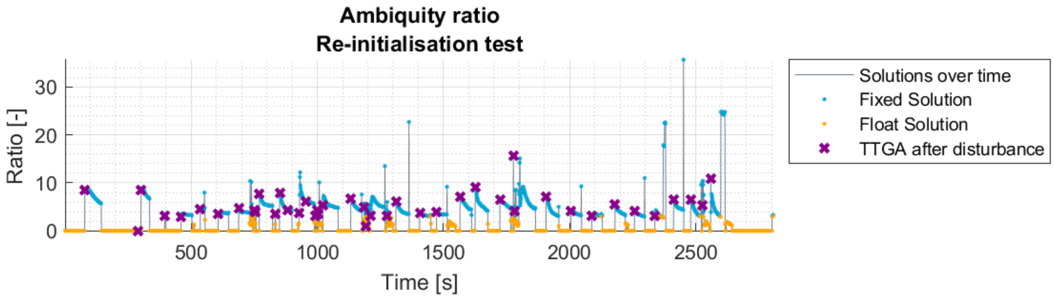


Figure 5.31: Ambiguity ratio test over time, for the experiment at 6km distance from the reference station.

Again, it was decided to display the results in table form, Table 5.7. Again it applies that if there is a >60s noted than no fixed solution was achieved within one minute. The average of all solutions, minus where no fixed solution is reached, is 1.47s.

Table 5.7: Re-initialisation experiment in Dar es Salaam with a baseline length of 6km.

Disturbance	1	2	3	4	5	6	7	8	9	10	11	12
TTFA (s)	1	1	1	1	1	1	1	1	6	2	1	2
Disturbance	13	14	15	16	17	18	19	20	21	22	23	24
TTFA (s)	1	3	3	2	1	1	1	1	1	1	4	1
Disturbance	25	26	27	28	29	30	31	32	33	34	35	36
TTFA (s)	1	1	1	1	>60	>60	1	1	1	5	2	1
Disturbance	37	38	39	40	41	42	43	44	45	46	47	48
TTFA (s)	1	1	1	>60	>60	>60	1	1	1	1	1	1

For both re-initialisation experiments it should be noted that the 30 to 60 second alternation was not always exactly as accurate. In both experiments it was once forgotten to remove the obstruction from the antenna after 30 seconds. Fortunately, this was quickly discovered and the obstruction was not more than a minute obstructing the signal. In addition, the obstruction time of 30 seconds can be questioned. The first time the pan was placed over the antenna, the screen of RTKLIB was monitored, the signal was completely disturbed by means of grey bars that disappeared. When later in the experiment another look was taken at the screen, it became apparent that the signal did not disappear completely, but only strongly decreased.

6 Discussion

In this chapter, the results of the experiments are discussed and interpreted. The interpretation is mainly based on literature and compared to experiments carried out during this study. The discussion also mentions some limitations of the research and highlights striking results.

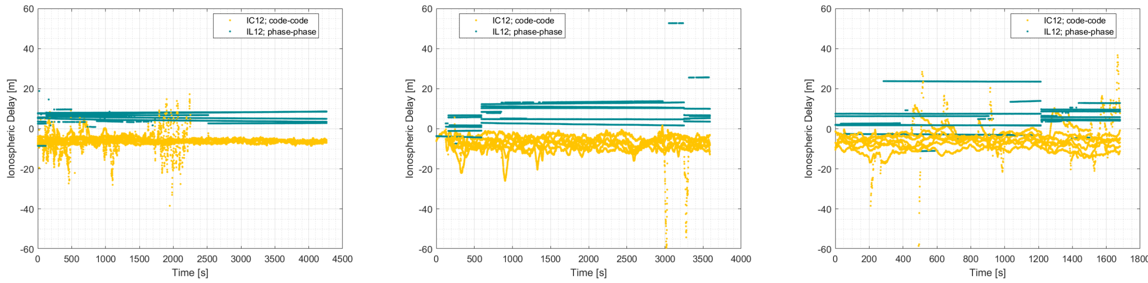
6.1. Missing ground truth

When determining the receiver's performance, a so-called ground truth is often used. If the position coordinates determined by a GNSS receiver are an estimate of a position, then the ground truth is the actual location on Earth. The *ground truth* is often called the *true position*. The accuracy of the estimated position is the maximum distance between the estimated position coordinates and the ground true. In Delft there are some documented ground truth points. However, to the best of HOT Tanzania's and the author's knowledge, there are no accessible locations in Dar es Salaam whose position has been accurate and precisely determined. Which means that the study has to be continued without a ground truth, as a consequence, the focus shifts from accuracy to precision. The absence of ground truths required an assumption about the true location. It was assumed that the average of all initial fix solutions was the truth. This assumption has already been made in previous studies, in which the ground truth was not present. An example is the study by Gill et al [23], for a short summary and conclusions of this research a reference is made to Section 3.1.
From this average based on initial fix solutions, the RMS, maximum and minimum deviation were calculated. This has a limitation: It is uncertain whether the average is a profound representation of the truth. An indication of the accuracy was obtained by plotting the fixed solutions on a map and studying the extent to which the location on the map corresponds with the GNSS solutions. Any discrepancies between these two locations could be explained by two factors: an offset of the map and/or an offset of the solutions. As already discussed in Section 5.4.4, it can be concluded that when using OpenStreetMap, the possible deviations are most likely caused by the GNSS receiver and not by the map-offset. The calculation of the RMS is adjusted after the removal of the outliers, this is also reflected in the results (can be reviewed in Table 5.1)

6.2. Differences between Dar es Salaam and Delft

One of the many differences between Delft and Dar es Salaam is the climate, where the climate is influenced by, among other things, the relationship between the atmosphere, the ocean, the land surface, snow and ice, and the vegetation. With the help of GNSS it is possible to look at the atmospheric delay of a GNSS signal during a measurement, which is an indicator of the atmospheric activity. In this research the differences between Delft and Dar es Salaam in atmospheric delay were addressed for the first time.

The -theoretical- differences in the ionosphere and troposphere between regions around the equator and at higher latitudes has already been discussed in Section 2.3.2. The expectation, based on the research of Wu et al [64] and information obtained from the GNSS handbook [57], is that the ionospheric delay in Dar es Salaam is more severe than in Delft. Thanks to the dual-frequency observations made during this research, this hypothesis can be tested. The results are presented in Figure 6.1a.



(a) Ionospheric delay for the experiment in Delft, with a baseline length of 6km.

(b) Ionospheric delay for the experiment in Dar es Salaam, with a baseline length of 6km.

(c) Ionospheric delay for the experiment in Dar es Salaam, with a baseline length of 9km.

Figure 6.1: Comparison of the ionospheric delay for three highlighted experiments.

In all three figures the linear combinations are not unbiased estimators. For a further explanation of the negative values that appear in these graphs and the difference in precision, please refer to Chapter 5 of the performance study. In this chapter the delay is discussed per experiment.

Now that the three figures of the atmospheric delay are presented next to each other, the differences can be studied. In which focus is on the phase-phase measurements that are less noisy than the code-code measurements. When comparing the experiments, three aspects are taken into account; the average height, the distribution of solutions and the presence of outliers. First of all, it becomes clear that in the *SP experiment* (Figure 6.1a) the delay during the entire measurement shows the least dispersion: all delay-solutions have almost the same value over time. Continuing with this mean value, it can be observed that the mean value in the *SP experiment* is lower than in the *Dar6km experiment* (Figure 6.1b). The *Dar9km experiment* (Figure 6.1c) shows an even higher average delay. Finally, the amount of outliers was examined, with the *SP experiment* again showing the best results. In the *Dar6km experiment* some outliers can be detected, at the end of the experiment a value of around $50m$ is measured for several seconds. Thereafter there is a measurement of several seconds with a delay of approximately $25m$. In the *Dar9km experiment* the magnitude of the outlier is decreased, but is last longer.
A noticeable phenomenon in these three graphs is that jumps occurring, in The *Dar6km experiment* around $600s$ and $3200s$, although interesting, they are outside the scope of this research.

6.3. Practical objections of experiments

Performing experiments can cause some practical objects, some of which are addressed in this discussion as they are an important aspect of the performance study. First, the *placing reference station in Dar es Salaam* experiment is discussed. After a few attempts it was possible to conduct an experiment for 24 hours, after which the necessary files were sent to the respective NRCAN website. Converting the raw measurement data to a RINEX file and uploading it to the website is done on a desktop computer of HOT Tanzania. After downloading the results, the files were unfortunately deleted, which meant that a further analysis of the results was not possible. Further analysis of the data could have ensured that more information was available, possible errors and biases could have been discussed and further interpretation of the rover location could have taken place.
Already mentioned several times in this thesis, it is important for the receiver's performance that the antenna is placed at a suitable location in the field. In addition, it is important for the static experiments that the antenna remains at that position for about 60 minutes. During the *Dar9km experiment* this procedure could not be followed; the experiment was interrupted after 20 minutes. After performing the experiments in Dar es Salaam it appeared that halfway through the experiment the mean-members check whether the antenna was still attached properly, which caused the equipment to move. This movement is not reflected in the results, so it is possible that the movement was small, or the antenna is less precise than what can be concluded from the results.

These are a few examples of practical objections that can take place during experiments. Unfortunately, human behaviour can interfere with a well-functioning measurement. It was noticeable that by working with a manual, which described step-by-step what had to be done, people were more aware that their actions could have consequences for the results. After giving the workshop and sharing the manual the amount of incorrect actions were reduced. This shows that the introduction of the manual was beneficial, and that the workshop contributed to the performance study. More about this in the next part of the thesis; the case study.

6.4. Fix solutions

As previously mentioned, fixed solutions generally provide more accurate and precise results than float solutions. Therefore, it is decided to elaborate further on the obtained fixed solutions during the experiments. Bearing in mind that experiment *Dar9km* and *Dar6km* both achieved less than 15% fix solutions. For the results, please refer to Chapter 5.

6.4.1. From float to fix solution

With the start of a measurement, the first solutions were estimated as floating-point numbers. Solving the ambiguity takes some time, after which the fixed solutions were reached. This process is described in Section 2.5 and can be reviewed in the presented *positioning over time graphs* in Chapter 5. Consulting the GNSS book [57] gives a general idea of the *positioning over time* and the *scatter plot*. This is presented in Figure 6.2.

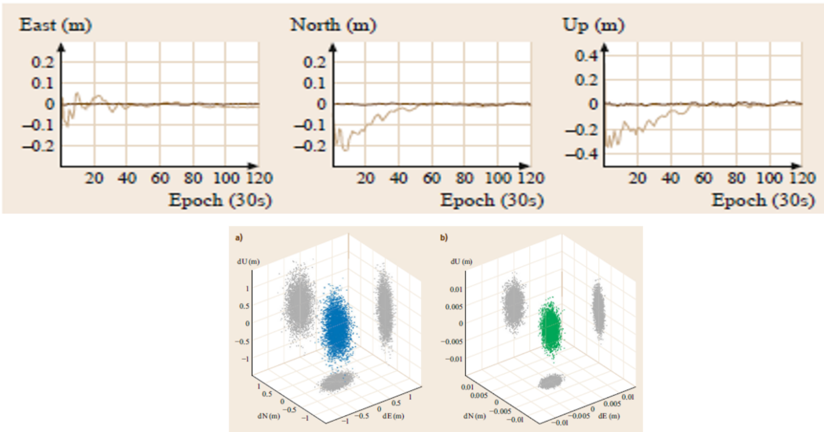


Figure 6.2: Progression from floated point solutions to fixed solutions according to GNSS handbook [57].

The course of the non-precise float to the precise fix solutions is clearly shown in these three left-hand graphs. The wider distribution of the float solutions is shown in this figure, where a 3D scatter plot is made instead of the 2D scatter plots presented in this study. The difference in horizontal and vertical components is further discussed in Section 6.5 of this chapter.

The theory discussed above is well presented in the positioning over time and the scatter plot of the *SP experiment*, for the results see Figure 5.4a. However, when reviewing the other highlighted experiments, this is less applicable. It is established that every measurement starts with a float-solution, as expected. A difference is observed in the time until the fix solution is reached. In all but the SP experiment an alternation between fix and float solutions occurs. Possible explanations for this are discussed in the following paragraphs.

6.4.2. Differences in baseline lengths

There is no maximum limit on the baseline length for RTK, however -theoretically- accuracy and precision degrades and initialization time increases with range from the base. This can be confirmed when reviewing the results of this thesis, however to draw a well-founded conclusion some aspects need to be taken into account. First of all, the percentage of fix solutions of all results is a tricky point (see Table 5.1) which shows a diversity. If only experiments with more than 25% of fix solutions inside the confidence ellipse are taken into consideration, it appears that there is insufficient data available to draw a well-founded conclusion.

6.4.3. Insufficient satellites in view

An intuitive reason for the lack of high performance may be an insufficient amount of satellites in view. The GNSS system is designed so that at least five satellites are above the local horizon at all times (except at in the pole regions). For several moments throughout the day, at least eight satellites might be above the horizon. Due to the fact that satellites are in orbit, the satellite geometry changes during the day, but repeats form day-

to-day. Even though only four satellites are needed to form a fix, RTK and PPK initialization demands that at least five GPS satellites are tracked. When additional constellations, such as Galileo, Glonass or BeiDou, are tracked, one of the satellites will be used to resolve the timing offsets between the concerning and the GPS constellation [45]. Obtaining this minimum number of satellites in view can sometimes not be achieved in an urban canyon.
A prime example of this is during the kinematic experiment that took place in Delft. The walk was through an alley, the width of the alley was less than three meters and the adjoining houses several floors high. As a result, little of the sky is visible and the receiver is not able to track many satellites, which has negative consequences for the performance of the measurement.
The consequences of insufficient satellites are discussed in detail in a study by Dutt et al [18] in which the importance of the distribution of satellites in view is elaborated on. Obolinski et at [45] and Liu et al [37] have examined the effects of a limited number of traceable satellites during a measurement. Liu's et al's conclusions are summarized in Figure 6.3, where the effects of few satellites in a PPP setup are clearly shown.

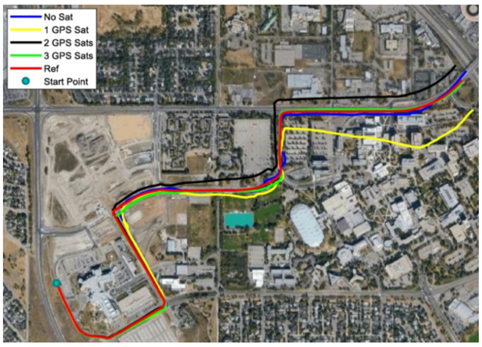


Figure 6.3: Conclusion of Liu et al's study in the performance of a GNSS receiver with different amount of satellite's in view [37].

This shows the far-reaching consequences for positioning performance, although it must be taken into account that this concerns PPP positioning in kinematic experiments instead of a static PPK experiment. During this thesis, GPS, Galileo and Glonass satellite constellations were used in order to have as many satellites in view as possible and to be able to enforce an optimal geometry. In addition, with each measurement the skyplot was analysed, to determine whether the satellites were well distributed over the sky.

6.4.4. Difference in integer ambiguity resolution configuration

In addition to the previous mentioned objections, there may also be a software setting that may affect the integer ambiguity resolution configuration. In RTKLIB there are three different options that can be selected for GPS integer ambiguity resolution; instantaneous, continuous and fix-and-hold. Instantaneous is the most conservative and recalculating the phase estimates every epoch. It therefore does not use previous estimations. Continuous is the default option; estimates of the phase biases are recalculated continuously over many epochs. Fix-and-hold takes the concept of "feeding" information derived from the current epoch forward to subsequent epochs a step further. In general, taking advantage of all the information there is can improve the positioning, especially taking into account the hypothesis that in low-cost antenna's there is more noise. During this study, only the configuration "continuously" was used, which is a certain limitation in the study. When is considered that post-processing was used to search for the best possible position, so the setting of fix-and-hold is worth considering in the future [53].

6.4.5. Minimal ratio to fix ambiguity

The next topic linked to the fix solutions is the minimal ratio to fix ambiguity. In general, the larger this number, the higher confidence there is in the fixed solution. If the ambiguity ratio exceeds a set threshold, then the fixed solution is used. Otherwise the float solution is used. The default value for this threshold is 3.0. If this value is adjusted downwards, it may be that more "fixed" solutions are achieved, however, the confidence in these solutions decreases. In summary, it can be said that adjusting this value is not a sensible choice, the trade-off between confidence and the number of fixed solutions does not outweigh the number of fixed solutions. [54]

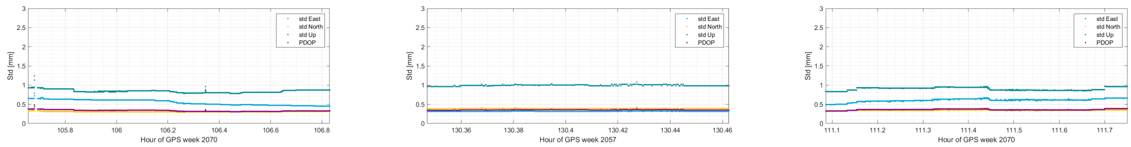
6.4.6. Cycle slips and ambiguity jumps

A cycle slip is a discontinuity in a receiver's continuous phase lock on a satellite's signal. The pseudo-range measurement is immune from this difficulty, the carrier-phase is not. In post-processing, the location and the size of cycle slips must be calculated; then the dataset can be repaired to reach a fixed solution for all the subsequent phase-observations. One approach is to hold the initial positions of the rover in the fixed solution, and edit the data manually. As this is a time-consuming job it is not recommended. Another approach is to model the data on a satellite-dependent basis to find the breaks in the continuous data followed by editing the data. In fact, several methods are available to find the lost integer phase value. Cycle slips are detected when a large residual appears, the residuals of the *SP experiment* are presented in this research. These residuals do not show a large outlier in the data, therefore there are no cycle slips in this experiment. Not presented, but studied are the residuals from the other experiments, therefore the same statement is valid.

For a detailed explanation of possible causes of ambiguity jumps, reference is made to the study by Wang et al [60] in which experiments have been carried out to investigate all possible explanations of ambiguity jumps. The overall conclusion can be summarized with the fact that the measurement noise and the ionospheric delay residuals have a (to large) effect on the ambiguity resolution of the carrier-phase observations.

6.5. Vertical component in the GNSS performance study

For the production of hydrologic and/or flood models, the performance of the vertical component is of particular importance.
Studying all the results, as presented in this thesis, it is observed that the results of the vertical performance are the poorest in comparison with the horizontal performance. This is confirmed in the presented PDOP and standard deviation graphs, as shown in Figure 6.4.



(a) PDOP for all fixed solutions inside confidence ellipse for the *SP experiment*.

(b) PDOP for all fixed solutions inside confidence ellipse for the 6km baseline experiment in Dar es Salaam.

(c) PDOP for all fixed solutions inside confidence ellipse for the high-end antenna experiment.

Figure 6.4: Comparison of the ionospheric delay for three highlighted experiments.

Now that the PDOP and standard deviations have been placed next to each other over time, it becomes clear that indeed all three experiments show that the vertical component has the highest standard deviation, and therefore a worse performance. The reason for this is a matter of visibility and geometry. Different aspects play a role in this; geometry and obstructions.
Firstly, a fair distribution of satellite constellations in the horizontal plane causes errors of satellites on the eastern and western sides to cancel each other out. For the vertical component this is impossible, as the signals cannot pass through the earth. So only the satellite above the receiver is visible, and there may still be a position estimated, but the error adding up instead of cancelling out.
Second, there is the problem of obstructions on the horizon. In most real world scenarios, a GNSS device will have buildings and other obstruction blocking the visibility of some satellites and preventing the device from using the best satellites to allow the most accuracy vertical and horizontal position. At this point the receiver must make a trade off between horizontal and vertical accuracy. Since most applications of GNSS equipment require more accurate horizontal position, the receiver's chip is tuned to favour better horizontal accuracy. With programming on the chip, it is possible to (partially) find a solution for this, so that the vertical component is preferred to horizontal performance. It remains to be seen whether this is actually desirable.
Both problems can partly be solved by using more satellites and consequently by using multiple satellite constellations. This is further discussed in Section 6.4.3.

6.6. Impact of the geoid in hydrological modelling

It has already been briefly reported in Chapter 2, the geoid in the Netherlands and Tanzania is different. When zooming in on Dar es Salaam the geoid has a rate of $0.07 m/km$. This means that in the city centre of Dar es Salaam (with a diameter of 10km) there is a change in the geoid difference of $0.7 m$. Most literature describes the effect of water on the geoid, but Naujok's [42] research mentioned the effect of the geoid on the flow of water. Naujok's research concludes that the hydrological variations are mainly caused by the topography, and the flow processes are highly dependent on the type of bedrock and subsoil. Despite the fact that his research into the relationship between the geoid and the hdyrological model is concerned, the geoid or gravity field as a whole is not mentioned in his conclusions.
There is not enough literature available to make a well-founded statement about this. Several hydrologists on the subject have indicated that it is probably irrelevant to take the geoid in hydrological modelling into account. However, the case may be that it is depend on the scale of the model.

6.7. Promising results; application of position determination

It has already been discussed in the Introduction (Section 1.3), but in addition to the case study mentioned in this thesis, there are other applications for the low-cost receiver. One of the possibilities mentioned is the mapping of the territory of farmers in Colombia. Or, the mapping of water flows in Indonesia. In the results, presented in Table 5.1, the RMS of the different direction components may be observed. The values for the horizontal performance (RMS East, RMS North) and for the vertical performance (RMS Up) of the fix solutions insofar as they fall inside the 95% confidence ellipse are of interest. The horizontal positioning performance ranges from 1.13 to $16.83 mm$. However the latter, the highest value is from a experiment with a very low percentage of fixed solutions. The vertical positioning performance shows less accuracy ranging from **3.56** till **34.02**mm. These results are promising for many projects in which precise position determination is desirable/required. The above mentioned applications -and many more- would benefit from using this low-cost dual-frequency GNSS receiver.

The use of the low-cost receiver to determine the position in surveys conducted for making hydrological models seems to be very promising. The results are more precise than using the Xiaomi smartphone. In order to implement the receiver in the Dar Ramani Huria project, a case study is required. This case study is presented in the next part of this thesis.

II

Case study

Introduction

It takes more than the performance study to decide if the GNSS receiver can be implemented in Dar Ramani Huria. The receiver must be suitable for use in the context of HOT Tanzania's community mapping; local community members will take it into the city and conduct surveys. Various methods have been used in this case study to investigate whether it is possible to implement the GNSS receiver and what steps still need to be taken to do so.

In this part the following research question is answered;

How can the receiver best be implemented in Dar Ramani Huria's project in Dar es Salaam, thinking of a user-friendly design, with local low-cost materials and a way of working with the receiver in such a way that the quality of the data is sufficiently high?

This part consists of a theoretical framework; Chapter 7. After which the methodology and the results are discussed. Finally, the discussion is presented. The conclusion and recommendations are combined with the performance study and can be found at Chapter 11 and Chapter 12.

7

Current process of surveying and map-making

The case study focuses on Dar Ramani Huria's community mapping project. First, a short introduction is given on flood modelling with the focus on the urban areas, so that the context of the project becomes clear. Then, step-by-step, it is explained in detail how Dar Ramani Huria works, how the surveys are carried out and how the maps are made. Attention is paid to the community aspect. Finally, community mapping projects that are described in the literature are examined, and a comparison is made with Dar Ramani Huria.

7.1. Flood modelling in urban areas

A hydrologic model is an approximation of the hydrologic cycle, which describes how the water moves in the hydrosphere [14], as simplified in Figure 7.1. Surface water evaporates and gets into the atmosphere, where it is moved as water vapour until it condenses and falls as precipitation on land and oceans. Precipitation is followed by several hydrologic processes; the water can be intercepted by vegetation, discharged as surface run-off, flow through the unsaturated zone in the soil as subsurface flow or infiltrate deep into the ground and recharge the groundwater storage. After this, the circle repeats itself and the water can evaporate again. Urban environments refer to urban hydrology, where the surface run-off plays a more important role than in rural areas, as shown on the right side of Figure 7.1.

Urbanisation implies that the soil is covered with artificial materials. As a result, water experiences fewer obstacles and can move faster. In other words, precipitation reaches lower-lying areas more quickly [12]. The surface run-off can be properly guided by drainage systems, that lead the surface water in drains to the closest water course, rather than over land.
Hydrologic models are thus an approximation of the actual situation of the hydrologic cycle and can be used to make a prediction of the behaviour of water throughout the cycle. This can be done by extending the knowledge of a water system, for this purpose an enlargement of the area should be considered. In addition, these models can be used to estimate how the system will react when there is a change in system characteristics. Gharari [22] argues that it should be "from the highest interest for decision makers to understand the effect of their decisions on hydrological behaviour and therefore the future status of a system". A flood model is defined as a hydrological model specifically aimed at predicting the spatial distribution of the water depth that appears for a certain rain event.
The accuracy and quality of a hydrological model is highly dependent on the data available [14]. Long-term measurements of the precipitation and discharge are important as forcing and as validation in the hydrologic models. In addition, clear boundary conditions must be set up, which indicate the limits of the model in time, space and indicate which assumptions have been made. The foundations of the model are the parameters that represent the relationship between the water and certain events, such as the evaporation rate. These parameters can be assigned via measurements or approximated if no data is available.

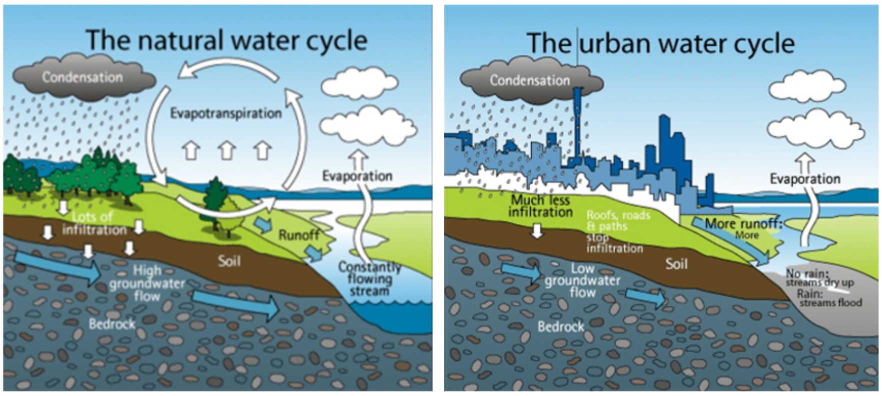


Figure 7.1: Simplification of the hydrosphere in both a rural and urban environment. [4]

7.2. Dar Ramani Huria's community mapping project

These sections aims to provide a description of the background and relevance of Dar Ramani Huria. It will support the understanding of how Dar Ramani Huria is initialised and developed over time. It will also relate this community mapping project to literature. The information that will be discussed here is based on HOT's [3] and Dar Ramani Huria's [1] website , blog posts [1], memos found at the office of HOT Tanzania, and the case study that was carried out by Iliffe [28]. In addition, all aspects became clarified through conversations, formal and informal, that took place with employees of Dar Ramani Huria and HOT. In Figure 7.2 an overview of the history of Dar Ramani Huria is shown.

7.2.1. Background

In the aftermath of the devastating earthquake in Haiti (2010) the community of the island was involved to evaluate and map the induced damage. This was such a success that the idea was copied by the World Bank in Dar es Salaam in 2011. In this pilot community mapping project, Ramani Tandale, there was collaboration between students of the Ardhi University and local NGOs. Students in urban and regional planning from this university were trained to use GPS devices and to collect surveying data, which were uploaded to OSM. The intention was to let the students bridge the gap between local citizens and more advanced ICT tools. In this initiative, meetings were organized in which the local residents had influence on decisions made. Concerning what should be mapped; roads, drainage, pharmacies, schools, sanitation, water access, waste disposals. The result was a detailed map of the Tandale ward in Dar es Salaam, openly available. This outcome led the World Bank to the more ambitious approach of the project and initiated Dar Ramani Huria 1.0, in 2012. The NGO HOT, was involved in the project; having gained experience elsewhere, now for the first time in Tanzania. For the first Ramani Huria project, the same working mode was used as for Ramani Tandale; let mappers collect data in the field and pass the collected data to data cleaners that edit it and upload it to OSM. More information about the current process of surveying and map-making is provided in Section 7.3. During this project, field papers to take notes and a GPS devices were used. The mappers were supported by aerial imagery tasks by drones of the flood prone areas.

The cooperation with HOT, the World Bank and local students ensured that Ramani Huria 1.0 could be expanded and a summer school, also called an 'industrial training', was organized. The first summer school was in 2015 and was called "Community Mapping for Flood Resilience". Students from the University of Dar es Salaam and volunteers were also welcome. After this successful initiative, Ramani Huria and HOT Tanzania continued as a group of development workers and supported several smaller projects in 2016, such as mapping out the cycling routes that Dar es Salaam has to offer. In addition, maintaining close contact with the residents of the previously mapped areas, revealed that the drainage and inundation maps created by Ramani Huria 1.0 had instigated measures for flood resilience on a local level. This includes regular cleaning of clogged drains, discouragement of dumping waste in drainage systems and construction improvements of the drainage systems.

In 2017, the methodology of drainage mapping was improved, and Dar Ramani Huria 2.0 was established. The drainage data from Ramani Huria 1.0 included the width and depth of cross sections, but missed data on elevation of the drains related to ground level. Also segments were missing or disconnected in the data set. In Dar Ramani Huria 2.0 the survey has been expanded to include this data and all data has been stored in applications for a smartphone instead of on paper. How the surveying and map-making process works is discussed in Section 7.3. Very recently, TU Delft graduate L. Petersson [49] conducted further research into flood modelling, including Dar Ramani Huria as a case study subject. Petersson's research shows that the drainage data collected by Ramani Huria is more extensive than that of local authorities. In addition the study proves that the mapping methodology applied by Ramani Huria has the potential to support decision making, flood resilience plans, risk reduction and urban development in resource-strained environments. This study also mentions the possible incorrect location determination by insufficiently adequate GNSS receivers as a source of error for surveying [49]

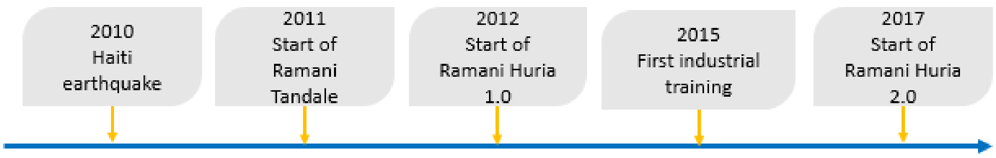


Figure 7.2: Timeline of the development of Dar Ramani Huria.

7.2.2. Management structure in HOT

As with any company, HOT Tanzania has a management structure, which is visualized in Figure 7.3. All these people are involved with Dar Ramani Huria in one way or another, in which the project associates play an important role. The management team, with Ivan Gayton, Willian Evans and Innocent Maholi, bear more responsibility for the final project, with Ivan Gayton maintaining the most contact with the stakeholders.

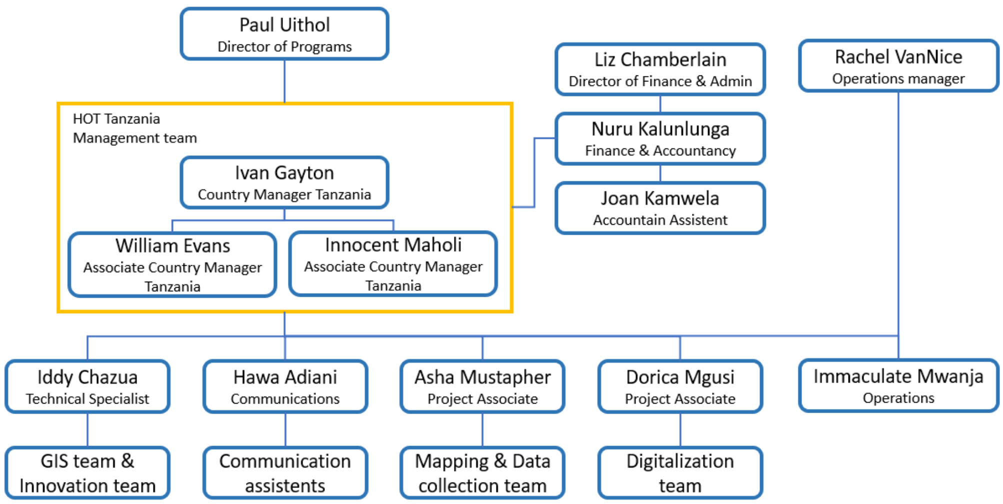


Figure 7.3: Management hierarchy in HOT Tanzania.

This structure was identified during the research period in Dar es Salaam, through informal conversations, after which a control was carried out together with Immaculate Mwanja.

7.3. Step-by-step approach to map the (sub)wards in Dar es Salaam

In most cases, maps are created remotely by cartographers with great knowledge in their field, but without any physical experience within the area of interest. This can result in inaccurate and/or insufficient data. The project of Dar Ramani Huria has a different approach; local citizens and students are trained to effectively create detailed maps of the city. In addition, community members are actively involved in mapping out their immediate surroundings and neighbourhood. There are several steps that need to be taken in the Dar Ramani Huria project before a map can be delivered, these steps are visualized in Figure 7.4 and discussed in the following section.

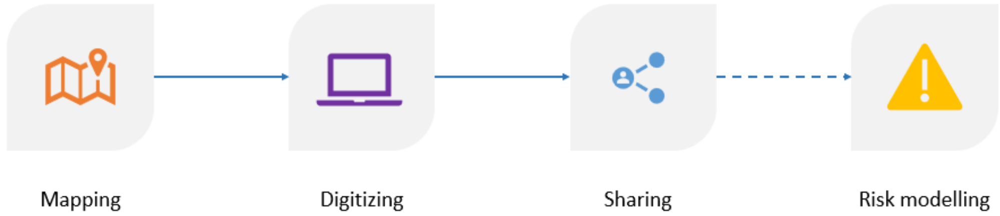


Figure 7.4: The steps that need to be taken in the Dar Ramani Huria project, to be able to make a sophisticated map of the city. Risk modelling is optional, the maps can be used for different purposes.

7.3.1. Mapping

The first step in map-making is to collect the relevant data. This step is known as the mapping phase. The data collection is done by students from the University of Dar es Salaam and the Ardhi University both located in Dar es Salaam, and local community members. The data-collectors, also called mappers, are trained during the Resilience Academy Industrial Training (RAIT), a six to eight-week programme during the months of July and August. In the summer of 2018, more than 500 students and volunteers received this training. In the first week of RAIT, they get acquainted with the different measuring equipment and software applications. The following five to seven weeks are devoted to do the actual measurements and mapping of the city. Figure 7.5a shows project leader Innocent Mahori giving a lecture about one of the phone applications.

Equipped with a smartphone and internet (and internet scratch cards) and supported by the Dar Ramani Huria team, students, community members and Wajumbe (community leaders) are able to collect data at the local level using two different android applications; OMK and ODK. These are intuitive smartphone applications that are equipped with imagery and forms for direct data collection while in the field. Every mapper has access to these applications and is able to use them for the surveys. Figure 7.5b shows an atmosphere impression during a data acquisition about trash in a suburb of Dar es Salaam.

One of the biggest challenges for the Dar Ramani Huria team during the mapping phase is to ensure the safety of the mappers. There is a lot of theft in Dar es Salaam, where violence is often used to confiscate the possessions. To be able to anticipate this, work is always done in groups, and a mapper is -in principle- never alone. This does not improve efficiency, but safety is a priority. In addition, the mappers may encounter unfriendly people who do not want to cooperate in the surveys. To prevent this, the Wajumbe (community leaders) are involved in the project and there is a lot of communication between the different community members.

In addition to the data collected by the community members, drones are used to make areal images, this is done in collaboration with Drones Adventure and Commission for Science and Technology (COSTECH).

(a) Lectures during the Resilience Academy Industrial Training 2019.

(b) Trash mapping in a suburb of Dar es Salaam, June 2019.

Figure 7.5: Sphere impressions of mapping in a suburb of Dar es Salaam and the industrial training of July 2019.

7.3.2. Digitalization

After the data is collected, Ramani Huria mappers help to develop the maps by digitizing their content via the web platform OpenStreetMap. This is a online platform built entirely by surveying volunteers. Users of OpenStreetMap may own, modify and share mapping data with the public, with as result freely and openly use of data and maps. This can be of interest for people, governments, researchers, innovators, stakeholders and other interested people. In many parts of Tanzania, there is no incentive for mapping companies to develop maps. In these cases, OpenStreetMap, is an appropriate alternative for (among other things) urban planning. Everybody can contribute to the maps, with as only requirements an internet connection and basic computer skills. Presence at the location of interest is not required, one can use satellite imagery to pinpoint points of interest. The students and community members make use of the desktop application, J-OpenStreetMap, through which data can be directly added to maps created in OpenStreetMap.

7.3.3. Sharing

The last step is to share the maps that are made. Since OpenStreetMap is used, the maps are public and accessible to everyone on the OpenStreetMap website In addition, the Dar Ramani Huria team writes a report. This discusses in detail the methods used to collect the data, how the process of digitalization worked, the challenges during the process and the problems that have been overcome.

7.3.4. Risk modelling

The overall aim of Dar Ramani Huria has been to improve the flood resilience of the mapped regions in Dar es Salaam. To accomplish this, community mappers identify areas on a map that are most presumably affected by flooding. Flood prone areas are indicated on tracing paper that is put over a base-map. The findings of this is scanned and the data is digitized into shapefiles and uploaded onto OpenStreetMap. The digitized maps are combined with other data in flooding scenarios. It will provide a straightforward and modestly, but rigorous way to combine data from scientists, local governments, donors, stakeholders in general and communities to provide insights into the possible impacts of future disasters. The data can be used for more than flood modelling, as it is highly dependent on the stakeholder and the decision maker what the purpose is of the collected geospatial information.

7.4. Quality assurance

During this process of making maps of the (sub) wards in Dar es Salaam, several things can go wrong. To assure the the quality of the data and maps the project is designed with iterative communication processes and community engagement.

7.4.1. Iterative communication

By making the communication in the projects an iterative process in which many people look at the product with a critical eye, the project tries to guarantee the quality. In Figure 7.6 the iterative process is visualized and each responsibility is discussed in the following sections.

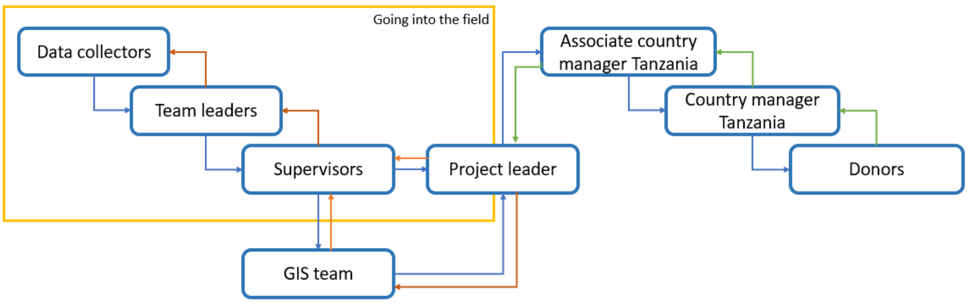


Figure 7.6: The various persons involved in a project; starting with collecting data in the field and ending with the customer or the donor.

The mappers have the responsibility to measure all buildings, roads, drainage channels, etc. and to determine their locations. They have to put all the collected information per survey in the android application ODK and OMK. This is done in close consultation with the team-leaders. For every five mappers there is one team leader, so during the RAIT 2018 there were about 100 of these leaders. They are responsible for ensuring that all mappers go to the right location, and that all the collected data ends up on the server. There is one supervisor for every 4 to 5 team leaders (depending on the project and how experienced the supervisor is). The supervisor checks whether all data is correctly placed on the server by the team leader, and this is done in close consultation with the GIS team and the project leader. If errors are detected by the GIS team or the project leader, this is passed on to the supervisor, who then passes it on to the team leader, who can possibly give it back to the data collectors. The GIS-team is responsible for the analysis of the data and the execution of the hazard risk analysis. In addition to this feedback, there can also be a direct feedback loop between the project leader and the GIS team. If the data looks decent, it will be passed on to the project leader, who will oversee the entire project. For the Dar Ramani Huria project there are two project leaders, one for the drainage aspect and one for the community mapping project. They are in close contact with each other to ensure that the process runs smoothly. The project leaders only go into the field once in a while, and then see if everything goes well. In the case of Dar Ramani Huria, Innocent Mahori is the actual project leader. He gives technical support, but is no longer involved in making the maps. The next step is to pass on the data to the Associate Country Managers. The Country Manager then communicates with the donors and is responsible for the reports that have to be written for the various stakeholders. In addition, they are also responsible for keeping an overview of all the projects that are going on next to Dar Ramani Huria. One can think of the trash-mapping project that takes place simultaneously in Dar es Salaam. As a final step, the end product is presented to the donors and other stakeholders.

7.4.2. Community engagement

Iliffe [28] was one of the first to look into OSM data in Dar es Salaam. His study focused on the analysis of road data, from the Tandale ward, the previous mentioned Ramani Tandale project. Which was also a community mapping project. Iliffe has come up with a framework for the concept of geographical information collected by volunteers.

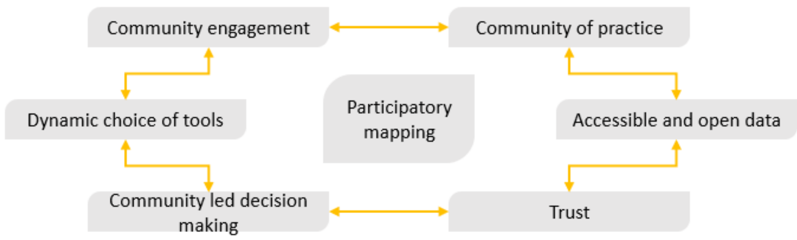


Figure 7.7: Visualisation of the concept community mapping according to lliffe [28].

The six different components of this framework are briefly explained below;

- *Community engagement.* Meetings are organised, brought to the attention of the representatives from the local government and community members. During these meetings, awareness for the project is created, the mapping activities are discussed, and results presented.
- *Community of practice.* In addition to the geographical information, the community itself is also mapped out. This could include various non-government organisations, local businesses and the various governments that have a controlling interest in the area.
- *Accessible and open data.* All data collected throughout the community mapping process and the products it has delivered are shared as open data.
- *Trust.* The decision makers, who make a decision on the basis of the shared data, must have confidence in the product that is delivered.
- *Community led decision making.* What is mapped and how this is done is determined by the community itself. This is one of the things that can be discussed at the meetings under the component 'community engagement'.
- *Dynamic choice of tools.* The tools used for community mapping must be comprehensible to the members of the mapping community. Particular attention should be paid to the fact that people with different levels of education and experience with ICT are involved.

In order to guide the project in the right direction, there is -from the very beginning of the project- a lot of contact with the people who live in the area where a map is being made. In case there is no map of the subward yet, the five mappers and the team-leader will organize a community meeting. For this meeting the Wajumbe (ward representative), subward executive officer, religious leaders, local youth and others are invited. The points discussed in the first meetings are aimed at getting acquainted with the mappers team and the project. In addition, groups of three participants are created, each accompanied by two mappers to enable group discussions and to identify possible assets and threats in the subward on printed (imprecise) maps.

During the process of data collection and digitisation, community members and leaders are involved. In this way, they remain involved in what is happening in their neighbourhood and they cooperate more often. Every year there are a few ward inhabitant who think they can make money from their contribution to Dar Ramani Huria's project, however, no cooperation has been forthcoming in this regard.

7.5. Dar Ramani Huria related to literature

As Dar Ramani Huria is build upon the foundation set during Ramani Tandale, it relates of the framework for community mapping in low-resource countries as described by Iliffe [49]. Community mapping is according to Parker [47], as "the action of producing a map together with or by the inhabitants of a particular location". This applies to an decent extent to Ramani Tandale and to a certain extent also to Dar Ramani Huria. Partly due to the advanced expansions that have taken place from the founding of Ramani Tandale until now, more and more survey activities require specific knowledge. Soil research, development of drones, high-quality positioning and the use of advanced smartphone applications require more training. And that's why it's only partly suitable to be executed by the local community [28] [47].

The initial approach of Dar Ramani Huria was practical and had no scientific purpose. However, the data collected is of sufficient quality that it also has added value for scientific research, such as studies aimed at climate change and rapid urbanisation in which the focus is on Dar es Salaam [49]. In addition to the data, the cooperation of students from the local university is also interesting for academic research.

With this in mind, it is of added value to study the feasibility and desirability of the implementation of an advanced GNSS receiver in Dar Ramani Huria. In the long term, it is possible to look at the application outside this specific project, and to realise initiatives at HOT or the World Bank with the help of the GNSS receiver.

8

Methodology

The methodology chapter, of the part case study, examines the methods used to study the possible implementation of the GNSS receiver in Dar Ramani Huria's project. During this research interviews were conducted, a brainstorm session was organised, a python course was held, and attention was paid to the portability of the receiver and antenna.

8.1. Interviews

During the period in Tanzania, unstructured and structured interviews were used to get full information about the working process in Dar Ramani Huria and HOT in general. The *unstructured* interviews were used to allow the interviewees to have freedom to give information in their own words, and to get a general idea of the working processes in the office. These conversation mainly took place in the first weeks of the stay in Tanzania. The structured interviews are used to establish requirements for the functional design. The interviews were done throughout the hierarchy of HOT, mainly focussing on the process of data collection in the field. In Figure 7.3 it is shown how the different layers of management relate to each other. Individual interviews were done when anonymity was preferred and where needed a translator was used. For each person, a list of questions to be answered was drawn up in advance. This list of questions often had the same core questions and the same structure, but the questions were adapted to the function and responsibilities that people have. An example of a core question is "What steps do you think need to be taken before the receiver can be implemented in Dar Ramani Huria or another HOT project?" Furthermore, the subject is complex and the questions were adapted to the knowledge level of the interviewee. These structured interviews mainly took place at the end of the research period in Tanzania. In addition to this, it is important to note that interviews with the people from the innovation department were done multiple times.

8.2. Workshop

To ensure that the implementation of the GNSS receiver in the Dar Ramani Huria project will run smoothly, a workshop was organised. The aim was to introduce the team members to the equipment and the necessary software. The training started with an introduction of an RTK network and the different components needed for this; think of the reference station, rover, laptops and cables. All equipment was exhibited and the setup was recreated inside, so everyone could easily (in the cool) see how everything was done. An experiment was carried out during the instruction lesson, so that it became clear why it was necessary to pay attention to everything. After everyone had asked their questions, the rest of the workshop took place outside. There the setup was made again for those who were interested, but with a more realistic setting. In Figure 8.1 is a atmosphere impression of the workshop.

Figure 8.1: Impression of the working environment during the workshop.

8.3. Brainstorm

In the last week of the research period in Tanzania a brainstorming session was held. The aim was to get the team members of Dar Ramani Huria and other interested parties to think about the possibilities that a low-cost GNSS receiver with centimetre accuracy or precision has to offer. The brainstorm was organised in such a way that everyone who was present got a stack of sticky-notes, four things had to be written on these notes:

- *Project*. In case the problem occurred in an existing project of HOT.
- *Stakeholder*. It had to be made clear who has a problem now. This can be an individual, a group of people inside or outside HOT, the government or something else.
- *Problem*. The problem or idea was explained. This required the most creativity and thinking outside the box was required.
- *Taking steps*. This involved discussing which steps should be taken so that a GNSS receiver can (partially) solve the problem.

These four points were written by each person present on a sticky-note, and then hung on a board. There are several ways to organise the sticky-notes afterwards; on stakeholders, on problems or on steps to be taken. During the brainstorm, the sticky-notes were organised in all three ways after which the arrangement was discussed, and people could add ideas, but could not remove them. Throughout this meeting, people could tell what they thought of the idea, whether or not it was applied to HOT or Dar Ramani Huria, what they thought of the problem or other things that occurred to them. In Figure 8.2 a few photo's are shown from during the brainstorm.

Figure 8.2: Impression of the atmosphere during the brainstorm.

All sticky-notes have been preserved, so that they can still be viewed in the Netherlands and further ideas can be derived from them. This brainstorm session proved to be very useful for writing the chapter with the recommendations, for more ideas please refer to Chapter 12.

8.4. Python course

In the theoretical case that the GNSS receiver is going to be implemented within HOT, it is important that the employees of HOT can become familiar with the equipment. Not only how the measurements are carried out, as explained in the workshop, but also that they can analyse the data from the measurements. During this research the programming environment Matlab was used, but this is an expensive program for which specific knowledge is needed. A generally accessible program is python, besides being free, it is also widely known and can be found on the internet. Many of the employees have little or no experience with python, which is why during the period in Dar es Salaam an almost weekly python course has been organized. The principles of programming were set out herein; assigning variables, displaying a figure, determining the average and using the first steps of python in combination with QGIS. This course is not covered by the research, but it ensures that it became alive within HOT. In addition, it was a great way to give back to the company that provided a free overnight stay during the research period in Tanzania.

8.5. Protection and user-friendliness of the receiver

An essential part of implementing the GNSS receiver is its ease of use, in such a way that it can be used by surveying community members. The GNSS receiver, as presented in Appendix C, is very sensitive and fragile. During the experiments, the receiver is exposed to the outside air, the weather and it is moved on (unpaved) roads. In addition, it is used by (different) people, and the receiver can be treated coarsely. A solution is needed to treat the receiver against these factors. A casing and support system were devised as a solution, but a design process was gone through to achieve this. In order to complete this process, guidance was found in the Delft Design Guide, in which various design processes are explained. The choice was made to use the models of Pahl and Beits, and Verein Deutscher Ingenieuere [59]. A more detailed explanation and pictures of the result is given in Appendix D. Some pictures are presented in Figure 8.3

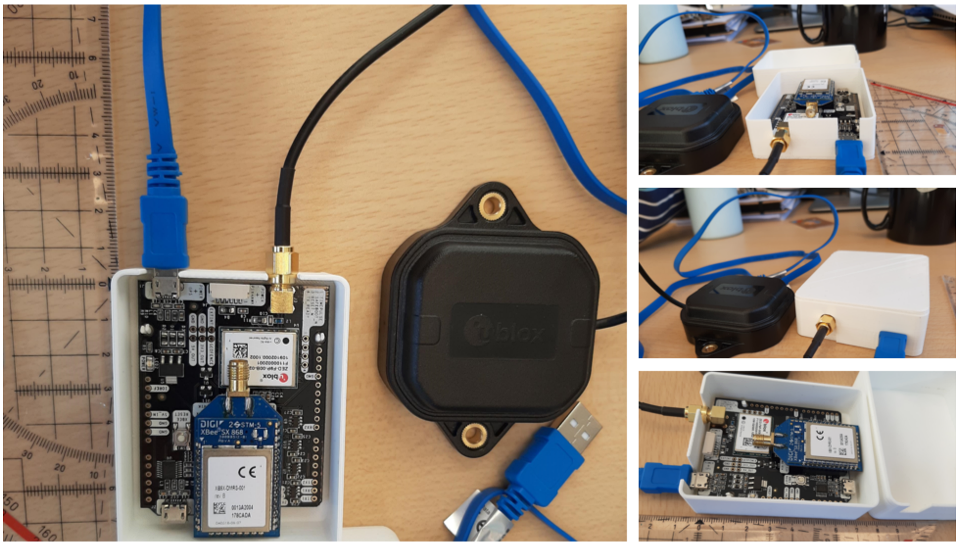


Figure 8.3: Casing for the GNSS receiver.

9 Results

This chapter discusses the results of the case study. Starting with the interviews, where a short summary is given. There are a few points that deserve extra attention, which will be explained after the summary. The results of the brainstorm are presented in Section 9.2.

9.1. Interviews

In this section, the results of the structured interviews are concisely presented. A summary of the answers of the interviews can be found in this section of the results, for the detailed interview please refer in to Appendix D. The questions in the interview were aimed at identifying the functional requirements of the GNSS receiver.

9.1.1. Concise presentation of the interview results

The results of the interviews are clustered; interviews with officials with similar involvement in the Dar Ramani Huria's project are presented next to each other. The first interviews presented were with Asha Mustapher and Iddy Chazua, who have a position in the management team (see Figure 7.3) and are closely involved in community mapping projects. Asha Mustapher as project leader and Iddy Chazua as head of the Technical Team, and the GIS Team, these interviews are presented in Table 9.1. Then the interviews with Glory Emanuel and Bornlove Ntikha will be briefly presented, Table 9.2 , whom are in the Innovation and Development team of HOT. Immaculate Mwanja is responsible for the operations, and was interviewed as such, Table 9.3. Finally, the interview with Wilfred Raban Chomba (called Wicho) is presented, Table 9.4. He is the facility manager and is the driver of the bajaj (tricycle owned by HOT). This last interview had a very different approach, with different questions, because the role of the interviewee was not related to the making of the maps but to the practical execution of the tests. If the answer is marked with an asterisk, a further explanation of the answer can be found below the relevant table.

Table 9.1: Summary of the interviews with people closely involved with Dar Ramani Huria's project.

Name	Asha	Iddy
Function	Project Associate	Technical Specialist
Department	Project Department	Tech Department
Projects involved	All projects	All projects
Implement GNSS receiver?	Yes	Yes
Steps need to be taken?	Don't know exact, but a lot	A lot
Spatial accuracy?	Less than a few cm **	5 cm
How fast a fixed solution?	Less than 10 seconds *	Less than 10 seconds
How many people involved?	Two; one for reference and one for rover	Two; one for reference and one for rover
Use of internet connection?	No ***	No
Use of interface?	Yes	Yes
Real-time or post-processing?	Post-processing	Post-processing
How many rovers at the same time?	More than 1	Many as possible

* *How fast a fixed solution: "Less than 10 seconds"*
If measuring takes too long or doesn't go well, the students and community members will fill in their own data and create information. This is because they don't dare to go to their team-leader with "it didn't work out" or "it took too long". Likewise, the team leaders don't dare to go to their supervisors if something didn't go well, so they try to adapt or create the data themselves.
Another argument is that the safety is compromised if the measurement takes too long.
** *Spatial accuracy: "Less than a few cm"*
Now often the accuracy is between the one and the five meters. This is - for most of the time- fine for Ramani Huria's project. However, the problem with this accuracy is that some of the housing/buildings are lost during the mapping process. Some of the houses/buildings are smaller than 5 meter. This has far-reaching consequences when research is done into health issues. For example, a location pin-point is then made of a house where a sick person is living. If the accuracy is too low it may be that it is seen as the neighbouring house, causing the care-workers to go to the wrong location. An accuracy less than a few centimetres is not necessary, because the human errors that are made outweigh it.
*** *Use of internet connection: "No"*
There are several arguments for being independent of a internet connection. Firstly, not all projects take place in Dar es Salaam, and in the villages is there's rarely internet connection or a network. Secondly, the costs are too high to buy for everyone access to the internet. There are projects with more than 500 students, and if you have to pay for internet for everyone (even if it is only 1G) it might raise the costs beyond budget. Working with a limited budget, it means that one can involve fewer people for the project. At last; the app that is used is offline, where at the end of the day the data (by students) is uploaded and the data is checked by the team-leader. So internet is required only for uploading.

Table 9.2: Summary of the interviews with people form the Innovation Department.

Name	Bornlove	Glory
Function	Head Innovation Department	Member of Innovation Department
Department	Innovation Department	Innovation Department
Projects involved	All projects that need aerial data	Among others; Ramani Huria
Implement GNSS receiver?	Yes	Yes
Steps need to be taken?	Compatible with drone GNSS receiver *	More testing
Spatial accuracy?	Less than 5 cm	5 cm
How fast a fixed solution?	Less than 10 minutes	fast as possible
How many people involved?	Two; one for reference and one for rover	Maybe one
Use of internet connection?	No	No
Use of interface?	Yes	Yes
Real-time or post-processing?	Post-processing	Post-processing
How many rovers at the same time?	More than 1	Two for one location

* *Steps need to be taken: "Compatible with drone GNSS receiver"*
It is important that when the Innovation Department implements the GNSS receiver, that can be mounted on home-made (lightweight) drones and that it cooperates with the existing and used programmes.

Table 9.3: Summary of interview with Operations.

Name	Immaculate
Function	Operations
Department	Operations
Projects involved	Ramani Huria en OMDTZ projects
Implement GNSS receiver?	Yes
Steps need to be taken?	Among other things; training
Spatial accuracy?	Less than 2 cm
How fast a fixed solution?	Less than 10 seconds
How many people involved?	Two for one location
Use of internet connection?	No*
Use of interface?	Yes**
Real-time or post-processing?	Real-time
How many rovers at the same time?	Two for one location

* *Use of internet connection: "No"*
Sometimes fieldwork is conducted in very remote areas where the mobile network does not reach, therefore without internet the work will not be conducted effectively. Using an internet connection means that mobile charges run very fast! ** *Use of interface: "Yes"*
It is really convenient to use an interface, so the mappers can determine its location. Some of the places are unfamiliar to the mappers and they will need something like a map to show where they are. It is also nice to see if the measurements are actually going well, and if the data is being written down somewhere.

Table 9.4: Summary of interview with the facility manager.

Name	William
Function	Driver of bajaj and facility manager
What kind of roads in Dar es Salaam?	Unpaved, asphalt and concrete
How many people in bajaj?	Three passengers plus the driver
How fast do you drive on a unpaved road?	20 km/h
How fast do you drive on a well maintained paved road?	70 km/h
How fast do you drive on a bad maintained paved road?	30 km/h
What was the max speed during the experiments?	50 km/h
How many days can one use the bajaj?	365 days a year
Can you reach every neighbourhood in the bajaj?	Yes
Can you go outside Dar es Salaam with the bajaj?	Theoretically yes, practically no.

9.1.2. Summary of the interview results

Based on the unstructured, and structured interview carried out, and the associated impressions and results, as partially presented above, requirements have been set for the performance of the GNSS receiver in order to be able to implement the GNSS receiver. The requirements consist of two parts; design requirements and functional requirements as presented below.

Design requirements

The general requirements are the wishes and requirements that higher layers in the management of Dar Ramani Huria have set. These requirements should be met by the receiver and the network to ensure that implementation can be considered:

- Few centimetres accuracy.
- Do not have to wait more than 20 seconds after interrupting the signal for a position to be known.
- Do not use the internet, because costs are too high and the internet connection is not everywhere available.
- There is clear feedback on whether the measurement is going on, and whether it's in RTK mode.
- As many local materials as possible.
- Maximum of 2 people necessary to set-up the network and do the measurements.

Functional requirements
The functional requirements focus on the operational aspect of the use of the receiver and network. They take into account that students, volunteers and mappers should all be able to deal with the system in the easiest way possible. The functional requirements are established strongly on the basis of the ideas and experiences of the people closely –on an operational level- involved in the project. An overview of the functional requirements are:

- For all types of education levels to be used.
- People responsible for the data collection in the field should not be in any (higher) danger by wearing the equipment.
- Observations can be done during a conversation.
- Minimal configuration in the hardware and software.
- Make use of totally open software as much as possible, preferably software from GitHub.
- Designed to be compatible for future developments.

These requirements are taken into account in determining whether this receiver is suitable for Dar Ramani Huria's project and in answering the research questions for both the performance study and te case study in this study.

9.2. Brainstorm

In the brainstorming session participants investigated which problems might occur in HOT projects for which a low-cost GNSS receiver with centimetre accuracy might offer a solution. Based on the brainstorm, seven categories were created; *transport, drones, shina* (means trunk in Swahili), *sediment, boundary mapping, Dar Ramani Huria* and *miscellaneous*. The three categories that covered most of the problems written on sticky-notes were; boundary mapping, transport and Dar Ramani Huria. For each of these three categories a sticky-note, that gives an impression of the subject, is digitalized, as shown in Figure 9.1. For pictures of the other sticky-notes please refer to Appendix D.

Project: (Hyper)local administrative boundary mapping

Stakeholder: Field Mapping

Problem: Mapping of boundaries is a very sensitive subject, inaccurate boundaries may cause problems among citizens.

Solution: GPS with the best accuracy to map better boundaries in the city.

(a) Sticky-note in the category *boundary mapping.*

Project: Bus routes in Dar

Stakeholder: Government

Problem: We don't have maps of the exact bus routes. Maybe it could be integrated into a city map for new-comers

Solution: Put a GPS unit on buses on different lines. Can also be used to map the stops.

(b) Sticky-note in the category *transport.*

Project: Dar Ramani Huria

Stakeholder: Field mappers

Problem: Drainage mapping was conducted in order to better understand the flow of drainage channels in Dar. To achieve this, the team had to know the beginning and endpoints/outflow of the drains. Inaccurate drain point mislead the making of a better flood model.

Solution: Use better GPS/GNSS to get drain points that reflect reality for the creation of a flood model.

(c) Sticky-note in the category *Dar Ramani Huria.*

Figure 9.1: Summary of the three most popular categories during the brainstorm.

10
Discussion

The case study in this thesis focuses on the possible implementation and commissioning of the GNSS receiver in Dar Ramani Huria's project. In carrying out the interviews and holding the workshop, but to some extent also in other aspects, some points of discussion have emerged. These discussion points are described in this chapter.

10.1. Language

Firstly; language formed a barrier. Most of the managers in HOT spoke English, but for them explaining specific information in their second language was often a challenge, leading to information lost. The mappers and digitalisers often barely spoke English, or they where too shy to speak. Sometimes a translator was used, which was most of the time a person in the group of mappers that was more familiar with English. However the second translation is more cause for possible missed information or miscommunication during an interview, as answers are no longer seen objectively but have already been partially interpreted. Sometimes it was unclear whether the interviewee answered, or the translator was answering . Despite this restriction on working with translators, they are often engaged in the interviews because they made it possible to interview all people involved in the map making process, resulting in a more information and opinions.

10.2. Cultural differences

Cultural differences play an important role within any research with people from different parts of the world involved. Tanzania and the Netherlands have different cultures in many aspects. One aspect is the 'atmosphere'. One might say that Tanzanians create a more closed atmosphere than people in the Netherlands are used to. At HOT Tanzania it is somewhat unusual to be negative about colleagues or projects/processes that are not going well. This created a positive atmosphere in the office, but also made it difficult to determine which (human) errors could take place during the process of making a map. In the part of the research that focused on the implementation of the GNSS receiver, this led to some misconceptions.

10.3. Difference in the level of education

The third aspect which may have influenced the gathered information is the difference in the level of education between the interviewee and the interviewer. Especially at the beginning of the period in Tanzania this posed challenges, but it could easily be overcome by explaining the subject until the public had mastered the subject well enough and by asking questions in different ways.

11
Conclusion

The research carried out in this thesis has been guided by three research questions; two related to the performance study and one to the case study. In this chapter, both aspects of the research are combined, all three research questions will be answered and a final conclusion is drawn.

11.1. Implementation of the reciever, in community mapping context

Before answering the research question about *how* the receiver can best be implemented in Dar Ramani Huria's project, the first step is to determine whether the receiver meets the requirements to be implemented in a community mapping context *at all*.

The requirements for implementation are based on the conducted unstructured and structured interviews in combination with the associated impressions, and they are summarized in Section 9.1. To check whether these requirements are met by the experiments will help determine whether the implementation of the GNSS receiver in Dar Ramani Huria is feasible.

Table 11.1 shows for each experiment whether it meets the design and functional requirements that have been drawn up. This is represented in such a way that if it meets the requirement, the cell is made green, red if it does not and yellow if it meets it to a certain extent. Not every experiment is equally relevant to determine whether the implementation of the GNSS receiver in Dar Ramani Huria is feasible. Only experiments that can map a larger area with a single reference station are relevant, these are the experiments with a baseline of $4km$ or more. The three experiments that are not relevant in this respect are marked red; the two experiments that are rated moderately relevant are marked yellow.

Table 11.1: Combinging results performance- and case study; the conclusion

	Requirements	SPE	Darcm	Darm	Dar4km	Dar6km	Dar9km	Delftm	Delft14km	DelftUm	DelftUkm	DelftH
Design	Relevance	green	red	red	green	green	green	red	green	yellow	yellow	green
	Accuracy of few cm or less	green	green	green	green	red	red	green	yellow	green	green	green
	Position known in less than 20 sec.	green	green	green	green	green	green	green	green	green	green	green
	No internet connection necessary	green	green	green	green	green	green	green	green	green	green	green
	Clear feedback measurement going on	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	green
	Use of local materials	green	green	green	green	green	green	green	green	green	green	green
	Max 2 people necessary	green	green	green	green	green	green	green	green	green	green	green
Functional	Suitable all education levels	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
	No security hazard	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow
	Observation done during conversation	green	green	green	green	green	green	green	green	green	green	green
	Minimal configuration	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	yellow	green
	Open software	green	green	green	green	green	green	green	green	green	green	green
	Futureproof	green	green	green	green	green	green	green	green	green	green	green

The experiments *Dar6km* and *Dar9km* score negative on the requirement 'accuracy of few cm or less' and are coloured red in the table. In both experiments, the percentage of fix solutions is too low (11.68% and 8.99% respectively). As a result, it is not possible to attach sufficient value to the RMS values, which are an indicator of performance. The *Delft14km* experiment met the requirement 'accuracy of few cm or less' to a certain extent because the RMS values are high, and is therefore coloured yellow in the table.
All other requirements are fully met or met to a certain extend almost equally in all experiments: The *DelftH* (= high-end antenna) experiment scores more convincingly on two requirements. In the *DelftH* experiment the feedback on whether the measurement is going on is clear and the requirement 'minimal configuration in the hardware and software' is more broadly met. In the *DelftH* experiment, setting up the configuration takes half the time, since only the rover station needs to be set up.
On the basis of the above the conclusion is that, if the right choice of experiment is made, the implementation of the receiver in Dar Ramani Huria's project is well possible.

11.2. Answers of the research questions

Now that it has been established that implementation is possible, the three research questions will be answered.

What is the horizontal and vertical positioning performance of the receiver, what factor influences this performance? And what are the differences in these aspects between Delft and Dar es Salaam?

The positioning performance of the receiver varies between the different experiments. The conclusions regarding the positioning performance are based on the scatter plots in the horizontal plane and the positioning over time for the three separate directional components East, North and Up. The values for the horizontal performance (RMS East, RMS North) and for the vertical performance (RMS Up) of the fix solutions insofar as they fall inside the 95% conficence ellipse are decisive (see Table 5.1). Only the relevant experiments, namely those who can map a larger area with a single reference station are taken into consideration.
The horizontal positioning performance ranges from **1.13** till **16.83**mm. However the latter, the highest value is from the *Dar9km* experiment with a very low percentage of fixed solutions. If we disregard the experiments with low percentage of fixed solutions then the horizontal positioning performance ranges van **1.13** till **9.42**mm. The vertical positioning performance shows less accuracy ranging from **3.56** till **14.75**mm. If we compare this performance with the requirements for Dar Ramani Huria's project, even the strictest of $2cm$, the performance is more than adequate.
A factor that influences the performance is the antenna. The experiment with the high-end antenna shows with values **2.44**mm (RMS East) and **3.42**mm (RMS North) the best horizontal and with the value **3.75**mm (RMS Up) the best vertical performance. Another factor influencing the performance is the location, in particular the aspect of atmospheric delay that varies between Dar es Salaam and Delft.

Where to establish the reference stations and how to design the infrastructure of a network, taking into account the key performance indicators that need to be established and the rapidly changing situation in Dar es Salaam. What is the most suitable method of communication between the rovers, the reference station and other components?

The reference station must be placed in a stable location, where there is a clear view of the sky and at the same time easily accessible. The location must also be well recognisable so that it can be found again. In this study, the roof of HOT Tanzania's office in Dar es Salaam and the tower of the NMi in Delft met these criteria. The most suitable communication between the rovers, the reference station and other components is achieved with a design of the infrastructure working with a PPK position mode. No use is made of the internet.

How can the receiver best be implemented in Dar Ramani Huria's project in Dar es Salaam, thinking of a user-friendly design, with local low-cost materials and a way of working with the receiver in such a way that the quality of the data is sufficiently high?

The best way to implement the receiver in this community mapping project is to set up a PPK network. This gives the highest accuracy and no internet connection is required. In order to extend the lifespan of the receiver, and to increase the portability of the receiver, a 3D printed casing has been made. The receiver is suitable to a certain extent by mappers of different education levels. The implementation will be more successful if it is accompanied by training and knowledge transfer. The first steps have already been taken during the research period in Tanzania, with a workshop, manual, talks and the execution of experiments together with employees of HOT Tanzania. The implementation will benefit from continuous attention to limiting the security risk. This research thesis concludes that the implementation of the receiver in Dar Ramani Huria's project is well possible and that the performance of the receiver is adequate. This conclusion is confirmed by what is actually occurring in the field: HOT Tanzania and Dar Ramani Huria already started just a few weeks after the researcher's departure from Tanzania using the GNSS receiver and carrying out surveys with this receiver, and the implementation is now in full swing.

12
Recommendations

The final chapter of this thesis consists of a summary of ideas which could support improvement and further understanding of the performance of this particular low-cost, dual-frequency GNSS receiver. The outlook includes ideas for future policy recommendations, focussing on community mapping projects in Dar es Salaam and recommendations for further (scientific) research. These two differ in the depth in which the performance should be investigated. If the choice is made by HOT or the GNSS receiver will be implemented in Dar Ramani Huria's project (or another project), less so-called "hard evidence" is needed. Finally, a promising subject from the brainstorm has been chosen and is briefly elaborated upon.

12.1. Policy recommendations

During the work of this thesis af few expieriences have been acquired that could support future mapping campaigns and map-making processes with the use of the GNSS receiver.

- textitHeight determination. To use the maps Dar Ramani Huria produces for flood modelling, the elevation is an interesting component, more attention could be paid to this. First, there is the practical implementation; how is it possible to determine the height of parts of Dar es Salaam that are poorly accessible; think of drainage channels full of water or rivers with steep riverbeds. In addition, it is worth investigating whether there are ways in which the elevation levels can be better determined than with the help of this low-cost GNSS receiver. It may be interesting to take into account the slope of the geoid that runs relatively steeply in Dar es Salaam.
- *Placement of reference station in Dar es Salaam.* The GNSS receiver in Dar Ramani Huria's project would be easier to start up if the reference station in Dar es Salaam was easier to access. A suitable location needs to be selected for this, for which a field study is required.
- *User-friendlyness.* There is still a lot to improve in terms of ease of use. The process of setting up the GNSS receiver and collecting data is now a time-consuming process in which errors can easily be made. It is desirable that this process be optimised, so that more people can work with it with less effort. It would be nice for the users in the Netherlands, but because these receivers are intent to be used by non-academics it would be an improvement in Tanzania.
- *Applicability drainage mapping.* The GNSS receiver would initially be used for Dar Ramani Huria, where the drainage channels and obstructions of these channels can be mapped. This data can then be collected for flood models, however it is possible that these models require a different type of data to make the mapping process more efficient. In addition, until now, there is mainly worked with so-called point-locations, and it would be interesting to see if the kinematic experiments can also be implemented.
- *Link to smartphone applications.* This research mainly focused on the performance of the GNSS receiver, but working with a laptop does not work optimally so it is essential to investigate whether the receiver can be connected to a telephone and the observations can be stored in a surveying app. Dar Ramani Huria now works with two different smartphone apps (OMK and ODK); it would be ideal if it could be directly linked to these two applications.
- *Expansion of other projects.* HOT, but also other non-profit organizations can use this low-cost GNSS receiver in many ways. Other applications could be explored in more detail.

12.2. Recommendations for further research

Many research topics, of more or less technical character, can continued to be studied; a few areas of research are proposed here.

- *Atmospheric differences between Delft en Dar es Salaam.* GNSS can be used to study the atmospheric delay, which depends on the location. During this research, the differences in delay between Delft and Dar es Salaam were briefly discussed, but further research can be carried out in this field.
- *High-end antenna in Dar es Salaam.* One of the limitations in this research is that the focus was mainly on the low-cost, low-end (rover) antenna. The results of the *DelftHkm* experiment are so promising that it would be worth looking at whether a high-end antenna can be used in Dar es Salaam. Probably the high-end antenna used in Delft is too expensive to use in Dar es Salaam, but research on a more low-cost high-end antenna could be beneficial for Dar Ramani Huria.
- *Less satellites, but still fixed solutions.* In the presented *starting point experiment* it appears that when there are insufficient amount of satellites in view, that is the only moment during the measurement that the solutions are fixed. It is a small piece of the performance-puzzle, but the cause of this surprising result can further increase the performance.
- *More experiments.* In order to be able to draw an even better scientifically correct conclusion, it is advisable to carry out more experiments. This allows a similar approach to that used in this research, so that it can be determined with more certainty whether the performance is constant and of comparable value.
- *More experiments with more variables.* In addition to performing the same experiments more often, it is even more interesting to investigate more variables. The time of execution can be suggested as a suggestion; for example, continuing the research at night. In addition, it is also relevant for countries such as Tanzania to investigate whether the weather has a major impact; extreme temperatures are interspersed with intense rainfall and what is the effect of this on the GNSS solutions. The results that can be expected from this are strongly dependent on the chosen change in experiment. However, it can be expected that extreme atmospheric changes, such as intense rainfall alternating with high temperatures, will not improve performance.
- *Mapping currents with the help of the receiver.* If you think a bit further off the beaten track, it is interesting to be able to map currents with the GNSS receiver. This is actually a very good combination between scientific research and the implementation in Dar Ramani Huria; in this way the mapping of drainage channels and the obstacles that arise can be mapped.
- *Selecting Human Differences in Experiments* Bearing in mind that this research revolves around performance in a community mapping project, it is interesting to go deeper into the human based errors. In addition to the fact that this can be the subject of a technical study, an interesting psychological study could also be carried out in which the differences between the Dutch and Tanzania, for example, are worked out.
- *Implementing in the flood model.* As final recommendations, but certainly one of the most important, it is important to investigate the implementation in a flood model. After the graduation of a fellow student with the title "Community mapping for flood modelling, a case study of the Ramani Huria community mapping project in Dar es Salaam", it appears that the introduction of a GNSS receiver may drastically improve the flood modelling.

12.3. Detailed application GNSS receiver

This idea is based on conversations, interviews and brainstorming held during the period in Dar es Salaam. There was no in-depth study of the statements made about the social situation in Tanzania, as this was outside the scope of the study.

Tanzania, a developing country par excellence, is home to an enormous number of people. How many inhabitants Tanzania has is unknown, as there is no well-functioning national registration. Not only on a national level, but also on a provincial and municipal level the registration of inhabitants leaves a lot to be desired. Mainly in the remote areas, but also in the slums of the larger cities live many people who do not exist for the government, and therefore cannot have any recognized possessions. However, these people often have lived on the same piece of land for generations, but this is not their property according to the government. As can be predicted, this can lead to dissatisfaction among the population. This problem is going to have an ever-increasing impact, especially as Chinese investment companies increasingly want to buy up land and the Tanzanian government is willing to sell land. A related problem is that there is no land register in Tanzania, it is (mostly) unknown where people live, how big their land is and what it is used for. This is mainly the case for the poorer sections of the population, those who live in the slums and in small houses in the countryside. The inhabitants of Tanzania would benefit if the borders of their territory were registered. In order to achieve this, a low-cost, accurate GNSS receiver can be used. The GNSS receiver used in this study could be suitable for this purpose, as the results are promising and the costs are (relatively) low. Local community members, students from universities, or even officially recognised government agencies can use GNSS receiver to travel along the borders of the country. If this is not possible (e.g. by connecting buildings), a drone may be used. The data collected during the cadaster survey can be processed in real-time or post-processing into a file that records the location of a particular territory. Suppose, in the hypothetical case, that this is done without problems, people who are not recognized by the government can show that they own land. If someone owns land, then this person must exist, so that hopefully he can be recognized by the government. In this way, two problems will be solved, which will benefit Tanzania's development. There are still many steps to be taken before this can be applied in Tanzania, but if it can be done, it can be implemented in many countries in Africa. The biggest obstacle to overcome is the arrangement of the base. There are few points where the location is known and suitable for a reference station. In Dar es Salaam, Dodoma, Arusha and some other big cities this problem can probably be solved without too many problems, but in the remote areas this will be a bigger challenge. In addition, there is still a lot to be done for ease of use, such as connecting the GNSS receiver to a smartphone and storing it in a land register app. The possibility that so many people were given a voice, partly due to research into the performance of the receiver, was an enormous motivation during the research.

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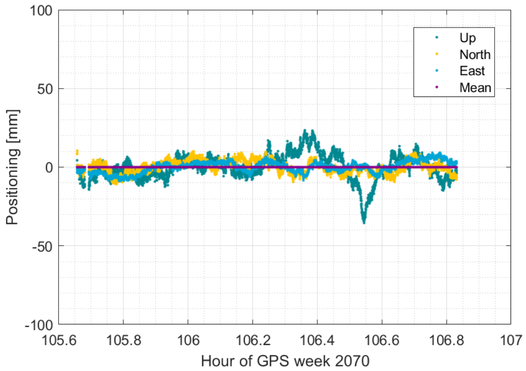
Appendices

A

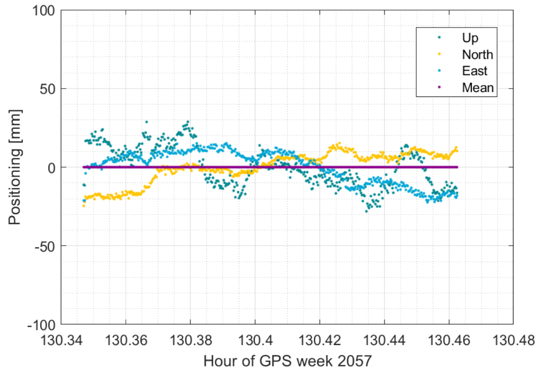
Results

In this appendix all positioning over time graphs and scatter plots are shown, this concerns the highlighted and the non-selected experiments. It concerns the fixed solutions, where no outliers are removed.

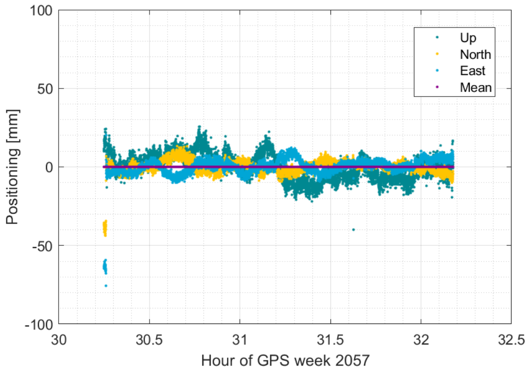
A.1. Positioning over time



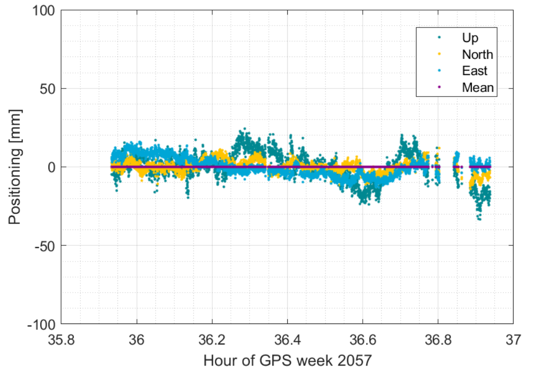
(a) Delft, 6km baseline.



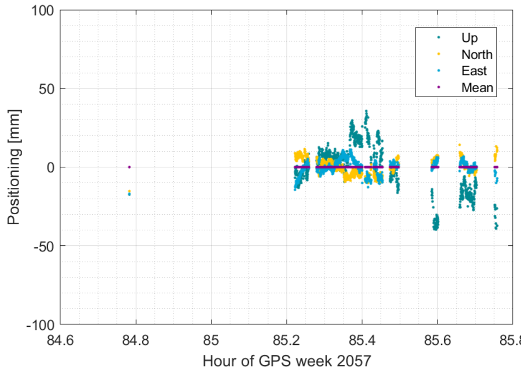
(b) Dar es Salaam, 6km baseline.



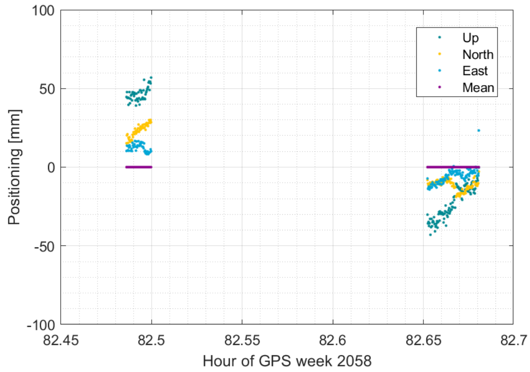
(c) Dar es Salaam, cm baseline.



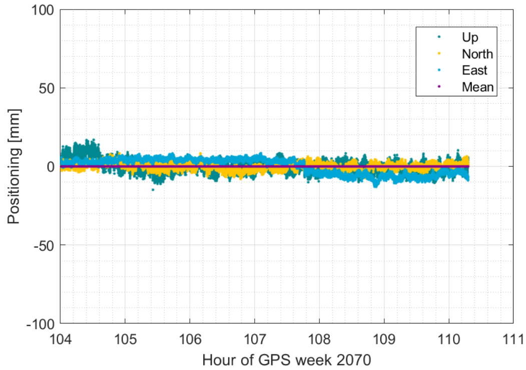
(d) Dar es Salaam, meter baseline.



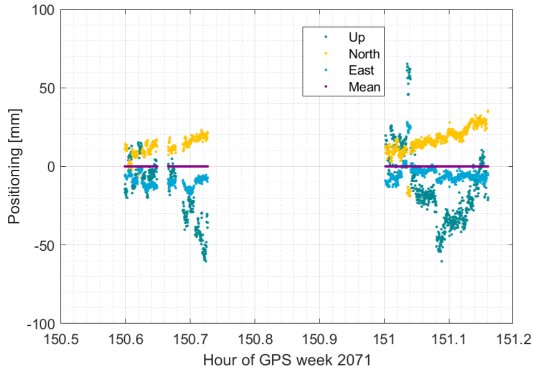
(a) Dar es Salaam, 4km baseline.



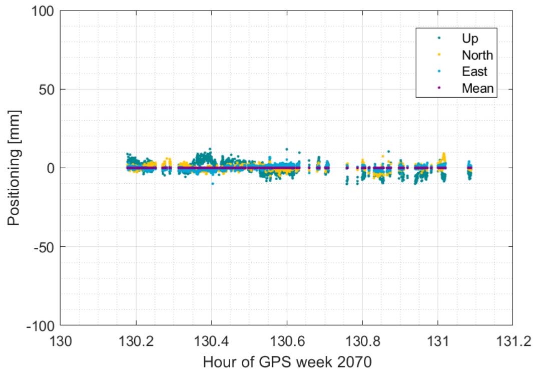
(b) Dar es Salaam, 9km baseline.



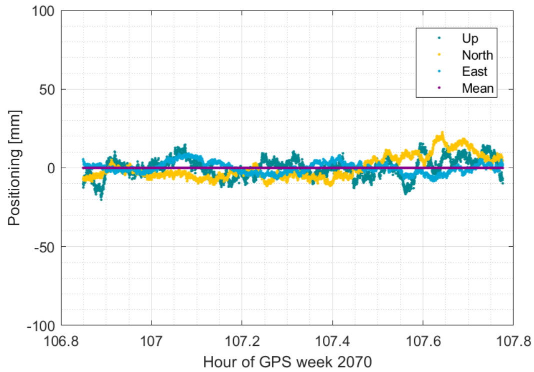
(c) Delft, cm baseline.



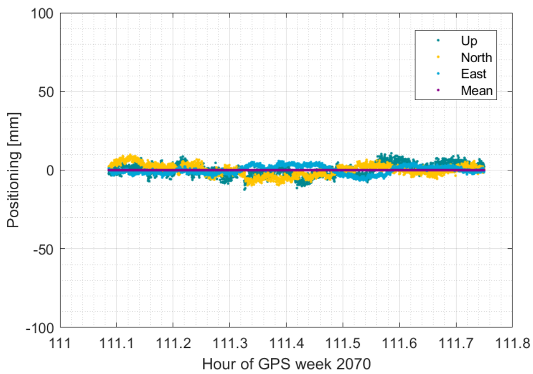
(d) Delft, 14km baseline.



(e) Delft, cm baseline plus U-center.

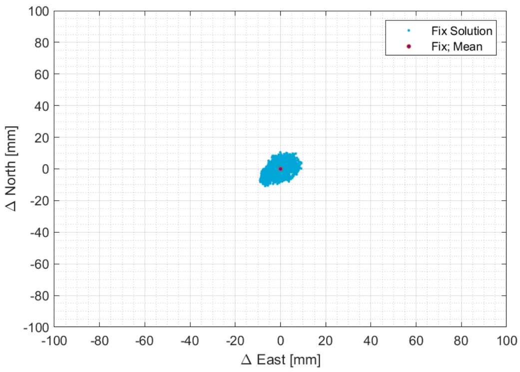


(f) Delft, 6km baseline plus U-center.

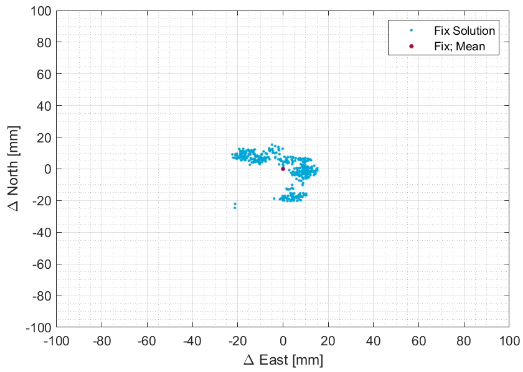


(g) High-end antanna.

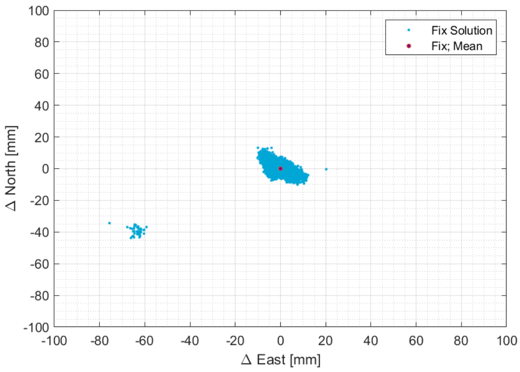
A.2. Scatter plot



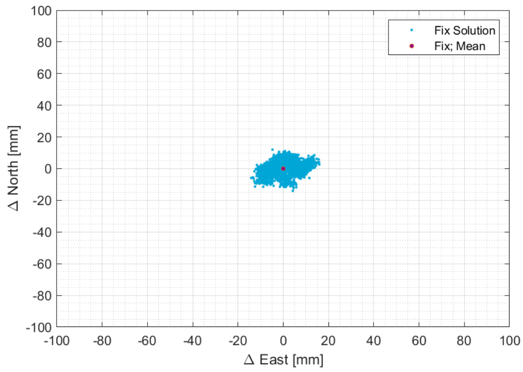
(a) Delft, 6km baseline.



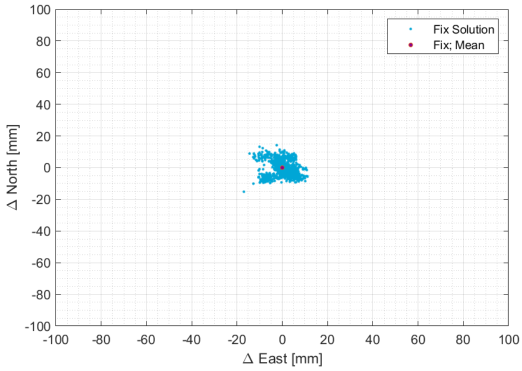
(b) Dar es Salaam, 6km baseline.



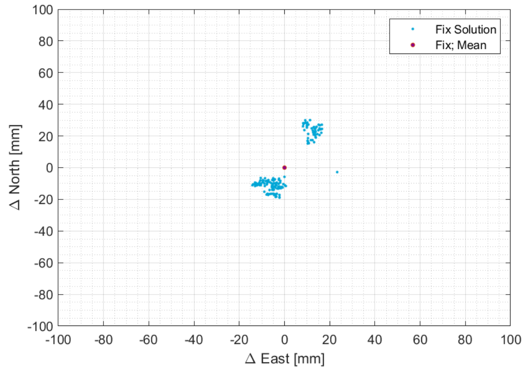
(c) Dar es Salaam, cm baseline.



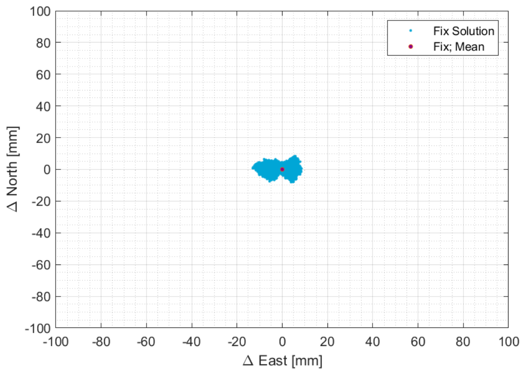
(d) Dar es Salaam, meter baseline.



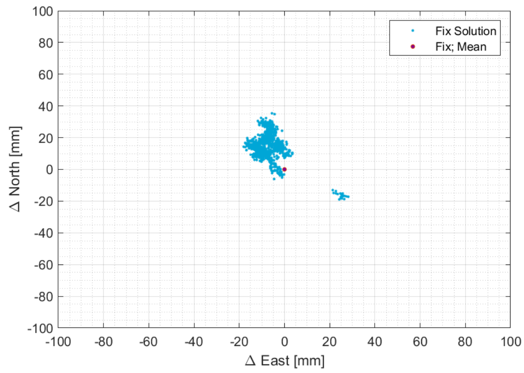
(a) Dar es Salaam, 4km baseline.



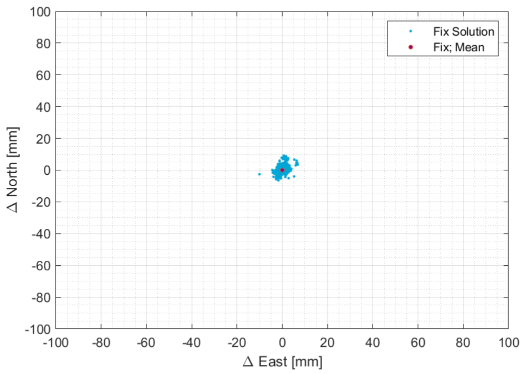
(b) Dar es Salaam, 9km baseline.



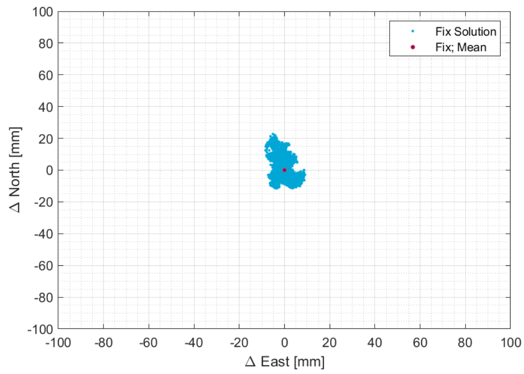
(c) Delft, cm baseline.



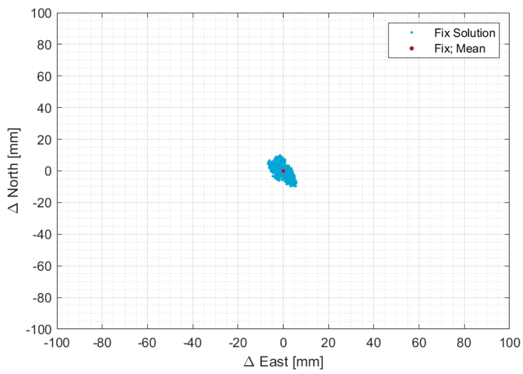
(d) Delft, 14km baseline.



(e) Delft, cm baseline plus U-center.



(f) Delft, 6km baseline plus U-center.



(g) High-end antanna.

B

Setting up the experiments

In this appendix is elaborated on different settings necessary to conduct the experiments. This includes a detailed description of the positioning mode choice ans set-up. Followed by a discussion of the different components used in a PPK network. Finally, the manual for the experiments in presented.

B.1. Positioning mode choice and set-up

In order to be able to make a well-founded choice as to which positioning mode will be used and what the set up will look like, it is first necessary to look at which method of surveying is desired and which requirements the system must meet, after which the design of the positioning can only be presented.

B.1.1. Design of surveying

The complexity of land and sea surveying tasks requires professional judgement: to select the appropriate technology and operational techniques. There are different kinds of land-surveys, for various purposes;

- *Control surveys.* The objective is to determine the coordinates of ground control points referred to a project, mapping or geodetic datum during a field survey campaigns.
- *Deformation surveys.* These surveys determines the displacement of a GNSS receiver relative to some rest position and is measured over time. It is often used to determine ground surface movement, by tectonic motion, volcanic activity, land uplift or subsidence or caused by engineering projects.
- *Topographical surveys,* also called *detail surveys.* These surveys focus on small-area mapping. During such surveys the coordinates of ground features, natural and engineered, are determined. The output of these kind of surveys is a set of coordinates and feature attributes that permit the data to be exported to a GIS software package
- *Mapping surveys.* Mapping surveys are concerned with the determination of coordinates of many points across an area for the purpose of describing the terrain, structure or built environment in a spatial sense. Typically the result is a database with the coordinates (where information), attributes (what information) and topography (how connected information).
- *Cadastral surveys.* As the name suggests, these surveys are suitable for determining property boundaries and creating a land register.

For Dar Ramani Huria's project the mapping survey is particularly important. Therefore, the chosen method of surveying, and the necessary steps will be discussed. However, in the long run the cadastral surveys may also be used.

B.1.2. Design of positioning

The first step in achieving such accurate, precise and fast measurement results, in a mapping survey context, as stated in the general requirements is to determine the GNSS positioning mode. In Chapter 2, the different modes are explained in detail. When comparing these methods, the local DGNSS, RTK and PPK methods appear to be the best ones to use for Dar Ramani Huria's project. For an overview of this comparison, please refer to Figure 2.15. When considering the accuracy over the baseline length, the choice is made to use RTK and PPK. The difference between these two positioning modes is that PPK involves post-processing, which provides greater flexibility. Based on the interviews, this is considered an advantage, mainly because it meets the general requirement that no internet connection is used. The starting point for the experiments is therefore PPK, with as a variable the real-time processing method RTK. In the period before the research took place in Dar es Salaam, it was still assumed that RTK was the best solution. There had not yet been a good opportunity to talk to the team members of Dar Ramani Huria on a one-to-one basis in order to find out the general and functional requirements. Only after side visits could be made and the first discussions with the employees of HOT had taken place, the choice was made to continue with the PPK method.

B.1.3. Components of RTK and PPK network

In general, the RTK and PPK positioning mode consists of three different components: the rover, reference station, and a communication link. The possible ways to set up these components are discussed below. Through a trial-and-error process, the components and combinations were inspected, this took place in Delft even before the experiments were actually started. The communication link is discussed in Chapter 2, no further attention will be paid to this is component.

Reference station

The way in which the reference station is arranged differs per chosen positioning mode. With PPK is a self assembled reference station used; consisting of a laptop on which the program RTKLIB NAVI was running. RTK is only used in the period the research took place in Delft, therefore a NTRIP Caster provided by the TU Delft was used. For this purpose a fixed, high-end antenna is used on top the tower of the NMi, which measures its position since 2005, resulting in a great certainty of the position.

Rover

Most choices can be made for the rover. Bearing in mind the community requirements, the focus can be on portable rovers that are easy to move around; therefore laptops, smartphones and loggers were considered.
The most preferred hardware is the smartphone; in order to determine the position, a smartphone with a GNSS application must be used. Only smartphones that work on the control system of Android have been looked at; besides the fact that there was already experience there, this is the kind of phone that is used in Dar Ramani Huria's project so far. There is a large number of GNSS related applications found in the Google playstore. Some of these applications only use the internal GNSS receiver, while others, such as RTKGPS+, GNSS Commander, MapIt, SW Maps, are built to convert data from an external GNSS receiver into a position. However, the development of these applications is not yet so advanced that it can convert data from a dual frequency external GPS into a position, only from single frequency receivers. There are some applications; GNNSS Test, GNSS Test, GNSS positioning that can handle the dual-frequency signals, provided the signals come from an internal GNSS receiver. These application cannot process signals from an externally connected GNSS receiver. An application than can handle dual-frequency signals from an external receiver is GNSS Commander. It can also make a connection to an NTRIP server, making the creation of an RTK network within the options. A big disadvantage of this program is that there is only a limited choice of settings; for example, no choice can be made as how to handle the ambiguity solution when the GPS positioning goes into fix mode. Furthermore, the application is moderately reliable; during testing complications often occurred, where the only solution was to restart the application and in some cases even restart the phone completely. After (too) many attempts it has been decided that this application is too unreliable and inaccurate for this research. In the beginning of August 2019 there has been an update of the GNSS commander application, the reliability has been increased. However, this update came too late for this study.
As an alternative to a smartphone a laptop has been reviewed, a computer also needs a program to convert the incoming signals to a position. Two programs have been considered: RTKLIB and u-center. u-center is software created by U-blox itself, where the processing takes place in the receiver. In the program there are many options, which can be adjusted to the applications of the GNSS receiver. An alternative program is RTKLIB, in which the position determining calculations are performed on the computer. RTKLIB is a program that can be downloaded for free from GitHub, which is why many people prefer it. Before this software package can be used, the GNSS receiver must be configured in u-center, so that the receiver is tuned to transmit the correct information to the computer.
A disadvantage of using a smartphone and laptop is that during the data collection the volunteers become a target for a robbery. If the processing does not need to be in real time, one can look at the use of loggers. These loggers keep track of the position per unit of time, for the reference station and the rover; after which -in post-processing- the measurements can be brought together and the correction can be carried out. This option has the advantage that once it is working, it is very reliable and independent of the internet. These

loggers can be anything from a SD logger to Raspberry Pi. This option was not explored further as it was too challenging to install the loggers on the receiver's computer board with the limited resources that could be found in Dar es Salaam.

Conclusion of the components used

Two different reference stations are used in this study. In Delft this is the receiver that is placed on the NMi tower and is managed by TU Delft. In Dar es Salaam a self set up station is used, using a laptop. After a trail-en-error process, the choice was made to use a laptop for the rover. The GNSS receiver is connected to it, after which RTKLIB NAVI and u-center are used. How this is done is described in the next section.

B.2. Manual; how to conduct the experiments

Manual post-processing

Necessary equipment

Rover	Base	General
- Ardusimple with u-blox receiver	- Ardusimple with u-blox receiver	- Field book
- Antenna	- Antenna	- Pen
- USB data cable	- USB data cable	- Water
- (charged) Laptop	- Laptop + charger	- Phone (with credit in case of questions)
		- Permit(s)

Download the necessary programs

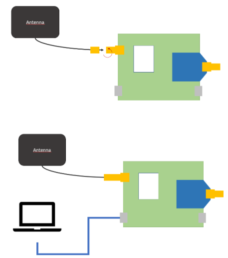
Download U-center:
https://www.u-blox.com/en/product/u-center
Download RTKLIB, Demo5 31a
http://rtkexplorer.com/downloads/rtklib-code/

Connecting the GPS receivers to a PC

In these experiments, we will connect the Ardusimples to two different laptops. You will not get usable data if you try to collect data inside a building, so don't waste trying this on a desk computer. It's fine to get the everything configured on the laptop behind your desk in the office, but be sure to choose a location with open skies away from buildings and trees when you are ready to collect your data, especially for the base station.

1. The first thing to do is to connect the antenna to the ardusimple. How this is done is made clear in the figure on the left →

2. Followed by connecting the ardusimple to the computer with a usb/micro-usb cable, which can transmit data. Not every usb-micro usb cable is suitable for this. If you are using Kirsten's kit, take a purple, blue of green usb-micro usb cable. The micro-usb goes into the entrance on the ardusimple where it says "gps + power" and the usb goes into the laptop, making sure a connection is made.
This set-up is shown in the figure on the left →.
It is essential that the antenna is connected first, then the power, otherwise the antenna will not be recognized as part of the instrument.
This must be done for both the rover and the base.



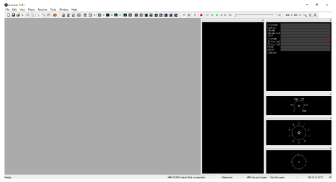
Configuring and testing the GPS receiver

At this point, the GPS receivers are connected to your laptops through the USB port and are ready to configure and verify that everything is working fine. These steps have to be done for both the rover and the base.

3. you need to open de U-center software package. It makes it easy to explore all the possible configuration for your u-blox receivers (not only the u-blox ZED-F9P, but also all other receivers) and make sure everything is working properly before you move to the RTKLIB software.

After you started up the program, it will look like Figure \ref{}

Functions in the taskbar



The taskbar consist of four different parts, each is described below.

With this part of the taskbar two things have to be done.

4. Press the leftmost icon, this allows you to set the correct USB port. When the correct COM-port is selected, the icon will turn green and at the bottom of the page this will appear: COM5
5. With the second leftmost icon, the Baudrate can be set. This is the number of events or signal changes that occur in one second. For best results set it at 115200.

This section of the taskbar shows different parts. Mainly some graphs are switched "on" or "off". It depends on the research if it's important to switch some graphs on, for example the skyview, location, altitude, information about the different satellites and the time. I recommended to use the information table with the location/altitude/TTFF/PDOS/DOP etc, it gives a good overview of the status of the receiver. If the receivers are correct connected to the computer, these graphs are changing (every second).

This part of the taskbar is of great importance. It shows all the output of the measurements.

- The leftmost icon, the "Packet Console" shows which output is being collected. By default, these are NMEA outputs.
- Second leftmost icon: shows the "Binary Console", i.e. all the binary values that come in.
- Third leftmost icon: shows the "Text Console", it gives all NMEA with the corresponding values
- Fourth icon: shows the "Message View", which shows all the output to be received. Files to be received are coloured black, files that are not received are grey. By clicking here you can see the

incoming values of such a file type. By double clicking you can turn it on or off, so it will (or will not) be received. Another method is to click on your right mouse button and decide whether you want to enable or disable the messages. Be aware, the u-center software is using the NMEA messages. So if you enable them, the display windows will stop updating.

6. For this research the default NMEA messages and the UBX-RXM-RAWX messages are used. So be sure you enable them. Tip: if you have enabled something, it is useful to click in the "Packet Console" if it is actually received.

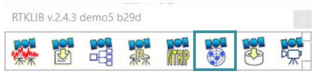
This part is only for your information, you are not using this for the experiments in this research.

With this part of the taskbar you can record a measurement, this is saved as an .ubx file. This can then be opened again at a later time in u-center or in other programs (like RTKLIB).

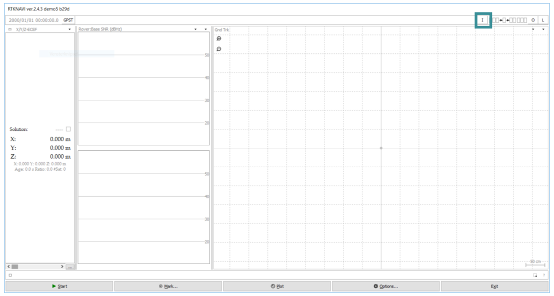
- With the fourth icon, the red icon, you can record a measurement. You then have to save it immediately on your computer, where the incoming information is put, until you actually press stop. Stopping a measurement is done with the second icon, the black square.
- With the green play button, a measurement can be opened.

Getting started with RTKLIB - RTKNAVI

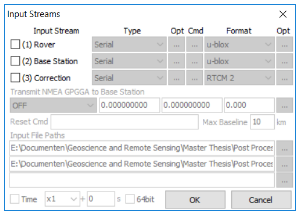
At this point, we have verified that the GPS hardware and the link to the laptop are working properly, and you are ready to start using RTKLIB to collect and process the raw GPS data. If you open the RTKLAUNCH software, the following figure will appear:



7. Press the RTKNAVI button. The following screen will appear;



8. Press on the [I] on the upper-right top of the window. This is the the Input Stream Settings. The following screen will appear;

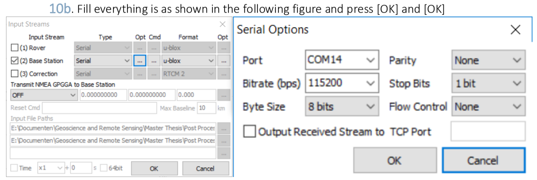


From now on it will be different what has to be done with the base and the rover, so pay attention! If you are in charge of the BASE, see point 9b till 17b. If you are in charge of the ROVER, see point 9r till 17r.

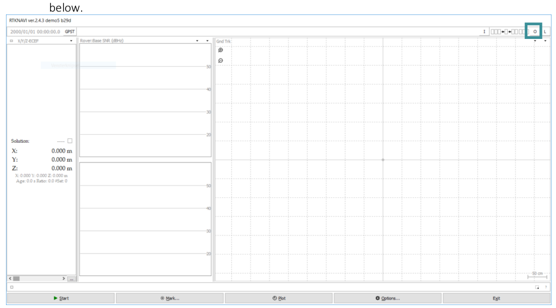
BASE – RTKNAVI

9b. Select the (2) "Base Station" in the Input Streams setting.

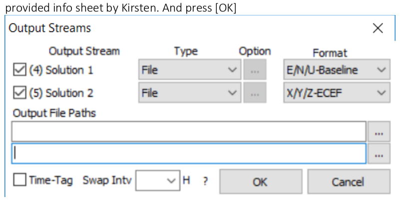
10b. Fill everything is as shown in the following figure and press [OK] and [OK]



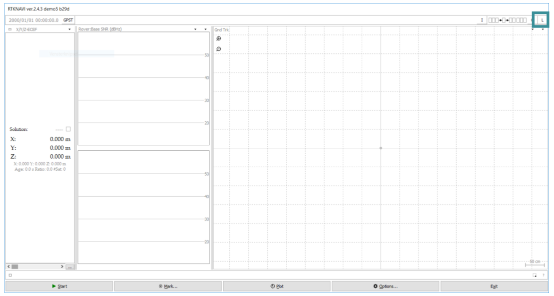
11b. Press on the [O] in the upper right corner to set-up the Output Stream as shown in the figure below.



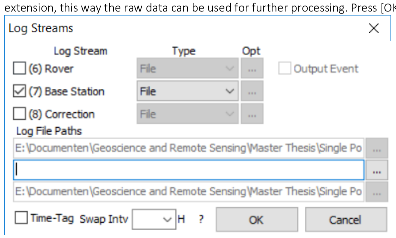
12b. Fill the Output Stream in as in the following figure. The output stream is a .csv (excel) file that can be used for further analysis. So be sure you save this at a good location (Output File Paths) and be sure you use the name of the correct experiment. For the name of your experiment, see your provided info sheet by Kirsten. And press [OK]



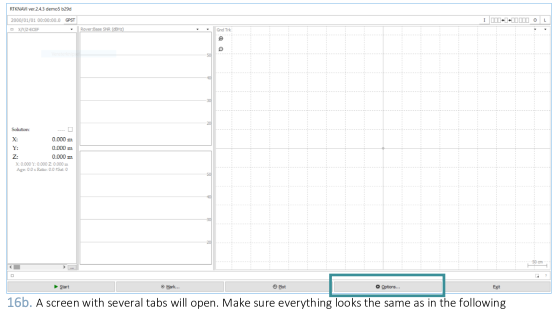
13b. The last step is to create a log-file. This is done by pressing on the [L] in the upper right corner of the start-screen.



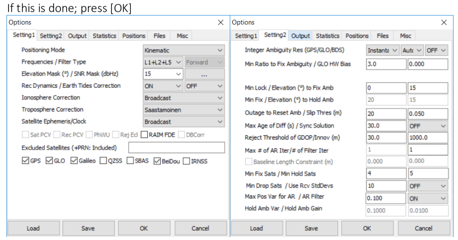
14b. Fill everything in as in the figure below. In the log-file the raw measurements are stored, and are a .ubx file. Again, it is very important that you choose a good location to store these files (Log File Paths) and give the file the name of the experiment. At the end of the filename put the .ubx extension, this way the raw data can be used for further processing. Press [OK]

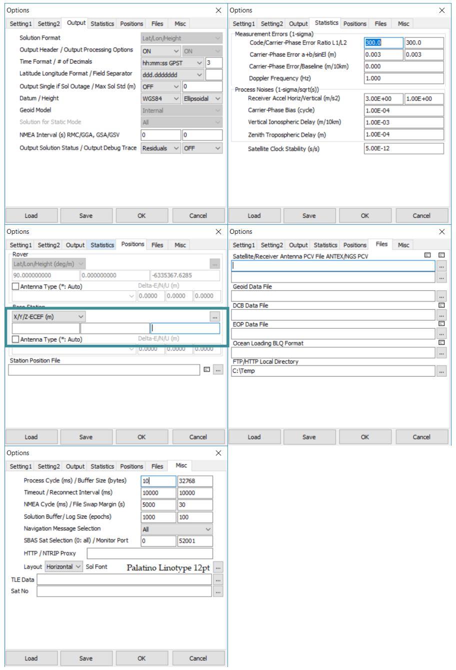


15b. Now all the streams are set correctly, but we're not there yet. You are now back in the start screen of RTKNAVI and go to options, as you can see in the next picture.



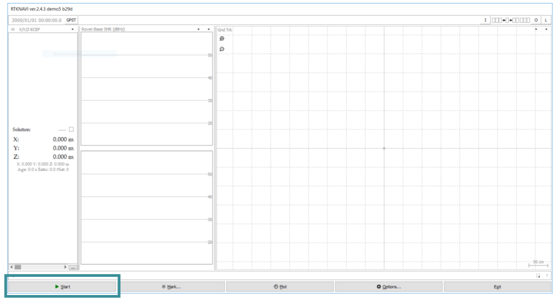
16b. A screen with several tabs will open. Make sure everything looks the same as in the following pictures. After that is done press [OK]. In the 5th window, in the green box, fill in the following parameters;
X = 4904285.6198
Y = 4008272.3724
Z = -747305.3348
If this is done; press [OK]





17b. Make a line-up. Choose a good spot where there are no trees/buildings/houses/water in the immediate vicinity. Place the green box on a stable, horizontal surface as much as possible and place the antenna on top of it. Make sure that the setup cannot be disturbed by yourself or by other people. Indicate - somehow - where exactly you have placed the antenna, so that it can always be found. Take as an example:

18b. One can start the measurements by pressing start in the main screen.

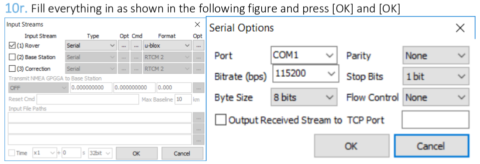


If you've done everything right, the screen will look like this;

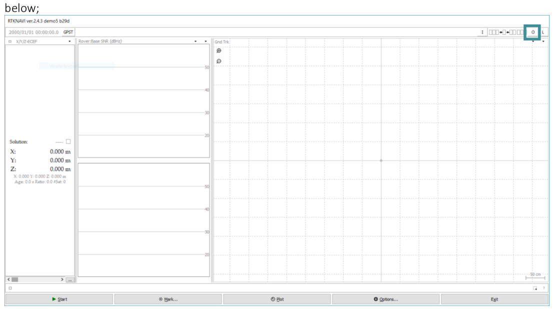
Figure
Keep it this way for …. Minutes (see, experiment info-sheet)

ROVER – RTKNAVI

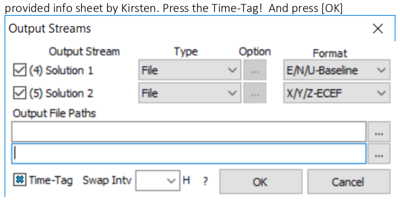
9r. Select the (1) "Rover" in the Input Streams setting.
10r. Fill everything in as shown in the following figure and press [OK] and [OK]



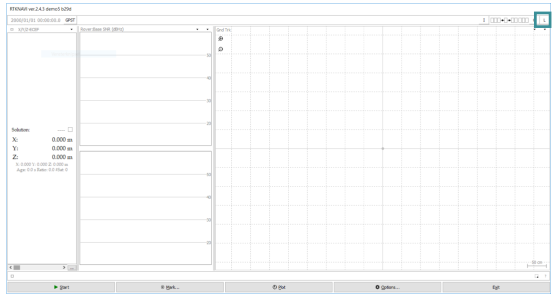
11r. Press on the [O] in the upper right corner to set-up the Output Stream as shown in the figure below;



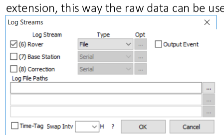
12b. Fill the Output Stream in as in the following figure. The output stream is a .csv (excel) file that can be used for further analysis. So be sure you save this at a good location (Output File Paths) and be sure you use the name of the correct experiment. For the name of your experiment, see your provided info sheet by Kirsten. Press the Time-Tag! And press [OK]



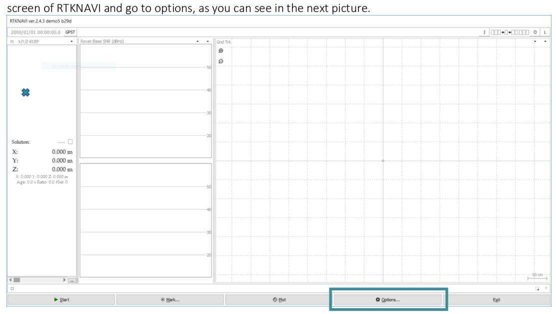
13b. The last step is to create a log-file. This is done by pressing on the [L] in the upper right corner of the start-screen.



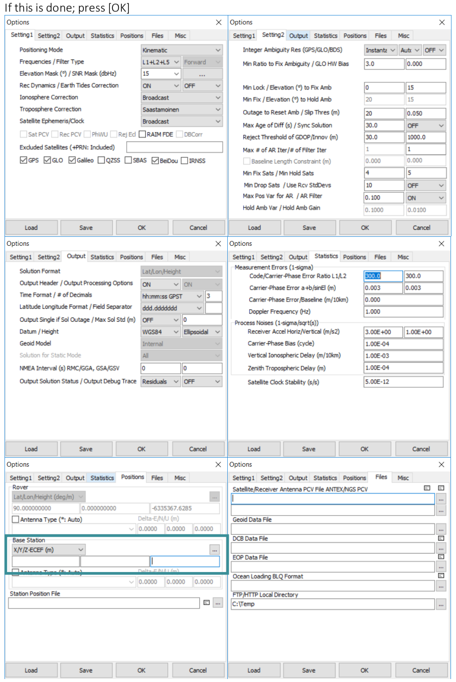
14b. Fill everything in as in the figure below. In the log-file the raw measurements are stored, and are a .ubx file. Again, it is very important that you choose a good location to store these files (Log File Paths) and give the file the name of the experiment. At the end of the filename put the .ubx extension, this way the raw data can be used for further processing. Press [OK]

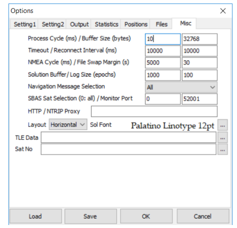


15b. Now all the streams are set correctly, but we're not there yet. You are now back in the start screen of RTKNAVI and go to options, as you can see in the next picture.



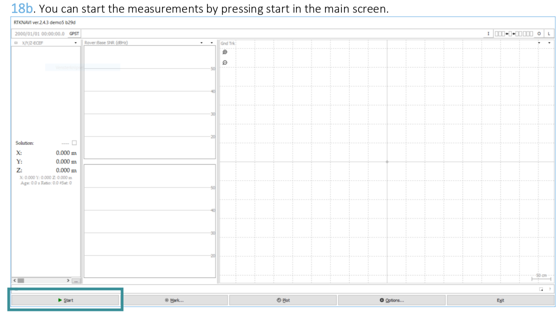
16b. A screen with several tabs will open. Make sure everything looks the same as in the following pictures. After that is done press [OK]. In the 5th window, in the green box, fill in the following parameters;
X = 4904285.6198
Y = 4008272.3724
Z = -747305.3348
If this is done; press [OK]





17b. Make a line-up. Choose a good spot where there are no trees/buildings/houses/water in the immediate vicinity. Place the green box on a stable, horizontal surface as much as possible and place the antenna on top of it. Make sure that the setup cannot be disturbed by yourself or by other people. Indicate - somehow - where exactly you have placed the antenna, so that it can always be found. Take as an example:

18b. You can start the measurements by pressing start in the main screen.



If you've done everything right, the screen will look like this;

Figure

Keep it this way for …. Minutes (see, experiment info-sheet)

Fill in the logbook

19. Write in the logbook the following information;
    - Name experiment (see info-file)
    - Who did the experiment
    - Date
    - Start time
    - End time
    - Weather conditions
    - Equipment used
    - Notes
20. Measure the distance between the Antenna and the ground (on 4 different points)
21. Take some pictures of the set-up

Short summary of the steps for rover and base

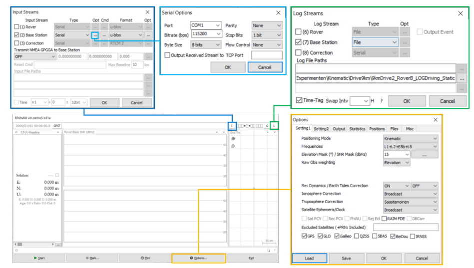
BASE

1. Configure the GPS receiver in U-Center
   a. All NMEA messages
   b. UBX-RAWX messages
2. Fill in the Input Streams in RTKLIB
3. Fill in the Output Streams in RTKLIB
4. Fill in the Log Streams in RTKLIB
5. Check the options-menu in RTKLIB
6. Start the measurement
7. Fill in the logbook and the Experiment info-sheet
8. Give the files to Kirsten

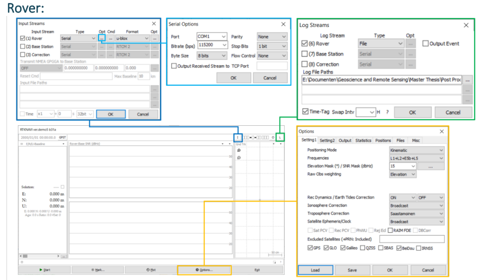
ROVER

1. Configure the GPS receiver in U-Center
   a. All NMEA messages
   b. UBX-RAWX messages
2. Fill in the Input Streams in RTKLIB
3. Fill in the Output Streams in RTKLIB
4. Fill in the Log Streams in RTKLIB
5. Check the options-menu in RTKLIB
6. Start the measurement
7. Fill in the logbook and the Experiment info-sheet
8. Give the files to Kirsten

Base:



Rover:



B.3. Shelter of reference station in Dar es Salaam

Here a few pictures and the design of the shelter are presented

Figure B.1: Google sketch-up design of the shelter.

Figure B.2: Pictures of the shelter.

C

Technical details equipments

Technical details about the equipment are provided in this appendix.

C.0.1. Technical detail of the u-blox ZED-F9P

The GNSS receiver used for this study is the U-blox ZED-F9P, developed by the company U-blox The type number is ZED-F9P-01B-00 with firmware version HPG1.12 installed. The dimensions are 17 x 22 x 2.4 mm, and can operate in temperatures between the -40°C and +85°C. The equipment has integrated U-blox multi-band RTK technology for centimetre level accuracy. It included the so called moving base support, allowing both the base and rover to move while positioning in RTK setting. Moving base is developed for unmanned areal vehicles (UAV) applications where the UAV is programmed to follow its owner or to land on a moving platform. The speed of the positioning observations is dependent on the different GNSS modes, therefore a overview is created in Table C.1. The receiver can receive and track multiple GNSS constellations; GPS, GLONASS (GLO), Galileo (GAL) and BeiDou (BDS) plus QZSS satellites. All satellites in view can be used to provide an RTK positioning solution, or combinations can be made of the four major constellations.

Table C.1: Performance of the U-blox ZED-F9P receiver in different GNSS modes.

GNSS		GPS+GLO+ GAL+BDS	GPS+ GLO+GAL	GPS+GAL	GPS + GLO	GPS+BDS	GPS
Acquisition time (s)	Cold start	24	25	29	26	28	29
	Hot start	2	2	2	2	2	2
	Aided start	2	2	2	2	2	2
Convergence time (s)	RTK	< 10	< 10	< 10	< 10	< 10	< 30
Horizontal position accuracy (m)	RTK	0.01	0.01	0.01	0.01	0.01	0.01
Vertical position accuracy (m)	RTK	0.01	0.01	0.01	0.01	0.01	0.01

The receiver is able to record and trace multi-band signals. Figure C.1 shows the whole spectrum of frequencies that can be transmitted by different satellite constellations. The red blocks in this figure show which frequencies this U-blox GNSS receiver can process into a position. However, it must be taken into account that the antenna must (of course) also be able to receive these signals. This picture is already represented in the literature review, however it will make the table more understandable.

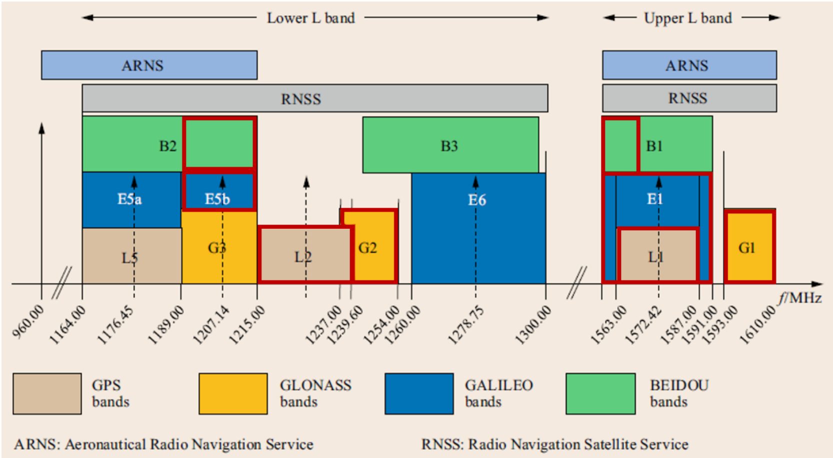


Figure C.1: Supported signals from both the upper- and the lower L-band, the red blocks show which frequencies the receiver can process into a position.

The receiver can be configured using the U-center software package, which is described below.

C.0.2. Technical details of the Ardusimple

The low-cost GNSS receiver is installed on a Ardusimple, version *simpleRTK2B*. This is a stand-alone application board that allows to evaluate multi-band GNSS technology, including RTK functionality. The simpleRTK2b is fully compatible as a shield with Arduino, Raspberry Pi, Nucleo and Pixhawk autopilot. The lay-out of the shield is shown in Figure C.2, where the white component on the shield is the GNSS receiver, as discussed above. the antenna is connected to the shield with a rotating system and transmits the received signals to the GNSS receiver. The power the GNSS receiver needs to operate is delivered to the shield at the bottom left of the shield, at the "power connection". The power can come from a computer, powerbank or smartphone, as long as there is a cable with a micro-USB output that can connect to the shield. One the right side there is also a power-connection, this is to power the radio-module. In addition, if a link is made between this power connection and the GNSS receiver, using a "bridge" instead of the radio-module, this power source can be attached to this output-point on the shield. The connection points can be used to attach additional elements to the shield, it has the same way of working as with an Arduino

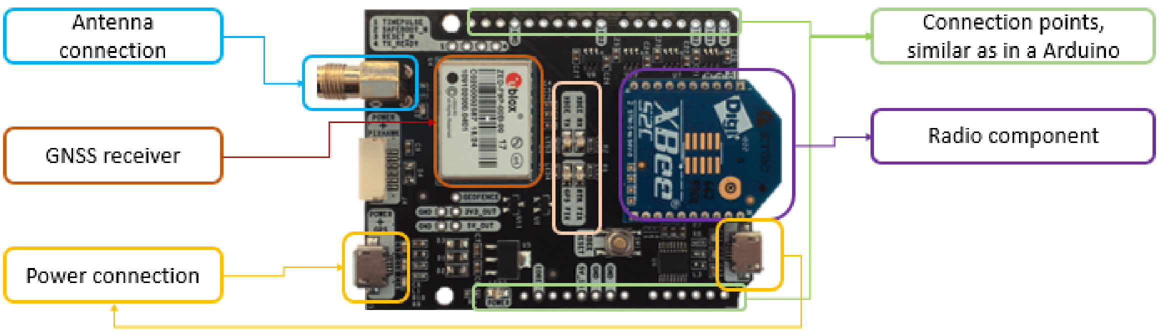


Figure C.2: Lay-out of the Ardusimple, with an explanation of the components

The simpleRTK2B support different operating modes; stand-alone, base-rover configuration, the base-multiple rovers configuration, RTK moving base configuration, and stand-alone with RTK/SSR corrections.

C.0.3. Software installation

During this research two different software packages will be used for the measurements; U-center and RTKLIB. In this section will be discussed how to install these two programs and what the requirements are for the laptop that is being used.

U-center is the free software package from U-blox (to be downloaded from;

https://www.u−blox.com/en/product/u−center), it can be used for evaluation, configuration, testing and performance (visualization) of the various U-blox GNSS receiver products. It has a structured graphical data visualization in real time of; satellite- ,and navigation summary view, compass, speedometer, clock, altimeter, data recording and playback functionality. In order to be able to visualize the results properly, there is an internal link to Google Earth maps. RTKLIB is an open source program package for GNSS positioning (to be downloaded from;
http://rtkexplorer.com/downloads/rtklib−code/). It has several applications; doing measurements, post-processing, real-time processing, Google Earth KML converter. It can make use of several models te improve the observations and the positioning; atmosphere-, antenna-, positioning-, Earth tides-, geoid- models. In addition, there are several functions that can be used; RINEX, solution-, Google Earth KML converter, SBAS-, stream data input and output-, integer ambiguity resolution, standard positioning, precise positioning, post-processing positioning, stream server functions, RTK server functions and at last downloader functions. For an overview see Table C.2

Table C.2: Overview of the software requirements

Program	U-center	RTKLIB
Developer	U-blox	T. Takasu
Version	19.03 used during this research	Demo5 b31a binaries
Release date	2019	2 May 2019
Space on a computer's drive	16,0 kB (16.384 bytes)	79,2 MB (83.075.072 bytes)
Manual exist?	Yes	Yes

C.1. NTRIP information

C.1.1. NTRIP; and introduction

Real Time Kinematic positioning is a method used by an RTK-enabled GPS receiver to obtain extremely precise positions by using data from an RTK base station that is transmitted over the internet. The NTRIP protocol (Networked Transport of RTCM via Internet Protocol) enables the mobile RTK GPS receiver (rover) to access data from the RTK base station over the internet to achieve 1cm accuracy.
RTK works by having the RTK base station set up at a known (geospatial) location. The RTK base station receiver is set to the known position of this point during setup. The base receiver continuously observes the satellites and calculates position corrections that are sent to the rover once every second in a data stream. This is also called the "base data". The rover uses location information from the satellites and the base correctional data to compute a precise coordinate.

C.1.2. How are the corrections sent to the rover from the base?

Before mobile devices were so well-connected to the internet, base data was sent via 900MHZ, VHF of UHF radios. This meant that the base receiver had to be connected to a radio capable of transmitting and the rover had to be connected to a radio capable of receiving. This working method has its limitations; radio signals can be blocked by hills, buildings, trees etc. The radio signals also have a limited distance they can travel. NTRIP provides a method for sending and receiving GNSS base data over the internet.

C.1.3. Benefits and limits of using NTRIP over radio set-ups

The pro's are;

- Less equipment to carry in the field. Almost all data collectors, smartphones, and computer have the capability to connect to the internet even in a field setting.
- No licence required
- Mitigate the change of radio interference
- No limitation on communication range

The con of using NTRIP is;

- Requires the work area is in range of cellular service for receiving corrections data via the Internet

C.1.4. How does NTRIP work?

NTRIP consists of 2 pieces of software which communicate over the internet. The server side runs NTRIP Caster software (Thus TU Delft has this software is use) . The rover side runs the NTRIP Client software (Thus on your android phone).
The NTRIP caster is responsible for receiving the data stream from the base receiver and rebroadcasting it over a specified TCP (Transmission Control Protocol) port, as shown in Figure C.3

	CASTER (BASE STATION)	CLIENT (ROVER STATION)
IP ADRESS	Computer running the caster software has IP address xxx	Tell the NTRIP client software to connect to the server at that specific IP address. *Do this on the android phone, app: NTRIP CLIENT*

Figure C.3: NTRIP information; caster and client.

D

Community mapping aspects

In this appendix the community aspects are presented. This includes the fully detailed interviews and brainstorm stickynotes. Followed by a more detailed explanation of the desing process of the receiver-casing.

D.1. Fully detailed interviews

Questionnaire Asha

What is your position in HOT? What are your responsibilities?
I am Project Associate. My job is to supervise all the projects in HOT
In which department of HOT do you work?
It's not really a department
What is the overall aim of you department?
See question 2
With which projects of HOT are you involved?
Among others; Ramani Huria, River mapping, Meteor project, Shina mapping project, Community mapping project, industrial training and trash mapping
You participated in the workshop, so you have somewhat an idea of what I have been doing. What is your first impression?
It looks good, but for now it's too complicated to work with.
Would you like to implement this GNSS receiver in HOT? For which projects?
It looks very promising, but there need to be some adjustments before it becomes really interesting for HOT. I think the cadaster project is gonna be the most interesting one.
Which steps need to be taken before the implementation is possible?
For now it's too complicated to work with. Maybe you, Glory and Imma fully understand what is going on, but for the people that are going into the field it's too much of a hassle and for the digitalizes it's too complicated to process all the data. Even with the manuals, there are too many requirements for a good measurement/test/observation
Another problem is that it's not very safe to work with this equipment if you go into the slumbs, because it's too valuable. And it's too expensive to buy it for many people
With which programs need the data processing to be compatible? Which programs do you use now for position determination?
OpenDataKit Collect (ODK)
OpenMapKit
OSMTracker

Ideally... Which (spatial) accuracy do you want? Why?
Cm level
Now often the accuracy is between the 1 and 5 meters. The problem with that is that some of the housing is so small that houses/buildings are lost. In addition, it is very important when research is done into health issues. A location is then made of a house where a sick person is, if the accuracy is too low it may be that it is seen as the house next to it, causing the care workers concerned to go to the wrong house. Important aspect is that there are many small buildings/houses.
The decision makers should be informed as well as possible, but it doesn't have to be lower than a few centimetres, because the human errors don't outweigh it.
Ideally... How fast need do you want it to give you a position? Why?
If measuring takes too long or doesn't go well, the students will fill in their own data and create information. This is because they don't dare to go to their team leader with "it didn't work out" or "it took too long". That's not how the culture turns out to be. Even the team leaders don't dare to go to the supervisors if something didn't go well, so they try to adapt or create it themselves. Another argument to make sure that everything goes fast
Ideally... How many people are needed to set-up the network? Why?
Don't know

Do you mind being depend on an internet connect? Do you prefer with or without internet connection? Why?

- Not all projects take place in Dar es Salaam, and in the villages is very often internet connection or network.
- The costs are too high if you have to buy internet for everyone. There are projects with more than 500 students, and if you have to pay for internet for everyone (even if it is only 1G) the costs are too high. So if you work with a fixed amount of money, it means that you can use fewer people for the project.
- The app that is used is offline, where at the end of the day the data (by the students) is uploaded and the data is checked by the team leader. So as it looks now, no internet is needed. But to upload the data, internet is already needed.

Do you want to use an interface while working with the GNSS receiver, so you can see where you are? Why?
Having no interface is not very bad. The students don't need to know exactly where they are, the team-leaders and/or supervisors know where people are. But it would be useful for people who have never worked on a project before or have never seen the ward/subward before.
Do you want real-time or post- processing? Why?
The one that's less complicated
How many rovers do you want to use at the same moment? Why??
Many as possible
Do you have anything you want to bring to my attention?
Keep up the good work and you are always welcome back!

Questionnaire Immaculate

What is your position in HOT? What are your responsibilities?
My position in HOT is Operations and I am responsible to make sure all the operations in the office are going accordingly. Overseeing Human Resources duties, managing both the operations process, and operations strategy.
In which department of HOT do you work?
Operations
What is the overall aim of you department?
Refer to 1 above :)
With which projects of HOT are you involved?
Ramani Huria
Apart from HOT, I also work in projects that are OMDTZ related such as the Innovation Ecosystem Map of Tanzania and River Mapping
With what kind of equipment do you work?
I nowadays mainly work with my laptop except if I am doing fieldwork then I work mostly with my phone
You joint me during the experiments, so you have (perfect) understand of what I have been doing. What do you think of the experiments and the GNSS receiver?
I think that the experiments done with the GNSS receiver and the GNSS receiver in general are very relevant to the works that we are doing at the office because most of the fieldwork need very accurate GPS for mapping and location
Would you like to implement this GNSS receiver in HOT? For which projects?
Yes, I would like to implement the GNSS receiver in HOT for projects such as Ramani Huria including drainage mapping, asset and threat mapping, hyper-local administrative boundary mapping and for the OMDTZ project River Mapping the receiver would be very useful in the field for drone mapping.
Which steps need to be taken before the implementation is possible?

- Having a portable GNSS receiver that can be used in the field, if not
- Have the GNSS receiver system installed in an app on the phone so it can be used easily by people in the field
- Since this is a more technical equipment to use other than the Garmin GPS receiver that the team is used to, it may be useful to have a training on how to use the GNSS, RTK, u-center and u-blox and how to analyze the data

With which programs need the data processing to be compatible? Which programs do you use now for position determination?
OpenDataKit Collect (ODK), OpenMapKit and OSMTracker for position determination.
Ideally… Which (spatial) accuracy do you want? Why?
At first I thought that obtaining the 2cm accuracy might be a fantasy, but seeing it come to reality I think that that is the most preferable spatial accuracy i.e. 2cm to 1m at most. This is because most of our works depend on positioning and accuracy of the GPS/GNSS
Ideally… How fast need do you want it to give you a position? Why?
If possible, at most, after 10 seconds. This is because some of the fieldwork is done in remote areas and it might not be safe to wait around for more than 1 minute for the GNSS to read your position.
Ideally… How many people are needed to set-up the network? Why?
2 people and above, because being in the field with Kirsten I can see how the data can go wrong in a very short time for example when the GNSS receiver fell from the bajaj, or when we were going back from the 4km point and one laptop stopped receiving signals. It would be better if more than 1 equipment is used.
Do you mind being depend on an internet connect? Do you prefer with or without internet connection? Why?
I do not mind using it with an internet connection but I would prefer to use it without an internet connection for two reasons:

- Sometimes fieldwork is conducted in very remote areas where mobile network does not reach therefore without internet then the work will not be conducted effectively
- Using an internet connection means that mobile charge runs very fast! And while in the field before finishing work, one might be out of charge and will not be able to finish the work

Do you want to use an interface while working with the GNSS receiver, so you can see where you are? Why?
Yes, I would really want to use an interface to see where I am because not all places that I will visit while in the field I will be familiar with. Some of the places I won't be familiar with and will need something like a map to show me where I am
Do you want real-time or post- processing? Why?
I prefer real-time because it is easier to monitor field work while people are still working rather than post-processing whereby if data was collected wrongly then it would require someone to go back to the field some other time
How many rovers do you want to use at the same moment? Why??
If possible 2 rovers at the same time because one rover might stop receiving signals or might just stop abruptly and that will disrupt my data, but having more than one rover means that I will be sure and confident to have 2 different but accurate data
Do you have anything you want to bring to my attention?
Nothing in particular, but I would prefer and love it if the GNSS receiver would materialize and come to use in HOT because I think that it is a very cool tool to use and it would mean that we now have very accurate positioning systems for our works

Questionnaire Bornlove

What is your position in HOT? What are your responsibilities?
I am in the innovation and technical department and responsible for that department. My boss is Iddy.
In which department of HOT do you work?
Innovation and technical department
What is the overall aim of you department?
Development of technical innovative tools that will assist the mapping such as drones, barometers, GPS related tools and so on.
With which projects of HOT are you involved?
All project that needs high resolution aerial data taken from low altitude, currently are river mapping and lusake city mapping and both of the projects needs GNSS ground base receiver as well as rover reciver to work togeterh.
With what kind of equipment do you work?
On the mission we work with ebee drone and ground station provided by sensefly. But we have tried to build our drone (rover) for aerial imaging but for precision output we have to work on development of GNSS ground base that is this project seems to be the solution.
You joint the workshop, so you have (perfect) understand of what I have been doing. What do you think of the experiments and the GNSS receiver?
I'm very much interested to implement this project ot our department or project
Would you like to implement this GNSS receiver in HOT? For which projects?
Yes, for everything that needs high accuracy areal pictures with rover and base station.
Which steps need to be taken before the implementation is possible?
Identify weather the GNSS receiver is compatible with drone GNSS receiver that I am using and if yes, will the output from the base GNSS receiver match with rover GNSS receiver for post processing if yes than it will be possible to work on it.
With which programs need the data processing to be compatible? Which programs do you use now for position determination?
With ebee drone emotion and pix4D. And with the drone what we are building – mission planner and QGround Control as well as OpenDroneMap
Ideally… Which (spatial) accuracy do you want? Why?
Less than 5 ckm, because of the maps.
Ideally… How fast need do you want it to give you a position? Why?
Start with less than 10 minutes for positioning, for fast data collection with rover.
Ideally… How many people are needed to set-up the network? Why?
Two, for base and rover one. One will be working with base receiver and another with rover receiver to different areas.
Do you mind being depend on an internet connect? Do you prefer with or without internet connection? Why?
No, I prefer to work without internet connection because you will not be able to get the internet connectivity in country side so better not to rely on internet during data collection.
Do you want to use an interface while working with the GNSS receiver, so you can see where you are? Why?
Yes, indeed for easy integrating with the GNSS receiver to view it is status.
Do you want real-time or post- processing? Why?
Post-processing. To save to time working at the field
How many rovers do you want to use at the same moment? Why??
More than one, for the case of drone, I need to be able to launch more than one drone with RTK with one RTK base station.
Do you have anything you want to bring to my attention?
Embed the system with wireless kind of communication; Bluetooth, WIFI or GSM to have management of it remotely using GUI. For the future, to have rechargeable battery that going to be two or more and good management of it in such a way that one will be used at a time and once it reached a certain value, the battery management system will allow another one to be utilized and give you possibility to replace a used one without affecting the operation of the device in negative. This will make the device portable for the site kind of activities.

Questionnaire Iddy

What is your position in HOT? What are your responsibilities?
I'm the head of the GIS department and involved in almost all the maps that HOT makes
In which department of HOT do you work?
I'm in the GIS department, that is working together with the innovation department
What is the overall aim of you department?
To make the maps
With which projects of HOT are you involved?
All the projects, but Ramani Huria is one of the bigger ones. Right know I'm trying to determine the political (sub)boundaries in Tanzania, this I'm doing with Aaron (American master student) and people from parliament from Dodoma (the capital of Tanzania).
With what kind of equipment do you work?
Computer/laptop
You joint the workshop so you have (perfect) understand of what I have been doing. What do you think of the experiments and the GNSS receiver?
It looks really nice, but I'm afraid it's a little bit too complicated. There are too many things you have to think of and too many steps to take. Maybe program the receiver in such way that you don't have to use U-centre, and only RTKLIB. And then make everything automatic, do you know if that's possible? [I don't know, would it help or do you want to know exactly what you are doing?]. No, it's fine if only a few people know what they are doing, the most mappers are not interested in it at all. I think.
Would you like to implement this GNSS receiver in HOT? For which projects?
Yes, for Ramani Huria and maybe for making a cadastre or maybe for trash mapping
Which steps need to be taken before the implementation is possible?
It needs to bee easier to work with and more experiments, so you can be more sure about the results.
With which programs need the data processing to be compatible? Which programs do you use now for position determination?
QGIS, and the smartphone apps they are working with.
Ideally… Which (spatial) accuracy do you want? Why?
Cm, so you can be very accurate
Ideally… How fast need do you want it to give you a position? Why?
Less than 10 seconds. Otherwise it will take too long for all the students/mappers/volunteers and then they are gonna create the data. We don't want that, because that is so difficult to remove from the data. And difficult to make maps.
Ideally… How many people are needed to set-up the network? Why?
Only one, because there are not many people with time and the expertise.
Do you mind being depend on an internet connect? Do you prefer with or without internet connection? Why?
No, we don't want that. A lot of surveys are in rural area's and there is no internet connection.
Do you want to use an interface while working with the GNSS receiver, so you can see where you are? Why?
No, we don't need that. It's not important to know where you are. It's important that de machine knows where you are.
Do you want real-time or post- processing? Why?
The easiest. The system is too complicated for now, so there need to change something.
How many rovers do you want to use at the same moment? Why??
Many as possible, so everything goes faster
Do you have anything you want to bring to my attention?
We liked it that you were here! Do you come back?

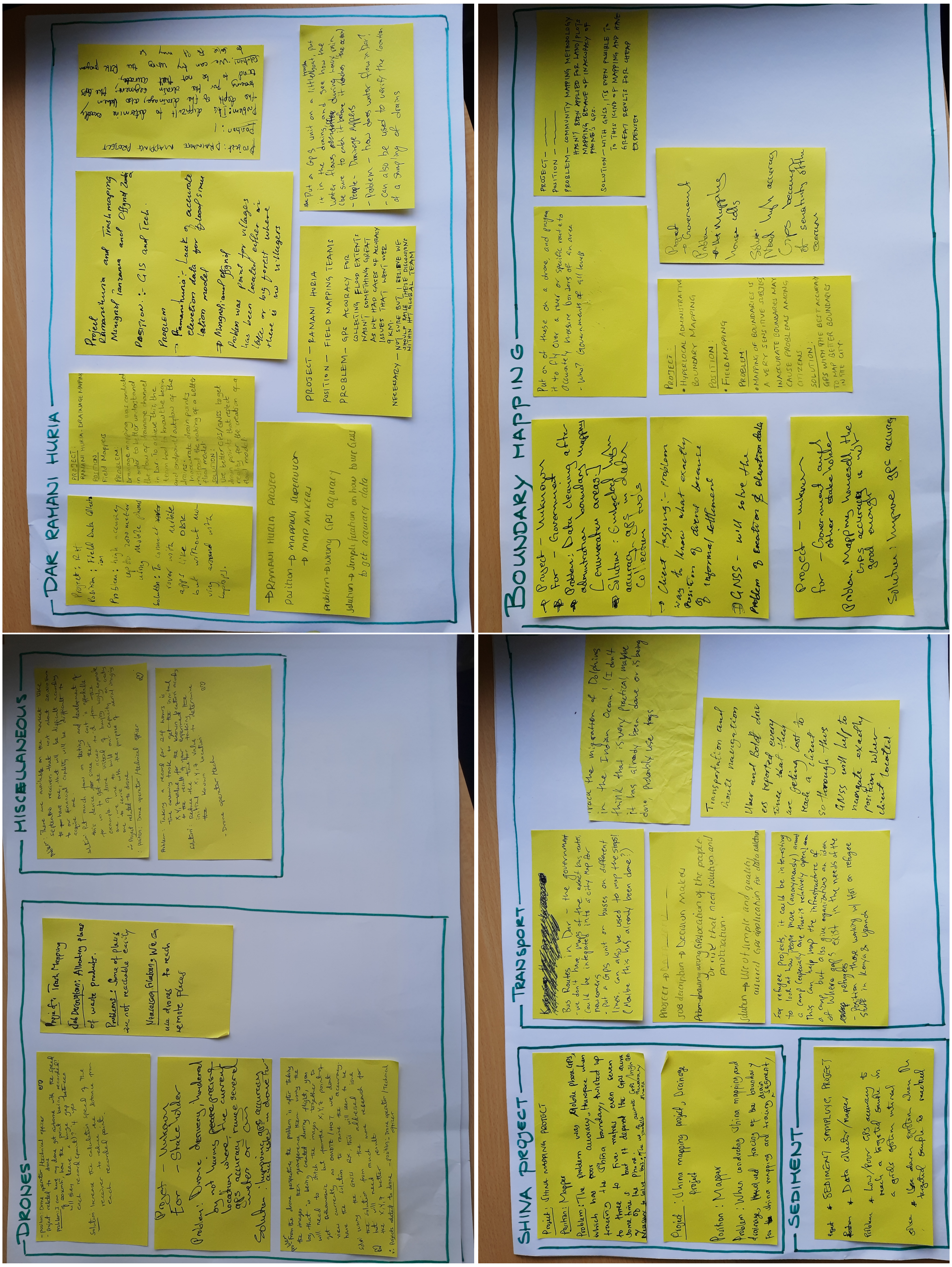
Questionnaire Glory

What is your position in HOT? What are your responsibilities?
Mapper, dealing with community mapping in different projects like river mapping project, community mapping project, Ramani Huria, Drainage mapping, Meteor project and shina mapping project.
In which department of HOT do you work?
Innovation Department
What is the overall aim of you department?
The overall aim of our department is to come up with new ideas/methods which we can change/restructure, because innovation is crucial to the continuing success of our organisation
With which projects of HOT are you involved?
River Mapping project, Ramani Huria, Meteor project, Community mapping project, Shina mapping
With what kind of equipment do you work?
I work with drones in aerial mapping and tape, measure and android phone GPS in community mapping and drainage mapping.
You joint me during the experiments, so you have (perfect) understand of what I have been doing. What do you think of the experiments and the GNSS receiver?
Yes! we have done so many experiments and the GNSS receiver showed a high GPS accuracy compared to the android phone GPS which we are using which absolutely great thing to us.
Would you like to implement this GNSS receiver in HOT? For which projects?
Yes, I would like to, especially in the projects which involves imagery taking, tracing like boundaries, segment etc, From the experiments we did, shows the GNNS receiver has a good accuracy up to 5 centimetres compared to android phone GPS which may have like 0.5- 8 meters accuracy which causes conflict sometimes on community boundary.
Which steps need to be taken before the implementation is possible?
I think, more experiments have to be done with their solutions as much as possible, also in different seasons in testing the GPS accuracy, so as to compare the results and satisfy ourselves with the best results then from there now, further steps can be taken to implementation
With which programs need the data processing to be compatible? Which programs do you use now for position determination?
I don't really know it
Ideally… Which (spatial) accuracy do you want? Why?
Just as good as from the rover and base of 5 centimetre, which shows a small different from the ground
Ideally… How fast need do you want it to give you a position? Why?
As fast as possible, because it saves time
Ideally… How many people are needed to set-up the network? Why?
Not really sure, may be just one
Do you mind being depend on an internet connect? Do you prefer with or without internet connection? Why?
NO, I would prefer without internet due to remoteness of some area which has no internet connection which may hinder my work, so working without internet will be the best.
Do you want to use an interface while working with the GNSS receiver, so you can see where you are? Why?
Yes sure, I would like to
Do you want real-time or post- processing? Why?
-I think real time is good and best if everything is fine and on set,
How many rovers do you want to use at the same moment? Why??
Two, I think it's good to have more than one rover especially when analysing your data, because i can be able to control them and compare my results between rover A and rover B.
Do you have anything you want to bring to my attention?
Can I have one rover pleeeeeaase!

Questionnaire Wicho

What is your function in HOT?
I am the driver and the facility manager
You joint me during the experiments, did you like it?
Yes, I liked it very much. It was nice to get out of the office
Do you have suggestions for me?
Your laptop battery ran out too fast, so we had to hurry a lot.
Sometimes it was unclear where you wanted to place the antenna. Maybe you'd better do some research on that beforehand.
Ensure permits are issued on time
Can you tell me a bit about the different kinds of roads there are in Dar es Salaam?
There are in general three different kinds of roads; unpaved, asphalt and concrete.
Some roads are very bad, with a lot of bumbs and holes. Some are quite new and very good, especially the bigger roads are fine.
Can you tell me anything about the onderhoud/status of the roads
During the rainy season (March/April/May) the unpaved roads are very bad, there are a lot of mud pools and puddles on the road. With the Bajaj you can drive around it reasonably well, but not by car. The poorly remembered asphalt roads are in poor condition; all the holes are filled with water and the verges become soft. The good asphalt roads are still easy to cross.
At the beginning of the rainy season the government maintains the roads, especially the important ones. The unpaved roads are flattened again and some holes are filled at the paved roads. This maintenance is done once a year
If it is an election year, more attention is paid to the maintenance of the roads.
How many people can sit in the bajaj?
3 + driver
How fast do you go on a...
Good paved road: 70 km/h
Poor paved road: 30 km/h
Unpaved road: 20 km/h
Maximum motorway during the experiment: 50 km/h
How many days a year can the Bajaj be used?
365 days in principle. Sometimes a day of maintenance
Can the bajaj come into any ward and subward in Dar?
Yes, that's the big advantage of the bajaj!
Can the bajaj come outside Dar?
Theoretically it can, but it is not suitable for that. The distances are too great and the engine can be overheated, especially if you take the main roads where you have to drive at least 80 km/h on the road. That is possible for a few minutes, but not more.

D.2. Fully detailed brainstorm sticky-notes



D.3. Casing design

An essential part of implementing the GNSS receiver is its ease of use, in such a way that it can be used by surveying community members. The GNSS receiver, is very sensitive and fragile. During the experiments, the receiver is exposed to the outside air, the weather and it is moved on (unpaved) roads. In addition, it is used by (different) people, and the receiver can be treated coarsely. A solution is needed to treat the receiver against these factors. A casing and support system were devised as a solution, but a design process was gone through to achieve this. In order to complete this process, guidance was found in the Delft Design Guide, in which various design processes are explained. The choice was made to use the models of Pahl and Beits, and Verein Deutscher Ingenieuere. Both models divide the design process into four different phases: problem analysis, conceptual design, embodiment design and detail design. As this is a small part of this master thesis research, a twist has been given to these models. A problem analysis was done and a design was made. The iterative process between conceptual design, embodiment design and detail design is limited.

D.3.1. Design problem analysis

The first step in the design process is to analyse the problem; think of different aspects and draw up a list of requirements. In this case, four different categories have been established: practical consideration, outdoor usage, users and experiments. For each of these categories there are several requirements. This is done based on own experiences, the workshop (as described in the part focussing on the case study) and observing others who used the equipment.

- Practical considerations
  - Use materials that are locally available in Dar es Salaam.
  - The costs must not be disproportionate.
  - The weight must be minimized, in such a way that it does not become a burden to carry.
- Outdoor usage
  - Can withstand temperatures up to 50 °C.
  - Can withstand sand and dirt to prevent it from entering the receiver.
- Users
  - Can withstand a drop (approx 1 meter), so that the receiver does not break.
  - To be used by all employees of HOT.
- Experiments
  - All required cables and components can still be attached to the ardusimple.
  - Must be able to held the antenna at the same location during static experiments.
  - Must be able to held the antenna at the same height during kinematic experiments.

D.3.2. Iterative process of design; conceptual-, embodiment- and detail design.

Based on the dimensions, an initial design was made in solid works, in order to be able to print it later on in 3D at the Faculty of Industrial Design. On the website of ardusimple there is a file that can be loaded into this design software, and around which you can work to make a casing. To make sure that the receiver stays firmly in place, it was decided to print some kind of plugs on the bottom, where the three holes in the ardusimple can be fixed. An opening has been left free for the connection to the antenna and the micro-ubs opening. After printing the first design, one should take a critical look at the result and checked whether it meets the requirements set out above. The iterative process of designing was set in motion and a second design was made. The thickness of the material was adjusted to make it stronger. In addition, opening and closing was simplified by attaching a wire to it and the height was slightly adjusted, so that the ardusimple had less room to move. The so-called crankbaits remained, but were slightly reinforced. The final result is shown in Figure D.1.

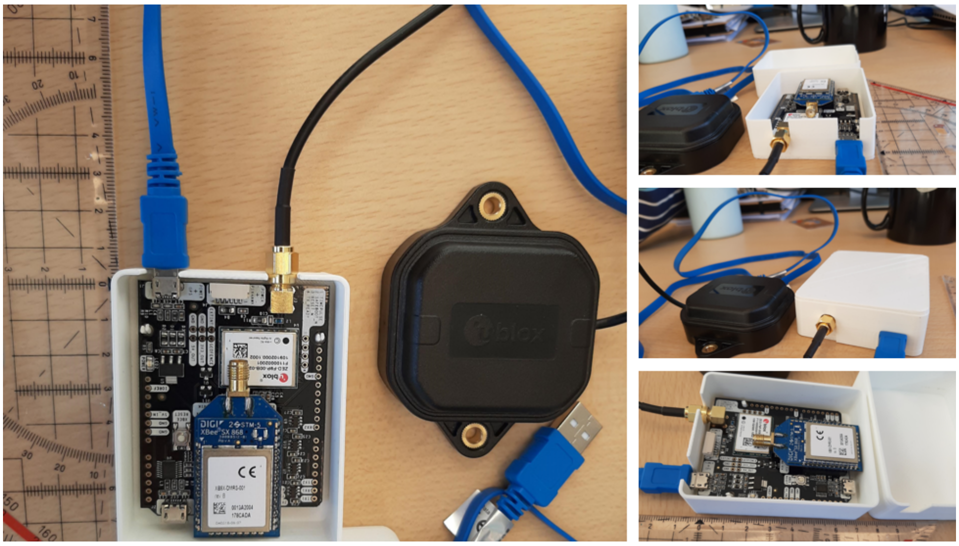


Figure D.1: Casing for the GNSS receiver.

E

Research day poster

On 9 October 2019, in collaboration with the Geoscience and Remote Sensing and Water Management Department, a research day was organised. In order to present my research there, as a textbook example of the collaboration between these two departments, I made a poster, which will be presented on the next page.

Community mapped elevation through low-cost, dual-frequency GNSS receiver

K.N.E. van Dongen,
Dr. ir. C.C.J.M Tiberius, Dr. H. Winsemius, Prof. dr. ir. R.F. Hanssen, Dr. ir. R. Hut

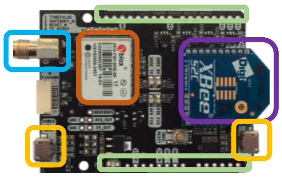
Introduction

Research focused on the **vertical and horizontal positioning performance** of the u-blox ZED-F9P and how this GNSS sensor can be practically setup in **context to Ramani Huria's project of community mapping in** Dar es Salaam.

Research motivation

Dar es Salaam suffers from devastating floods that destroys (public) buildings, may even result in deaths. The damage these floods cause, could be -partly-prevented using hydrologic models,. **These models require accurate mapping** data of roads, streams, floodplains and residential areas, for which a low-cost, dual-frequency GNSS receiver may be the solution.
Ramani Huria creates maps of Dar es Salaam with community members, and not only maps the city, but also it's communities.

Equipment



Methodology

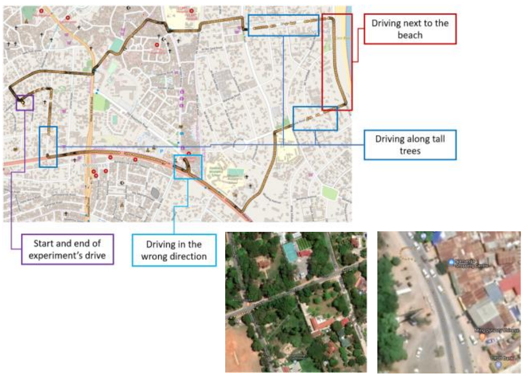
RTK and PPK Experiments conducted with different variables; movability, location, baseline, high- or low-end antenna and choice of software.

For case study aspects; interviews, workshop and a brainstorm

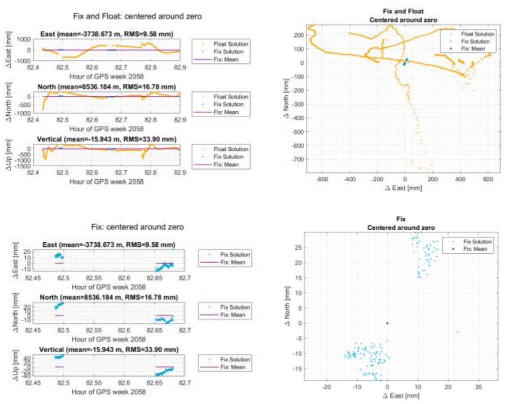
Results

Dar es Salaam, Tanzania

Kinematic experiment

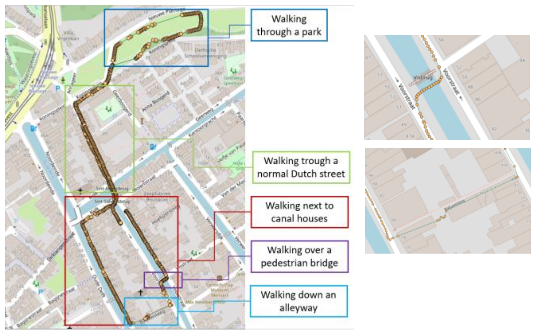


Static experiment



Delft, the Netherlands

Kinematic experiment



Static experiment