Rainfall Analysis through GPS SNR data in Uganda and The Netherlands

Additional Thesis

E.J. Roosenbrand

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Additional Thesis

by

E.J. Roosenbrand

in partial fulfillment of the requirements for the degree of

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Preface

This additional thesis was written as an elective of my master program Geoscience and Remote Sensing at the Delft University of Technology. As a second year master student you are given the choice within this elective to do an internship, courses at the university or do an additional thesis.

I chose to do the latter, primarily because I wanted to get more experience fully immersing myself in a research project for an extended period of time. This would give me a inside and detailed look into the academic research world, which I am interested in light of continuing my university career after my master, in the form of a PhD. Besides this factor the additional thesis, as the name suggests, would also prepare me for my master thesis at the conclusion of my master.

Another significant benefit of doing an additional thesis was the prospect of doing this abroad. I had never been to a developing country for an lengthy period of time and thought it would be an en enlightening and authentic experience which could teach me a lot. Especially considering that I would be setting up a research project and organizing most things on site, since little can be predetermined beforehand.

This project would not have been possible without the help of Prof. dr. Nick van de Giesen of the water resources management department at the Delft University of Technology, who helped us set up a large part of this additional thesis. I would like to thank him for the opportunity of doing a project in Uganda and all his help throughout the project. I would also like to thank Dr. ir. Sandra Verhagen for the very helpful advice and guidance during the processing and report writing. Additionally, I would like to thank Ass. Prof. Florence Mutoni D'Ujanga and Ssenyunzi Richard Cliffe for all their help in Uganda, who were always available and happy to help us logistically and with all other questions.

E.J. Roosenbrand
Delft, May 2019

Contents

Abstract

Gathering accurate and reliable precipitation data is essential in developing countries, since it applied to a wide range of applications, from improving short term weather models to global climate change research. The most common way of acquiring rainfall measurements is the rain gauge. However, this traditional measurement equipment requires frequent visits from researchers, due to the clogging risks as well as the risk of being easily tampered with by unauthorized people. This makes it impractical and expensive to create a extensive network of these rain gauges, whilst the demand for the precipitating data remains high.

A measurement equipment type which is more suitable for this remote and independent requirement for precipitation measurement in developing countries is GPS, since an aspect of GPS measurements is the possibility to use the equipment in relatively remote conditions, with little human interference necessary. In addition to this, due to the nature of GPS measurements, rain is expected to be an important component in GPS data, as a disruptive to the signal, a variable found in the Signal-to-Noise ratio (SNR). Considering the above, GPS seems like a good alternative to the traditional rain gauge for precipitation measurements. During this additional thesis, the question whether GPS can be used reliably for precipitation data, will be answered.

During a measuring campaign in Uganda from September to November in 2018, GPS data was gathered near precipitation measurement locations from TWIGA's School-2-School initiative. For the processing, graphs of the SNR and precipitation of the same days and locations were created and were visually inspected to see if a relationship or correlation was present. From these graphs this relationship between SNR and precipitation was not immediately clear.

The nature of the SNR can be caused by a multitude of reasons and variables and unless the correlation is very strong between variables, this correlation will not be very clear from just a visual inspection of these SNR and precipitation graphs. To untangle these variables, correlation matrices were used, where the variables can be looked at in pairs and instead of as quadruplets (or more). From the correlation matrix of the Ugandan data is is clear that correlation between precipitation and SNR is not significant, as it is similar to the correlation with a randomly generated variable. A slight correlation is present, however, with the GPS elevation angle.

During processing, data from Cabauw (the Netherlands) was used as an extra data set to compensate for the small amount of rain in the Ugandan data. This processing followed the same procedure as was applied with the Ugandan data; visual inspection of the SNR and precipitation graphs and generating a correlation matrix. In the Dutch data the relationship between the SNR and the precipitation was still small, however, larger than in the Ugandan data. Nonetheless, the correlation between the SNR and the elevation was very strong.

In conclusion, from both the Ugandan and Dutch data, the correlation between precipitation and SNR is not strong enough, or in other words, using GPS data to approximate rainfall, is not achievable using the methods applied and resources used during this additional thesis.

1

Introduction

As stated on the title page, this additional thesis was performed under the umbrella of TWIGA; Transforming Water, weather, and climate information through in situ observations for Geo-services in Africa. The project has received generous funding from EU's H2020 Research Innovation program.

In the grant application the aim of the project is stated:

> *The project aims to provide actionable geo-information on weather, water, and climate in Africa through innovative combinations of new in situ sensors and satellite-based geo-data.*

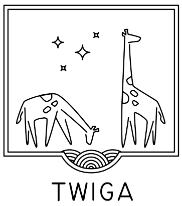

Figure 1.1: The TWIGA logo.

A nice aspect of GPS measurements is the possibility to use the equipment in relatively remote conditions, with little human interference being necessary. Each type of frequency equipment has its own benefits; the single frequency receiver functions on battery power and can thus be placed in remote areas, since a power socket is not needed, while a dual-frequency receiver, once plugged in to a power socket can be kept there for months, with the occasional check up, of course.

Contrast this low maintenance equipment with rain gauges, a common tool used in developing countries for precipitation data. These rain gauges require much more frequent visits from researches than the GPS equipment, due to the clogging risks as well as being easily tampered with by unauthorized people. This would make using GPS equipment as a type of rain gauge more beneficial to developing countries in providing precipitation data. Besides being able to improve short term weather models with this precipitation data, this data is also essential for climate change research. The potential in these two research fields are inhibited by the unreliability of the rain gauges.

In the traditional use of GPS data, for example exact positioning of a location, water vapour in the atmosphere (which is more prevalent during rain periods) causes errors, which influence the result of the positioning. This is called a wet delay. So due to the nature of GPS measurements, rain is an important component in GPS data. This will be further explained in the theoretical background chapter. Paradoxically, for the purposes of precipitation research this error is not the problem, but the solution. By looking at the entire estimation of the error in the position, precipitation data could be recovered. However, for this to work, the correlation between water vapour (and thus rainfall) and GPS data would need to present. Assessing whether rain may affect the signal-to-noise ratio will be analyzed in this thesis and fits in well with the aspirations and goals of the TWIGA project mentioned above.

The research was performed from the 5th of September till the 1st of November in and around Kamapala, Uganda. This period of time coincides with the rain seasons, which take place from March till May and October to November [1]. In light of the goal of the research being related to precipitation, this was an fitting time frame.

1.1. Measurement Equipment

Three dual-frequency receivers Trimble 5700 GPS receivers were used, which measure every 15 seconds. The dual-frequency receiver's measurements were stored on a SD card which could be read out through a UNIX computer operating system.

Dual-frequency receivers are a relatively sensitive and delicate measuring equipment. Due to the different error sources and noise in the data, it is required that the GPS receiver should be at the measuring site for a significant amount of time (several hours), in order to allow the filtering to converge for data processing. Besides this, a full 24 hour of measuring is favourable to perform, to see day/night effects. In practice, this means in the most efficient time-line of a dual-frequency receivers measurement campaign is three days of setup; the first day setting up the dual-frequency receivers allowing for stabilization, second day allowing the equipment to measure and log the data, and finally on the third day retrieving and disassembling the equipment. This could potentially make doing an efficient setup with a limited amount of time problematic and difficult, but luckily the dual-frequency receivers can be plugged into an electrical power socket, to provide the equipment with sufficient battery life. This way the measuring and logging of the data time period can be extended to overlap with the other equipment being set up, this way at some point they all measure at the same time.

With weather predictions being unreliable in Uganda, this causes difficulty when trying to measure rain. Since it is unclear when it will rain and measurement set-ups need to be prepared well in advance, one has little control over if rain is present on the measuring days.

1.2. Location Selection

The security and safety of the costly equipment is an important constraint to location selection. Preferably the locations would be in guarded and fenced secure sites, with the equipment itself being difficult to access directly (either high on rooftops or not being easily visible from the ground). In Uganda a sites which meet these requirements are schools, universities, government buildings or private homes of acquaintances and colleagues. The wish to keep the equipment safe high from the ground concurs with GPS stations, ideally, having an open sky above them. This is to avoid unnecessary multipath errors. This will be further explained in the Theoretical Background chapter.

1.3. Data Processing Software

After the measurement rounds had been completed the equipment was gathered and the data read out through the dual-frequency receiver's SD card. Once the data is made ready for processing on the computer, by converting the data to RINEX files. A step by step explanation of how this is done, can be found in the Appendix.

Maps throughout the report were made using QGIS software. Data analysis and graphs was done using Matlab software.

1.4. Research Questions

The research question of this additional thesis is:

> *Does rain affect the signal-to-noise ratio of GPS measurements to an extent where signal-to noise ratio data can be used to predict precipitation events?*

To answer this question, smaller questions need to be answered first, which will allow us to answer the bigger research question better; so called sub-questions. These sub-questions will form the structure and guideline of this thesis. The sub-questions are as follows:

1. Which aspect of the GPS data could be used to generate precipitation data?
2. What steps need to be taken to go from raw GPS data to precipitation data?
3. Is this reliable enough to substitute for rain gauges?

2

Theoretical Background

In order to make a connection between precipitation and GPS data, the nature of the GPS should be discussed, as well as what aspect of the GPS data could be used to generate precipitation data. This will be done in this chapter. Besides this, the basics of GPS will be explained and the errors present in the data will be discussed.

2.1. The Principal of GPS

GPS stands for Global Positioning System, which gives an insight to what the system is used for. Simply put, GPS is a system comprising of many satellites in orbit and stations on the earths surface. Each of the satellites in orbit are equipped with an atomic clock, which is very precise, and these satellites are continuously emitting this time information in radio waves. The ground stations then receives this time information from multiple satellites. Having it's own exact clock, the ground station can then deduce where the satellites are located, as well as where the ground station itself is located. A minimum of four satellites must be 'visible' from the receiver for it to be able to determine its location. This way GPS can be used as a positioning system over the entire globe. This four satellites effect can be seen in figure 2.1.

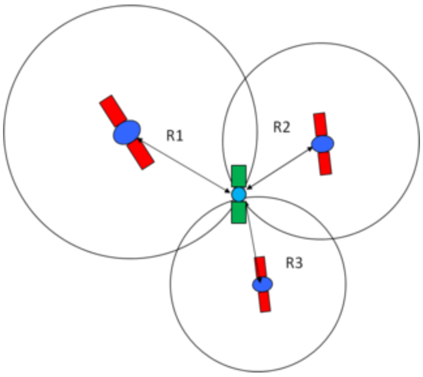

Figure 2.1: GPS system diagram [3]

However, during the long journey this emitted signal by the satellite, complications can arise when the signal is blocked or does not go directly to the receiver. The latter is called multipath, and occurs when the signals are reflected by obstacles such as high buildings or trees. That is why minimizing the multipath is an important factor to consider when determining GPS set up location. The mitigating steps taken to minimize the multipath during this research are discussed in Chapter 3. Nonetheless, this multipath is still registered by the receiver and present in the data.

2.2. Measurement Errors and Signal-to-Noise Ratio (SNR)

Measurement errors in the GPS data can have two sources; receiver noise, which affects the resolution of the measurement, and multipath, which introduces interfering signals which change the phase being measured. The multipath error of the data is considered noise when GPS data is used for positioning, since it contains little useful information. This leads to the next important term, the signal-to-noise ratio (SNR). This is defined as the ratio of the 'meaningful signal' to the 'unwanted signal'. However, the definition of what is noise and what is signal is subjective and related to the purpose of the GPS data is being used for. For the purposes of this thesis, the rainfall errors causing the multipath is the signal of interest, however during positioning estimations this would be considered noise.

Receiver noise is unrelated to the signal and introduces by the antenna, amplifiers, cables, and the receiver. The receiver 'sees' a waveform, which is the sum of the GPS signal and randomly fluctuating noise. This leads to the fine structure of the signal being masked by noise, especially with a low signal-to-noise ratio. The measurement error due to receiver noise varies with the signal strength, which in turn varies with the satellite elevation angle.

Simply put this elevation angle effect is caused the path length of the signal through the troposphere increasing significantly at low elevation angles. When a satellite is at the zenith, directly above the receiver, the troposphere delay of the signal from the satellite is minimized. However, when a satellite is close to the horizon, the troposphere delay of the signal is maximized. These two situations are illustrated in figure 2.2. During the day, the satellite rises and then descends in the sky. This means a change in elevation angle and thus SNR throughout the day. So during the day, the trend of the SNR first increases and decreases afterwards, to subsequently increase again. From P. Misra and P. Enge's Global Positioning System [6], a good 'cutoff' point for our purposes of the elevation angle was determined to be around 20°. This means that elevation angles below this 20°have too low or unreliable SNR values, to be of use for our research purposes.

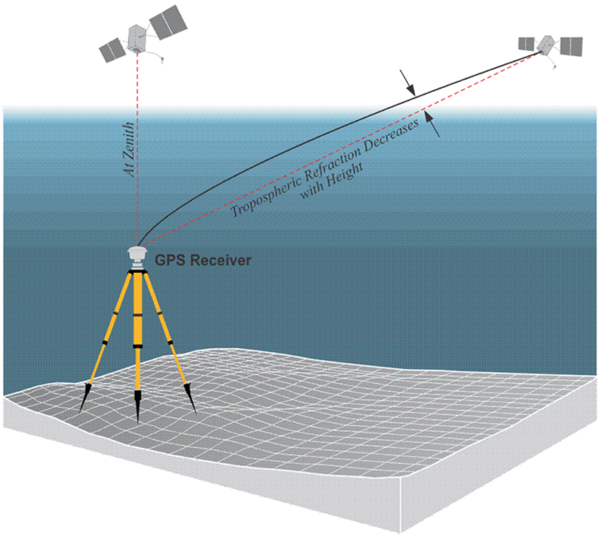

Figure 2.2: Elevation angle effects on signal path length [7]

Besides the errors caused elevation angle, another cause for measurement errors is multipath. Multipath is a phenomenon where the signal reaches the antenna via multiple paths. Besides a direct signal, the antenna receivers multiple reflections from structures in it's surroundings and from the ground. This reflected signal is delayed and typically weaker then the direct signal. The size of the measurement error caused by multipath, are dependent on the strength and the delay of the reflected signals.

The simplest way to mitigate measurement errors from multipath effect, takes place in an early phases of the measurement campaign, namely, the equipment location and set-up. The steps taken to prevent the multipath during the measurement campaign are discussed in the Chapter 3. Giving a slight preview to Chapter 3, the measurement locations and set-up was done so as to minimize the multipath from structures in the vicinity of the antenna. This leaves mainly multipath reflected by the ground. This leads to a link between precipitation and SNR.

Rainfall will cause moisture in the soil which increases the reflectively of the soil's surface, leading to more reflected signals, more multipath and thus a lower SNR. Besides this predictive indicator, the water vapour content in the atmosphere will be higher before the rainfall occurs, which would also provide a predictor. For this thesis we will be looking for a decrease in SNR before,during or after rainfall, due to increase in reflectively of soil due to water (after rainfall) and increased water vapour content in the atmosphere (before rainfall).

To be able to determine whether precipitation can be detected from SNR data, varying noise and errors unrelated to the precipitation should be removed. As discussed in this chapter, a lower elevation angle means the signal takes a longer path to the receiver, which means the signal will encounter more precipitation along the way, as well as encountering more 'noise'. This is why the cutoff point mentioned in this chapter of around 20°will be used in order to remove this noise. However, the increased reflectively of ground after rainfall as well as an increased water vapour content in the atmosphere, both provide a strong link to precipitation.

3

Method

In the two month period from the beginning of September to November 2018, two measurement rounds were performed. In this chapter both of these measurement rounds will be described, as well as the prerequisites necessary for achieving qualitative results.

3.1. Ideal measurement setups v.s. reality

An important caveat for this chapter is that the measurement setup was developed for another research project, namely, *Ionospheric Errors in GPS, Measuring and modelling the ionospheric delay using single and dual-frequency receivers in Uganda by Kathelijne Beenen.* Fortunately, precipitation data from the TAHMO School-2-School project was available at a few of the locations with the dual-frequency receivers, this was entirely by chance, rather than by design. If the measurement setup would have been exclusively for the purposes of this research project, the setup would have been more simple. Namely, only dual-frequency receivers would have been used, since these would give the best chance at seeing any differences in the SNR during precipitation, due to their higher accuracy compared to single frequency receivers, especially when the measurement takes place over a larger period of time and the dual-frequency receivers are allowed to settle.

In the ideal measurement setup for this research project, the three dual-frequency receivers would have spent a month at Makerere University (Dual 1), Ndejje High School (Dual 2) and Richard's Home (Dual 3). The next month the Makerere University (Dual 1) would remain in the same place, and Dual 2 and 3 would be moved to Bugema University and Entebbe Airport, for example (permitted that these locations have agreeable measurement set-up locations with little multipath errors possible and the GPS receivers are not easily tampered with). Basically, the dual-frequency receivers would have been placed at locations with the following attributes;

1. School-2-School precipitation measurements available for that location
2. Possibility for the equipment to stay for a longer period of time (more than 3 weeks), which allows for the GPS to settle, giving more reliable results, and allowing for comparisons between precipitation intensity for the same location
3. At safe and open-sky locations

The rest of this chapter will explain the actual measurement-set up and the reasoning behind this set-up. As mentioned above, this elaborate setup of single and dual-frequency receivers within a triangle area was not necessary for this research projects purposes, but for another research project *Ionospheric Errors in GPS by Kathelijne Beenen.*

3.2. Location Requirements

As mentioned in the introduction and the theoretical background chapters, one necessity concerning the setup is to keep the equipment safe high from the ground and having an open sky above them, to avoid unnecessary multipath errors.

The positional set up of the equipment is a triangle, with the dual-frequency receivers functioning as the

edges of the triangle, and filled with a smooth distribution of single frequency equipment, to be able to perform a qualitative interpolation.
Besides this, certain other requirements should be met to ensure correct measurement results. One of the most important prerequisite regarding the placement of the dual-frequency receivers is to ensure they have 10 km between them on each leg of the triangle the three dual-frequency receivers form together.
In this research project two of the three dual-frequency receivers were kept stationary, because the measurement site were secure, relatively tree-free (to assure an open sky look) and beneficiary location wise; these two dual-frequency receivers, were located on a north-south line and provide the option for the third dual-frequency receivers to be placed on the western or eastern side of this north-south line. The stagnant nature of these two dual-frequency receivers make meeting the 10 km vertices on a triangle requirement simple; since the two stationary dual-frequency receivers are already positioned as such, only the third and final dual-frequency receivers has to be positioned. So both rounds of measurements were based around the two stationary dual-frequency receivers; one located atop the Zoology building of Makerere University in Kampala and the other at Ndejje High School, 30 km north of Kampala, thus comfortably complying with the 10 km vertices rule.

For the first round of measurements these two stationary dual-frequency receivers were used and the third was placed at the home of PhD-er Ssenyunzi Richard Cliffe. This is around 15 and 30 km from the Zoology faculty and Ndejje High School, respectively (again complying with 10 km vertices). The campaign was started on 20th of September 2018 with the placement of the first dual-frequency receiver. Various suitable sites are located within this triangle of dual-frequency receivers, which were used as location for the single frequency equipment. A map of the locations used for round one can be found in figure 3.1.

Two of these single frequencies were placed in relative proximity to dual-frequency receivers equipment in the first round of measurements. The first being at the home of Mr. Cliffe, where a single frequency was placed at approximately 8 meters from the dual-frequency receivers. The second instance concerns a single frequency being placed around one kilometer from the Zoology faculty at Makerere University. This was done as a test to check the accuracy of the single frequencies compared with the more reliable dual-frequency receivers, which was a goal for the *Ionospheric Errors in GPS* research project by Kathelijne Beenen.

The second round of measurements again used the two stationary dual-frequency receivers as described before, as well as the third dual-frequency receivers placed at Wayenga Girls School, which is located near Jinja, around 80 km from Kampala and 60 km from Ndejje High School. Again, easily complying with the 10 km vertices rule, described before. The measurements were carried out on the 24th of October 2018.

Numerous suitable locations are positioned within this triangle of dual-frequency receivers, which were used as location for the single frequency equipment. A map of the locations used for the second round can be found in figure 3.2 . Unlike the first round, single frequencies were not placed close to the dual-frequency receivers, as to get a nice distribution of single frequencies within the triangle, to obtain a qualitative interpolation.

3.3. First measurement round

The first round covered an area relatively close to Kampala (capital of Uganda), covering an area of approximately 230 km ^{2}. An overview map of the locations of the dual and single frequency receivers for round one can be found in figure 3.1. The goal for the first measurement round was to achieve a successful measurement set up and set up multiple single and dual-frequency receivers in close proximity (less than 1 km) to one another. This was done in order to check the accuracy of the single frequencies compared with the more reliable dual-frequency receiver.

Since the dual-frequency receivers are able to have a constant power supply and thus can work longer periods of time unsupervised, it was decided to set up the dual-frequency receivers first and later set up the single frequency receivers. One of the three dual-frequency receivers was placed on the roof of the Zoology faculty on the campus of Makerere University on the 18th of September 2018. This was close to our residence in Kampala, so it was easy to check up on. Due to its central location and proximity to our residence, it was decided that this dual-frequency receivers should be kept stationary throughout both rounds at this site as well as be used as our reference station.

The second dual-frequency receivers was placed at Ndejje High School, which is around 30 km north of Kampala, on the 19th of September 2018. Due to the quality of the measuring site (open sky and secure area), it was decided that this dual-frequency receivers should be kept stationary throughout both rounds at this site as well. This allowed the option of placing the third and final dual-frequency receiver either to the west or east of the north-south line. Also this assured that the receivers are settled down, which gives a reliable measurement.

Since the single frequency receivers can only run for a limited amount of time (around 60 hours), it is necessary to dispense all five on the same day and have the following day be the data logging day. On the 22th of September 2018 all 5 single frequencies were distributed over the area of interest, as well as the third dual frequency, since it was at the same site (Richard Cliffe's residence) as one of the single frequencies.

As stated before, the single frequency receivers must all be dispatched in one day. One single frequency receiver was placed at our personal residence, around 0.5 km west of the reference station (the Zoology faculty). The second single frequency receiver was placed at Migadde High School, around 22 km north of the reference station. The third single frequency receiver was placed at Buloba, around 10 km west of the reference station. The forth single frequency receiver was placed at Onwards and Upwards High School, around 12 km west of the reference station. The fifth frequency receiver was placed at Richard Cliffe's residence, around 14 km west of the reference station, as well as being around 5 m away from the dual-frequency receiver placed at the same site.

On the 23th of September 2018 The single frequencies were retrieved on 19th of September 2018. After reading out all of the data of both single and dual-frequency receivers, it was concluded that no equipment failure had occurred and all receivers had functioned properly.

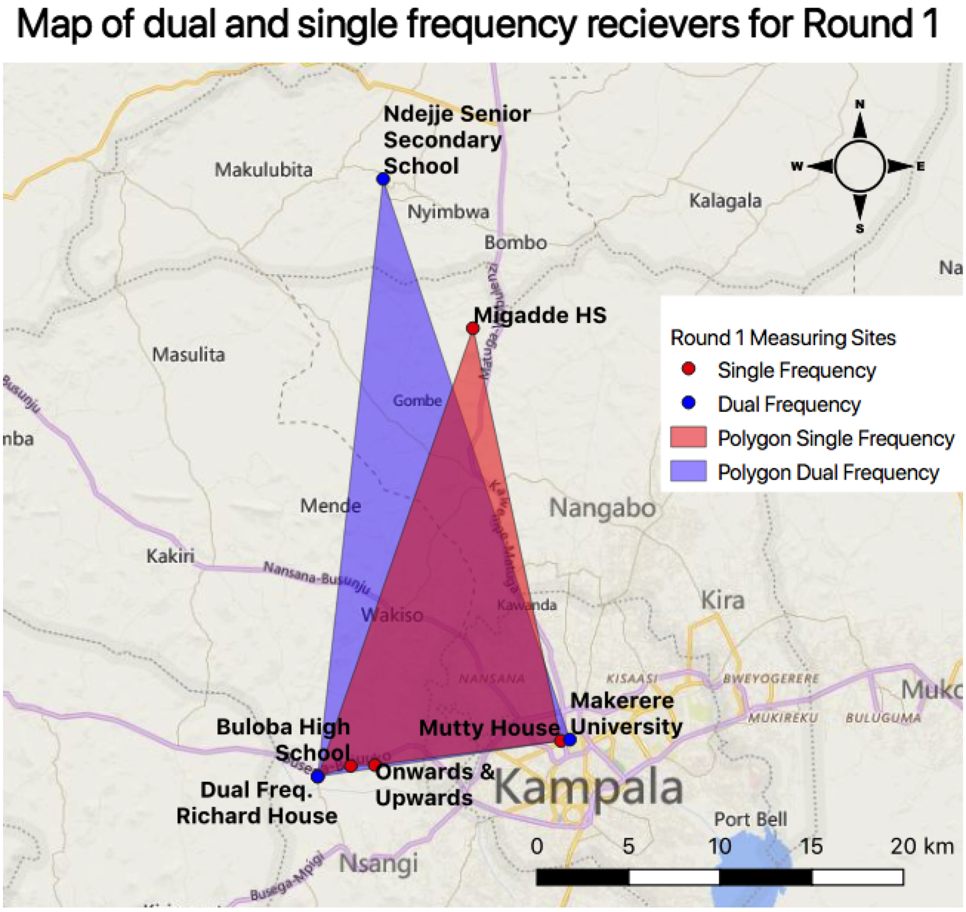

Figure 3.1: Map of dual and single frequency receivers for Round 1

3.4. Second measurement round

The second round covered a larger area between Kampala and Jinja (city 80 km to Kampala) , covering an area of approximately 1.2000 km ^{2}. An overview map of the locations of the dual and single frequency receivers for round two can be found in figure 3.2. During the first measurement round, the local rain radar [2] was checked and it was determined that little to no rain fell at the measurement site. In our second measurement round, our goal was to get at least some precipitation at multiple measurement sites. We noticed during our stay that several days before a thunderstorm or rain occurred the weather was relatively calm with little to no rain. Only the day before rainfall signs of turbulent weather would show. Using these telltale signs, the date of the single frequencies deployment was determined, to maximize the chance of precipitation measurements.

As stated before, two of the three dual-frequency receivers were stationary throughout the two rounds, at the Zoology faculty on the campus of Makerere University and Ndejje High School. When collecting the data of the first measuring round the equipment was checked and seemed to be working well. The memory cards were emptied and placed back in the equipment. The Zoology building was checked once again before the second measuring round, but due to the time necessary to reach Ndejje this equipment was not checked again before the second measuring round.

This left only the third dual-frequency receiver to be set up for this round. After searching at multiple locations for a suitable place to set up the dual-frequency receiver (clear sky view, stable and relatively flat surface) the Wayenga Girls School near Jinja was determined to be the best option. This is located around 80 km east of the reference station (the Zoology faculty).

As in round one, the single frequency receivers were all dispatched in one day, 23th of October 2018. One single frequency receiver was placed at World Ahead High School, around 17 km north of the reference station. The second single frequency receiver was placed at Gayaza High School, around 15 km northeast of the reference station. The third single frequency receiver was placed at the personal residence of a staff member of the Dutch embassy, around 4 km east of the reference station. The forth single frequency receiver was placed at the TAHMO headquarters of Kampala, around 7 km northeast of the reference station. The fifth frequency receiver was placed at Uganda Christian University (UCU), around 20 km west of the reference station.

24th of October 2018, was the measuring day and the single frequencies were retrieved on 26th of October 2018. When retrieving the dual-frequency receivers at Ndejje High School, it was discovered that the equipment had stopped logging data three days after our last check from round one. So it had not been able to record any data during measurement round two. After reading out all of the data of both single and dual-frequency receivers, it was concluded that no other equipment failure had occurred and all receivers had functioned properly, besides the dual-frequency receiver at Ndejje.

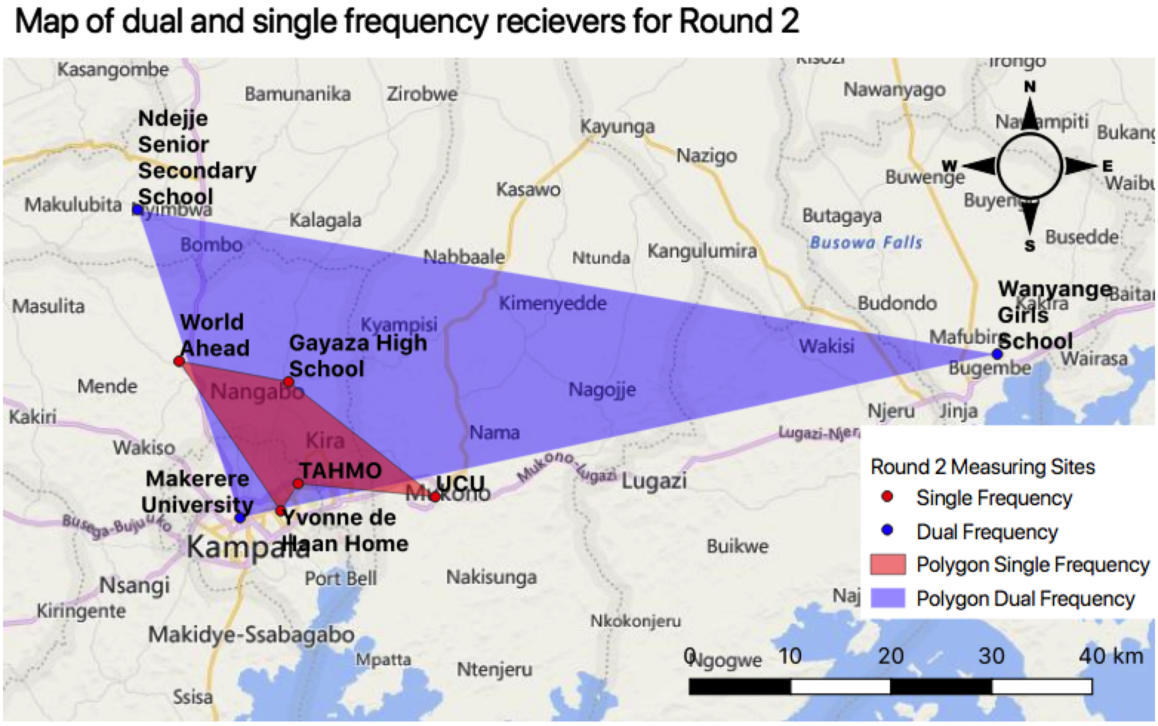

Figure 3.2: Map of dual and single frequency receivers for Round 2

4

Processsing

For the entire error estimation of the error in the position, which will lead to the precipitation data, the SNR, azimuth and elevation need to be determined. All these terms are discussed and explained in the Theoretical Background chapter. To get this data first some steps of processing need to be taken. In this chapter this procedure is detailed.

4.1. Data Conversion

Before any processing or displaying of data can be done the GPS data first needs to be converted to the .t01 files from the SD card, to a file format that Matlab can process, since this is were the processing will take place. The .t01 files were downloaded to the computer through reading out the SD card in the GPS devices. Using the ConvertToRinex programme [11], Rinex files are generated from the .ubx files. Before this conversion, however, the programme has to be set so the Rinex files include SNR Data. This is done by switching the 'Log SNR observations' control from `False` to `True`, after uploading the .t01 file. This way Rinex files (.18o files) containing SNR information from the original .t01 data were acquired.
To generate a Matlab-readable with the SNR, azimuth and elevation; the GLONASS, SBAS and Galileo have to be removed beforehand with teqc.exe from the RINEX files by running the command in the command prompt:

```
teqc.exe-R-E-SRinex_file.18o>new_Rinex_file.18o.
```

After running this command, the SNR data should be extracted using the RinexSNRv2.exe command from Professor Kristine M. Larson at the University of Colorado Boulder [10]. Before running this command, the broadcast navigation files from that day are needed. These were downloaded from `ftp://cddis.gsfc.nasa.gov/gnss/data/daily/` for each of the measuring days. The correct file can easily be found by the file name: YYYY/DDD/YYn/brdcDDD0.YYn, with YYYY being the full year, DDD being the day number, and YY being the abridged year. So for example the 23th of September 2018, the file would be 2018/267/18n/brdc2670.18n, since its the 267th day of the year. After getting this broadcast navigation file for the data day, this command can be run in the command prompt as well:

```
RinexSNRv2.exenew_Rinex_file.18oSNR_file.txtbrdc_file.18n99
```

The output file will give columns with; satellite number, elevation angle (deg), azimuth angle (deg), seconds of the day, east and north multipath reflection points for a 2 meter antenna, S1 values (db-Hz), S2 values (db-Hz).

4.2. Precipitation Data

The precipitation data needs to have a high frequency, ideally around the second mark, similar to the GPS data. Through suggestions from Prof. dr. ir. N. van de Giesen a contact with School-2-School [5] was made. The School-2-School initiative from TAHMO, who monitor and analyze on-site climate and weather data. Their precipitation data has a frequency of 5 minutes, so every 5 minutes precipitation is measured in mm. Precipitation data was only available for certain locations; Wanyange Girls School, Ndejje Senior Secondary

School and Makerere University. The locations of the precipitation measurement equipment are in the vicinity of the locations of certain dual-frequency receivers that were distributed for the purposes of this thesis.

4.3. Data Calculations

In the Appendix 7.2, the full Matlab code of extracting the data can be found. The step that needed be taken to extract SNR data from the .18o files, will be discussed concisely here. First the .18o file was imported to Matlab. After which, the main header and the time interval headers should be removed, this is in order to get an uninhibited list of just SNR data, without the satellite and time headers for each second of measurement. Subsequently, these time headers were edited to plot the time series better for analyses. Then the precipitation data for the corresponding date and location as the GPS SNR data, was imported as well. Finally, both the precipitation (mm/5 min) and GPS SNR (dB - Hz) data are plotted throughout the measurement day. This way correlations in SNR and precipitation can be seen.

4.4. GPS and Precipitation data from the Netherlands

In order to make the conclusion on precipitation and SNR more robust, data from the Netherlands was also analyzed in a similar method as the Ugandan data. Since the rain patterns in either country are quite different, Ugandan rain taking the form of explosive bursts, while Dutch precipitation takes a more gradual and abiding form. This contrast could potentially make the conclusion stronger.

GPS data was downloaded from the Dutch Permanent GNSS Array website [8]. The processing of this data was done through the *gunzip* and *crx2rnx* commands, also provided on the aforementioned website. Then the same *teqc.exe* command was run in the command prompt as with the Ugandan data. The graphs of the SNR data were created through a code, with contribution of Dr.ir. H. van der Marel at the TU Delft. This code can be found in the Appendix 7.3.

The Dutch Permanent GNSS Array website [8] supplies GPS data for multiple stations at various locations across the Netherlands. For the purposes of this thesis, the best data (location) to analyze should be near a location were precipitation was also reliably measured. For this the KNMI hourly data [9] was used, which provides trustworthy data on an hourly basis. It was decided to use the Cabauw location, since for this site both the GPS data and precipitation data are available and it is known that they are located at the same measuring site. In the following chapter, Results, this outcome of overlaying these to data sets will be displayed. In the 6th chapter; Conclusions and Recommendations, the differences and similarities between the two locations (Netherlands and Uganda) will be explored.

5

Results & Discussion

In order for GPS data to be able to be used for precipitation analysis, a relationship between precipitation and a GPS data feature should be found. As described in chapter 2, Theoretical Background, the expectation is that if precipitation occurs, the SNR will drop. To answer the question *Does rain affect the signal-to-noise ratio of GPS measurements to an extent where signal-to noise ratio data can be used to predict precipitation events?*, a potential relationship between precipitation and GPS SNR data will have to be present. In this chapter this is explored through graph analysis and correlation matrix discussion.

5.1. Combining GPS data with precipitation data

Only certain GPS measurements coincide with precipitation measurement locations, as can be seen in the tables 5.1 and 5.2. These locations for the 23th of September 2018 are; Makerere University, Richard Home and Ndejje High School. The locations for the 24th of October 2018 are; Makerere University, Ndejje High School and Wanyange Girls School. The Ndejje High School equipment failed during the 2nd measurement round, so cannot be used in the results.

Table 5.1: Measurement Round 1 (23th of September 2018)

Receiver number	Location	Comments	Precipitation data nearby (<1 km)
Dual 1	Makerere University	-	yes
Dual 2	Ndejje High School	-	yes
Dual 3	Richard Home	-	no

Table 5.2: Measurement Round 2 (24th of October 2018)

Receiver number	Location	Comments	Precipitation data nearby (<1 km)
Dual 1	Makerere University	-	yes
Dual 2	Ndejje High School	Data not logged	yes
Dual 3	Wanyange Girls School	-	yes

This gives us four locations with both precipitation and SNR data. The code used to generate this result, can be found in the Appendix 7.2 and is concisely explained in the section 4.3. In total, rain occurred on 17 days at these locations, so analysis can be preformed on 17 precipitation - SNR relations, of which several will be highlighted in this chapter.

5.2. Graphs GPS and Precipitation data

The file generated by the method described in chapter 4.1, sorts the SNR and elevation data by time. However, it makes more sense to track the data picked up by a single satellite throughout the day, since the general SNR of all satellites won't be reliable enough for this anaylsis. A typical graph generated by the code developed for this thesis can be seen in figure 5.1 . In the graph the SNR (dB - Hz), the moving average of the SNR (dB - Hz), precipitation (mm), elevation (°) and relative humidity (%), throughout a full day (visible in title) of a certain satellite.

As can be seen in the figure 5.1 , during the duration of the SNR data availability, the elevation is also available. A similar availability relationship exists between the precipitation and the relative humidity. However, no SNR data exists for the entire length of precipitation data. For example, in figure 5.1 no SNR data (black line) exists from satellite number 22, for the period in which the precipitation (orange line) takes place.

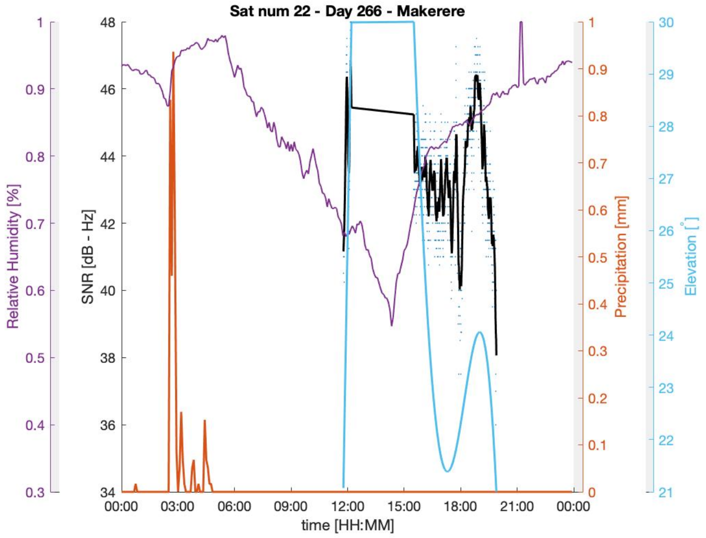

Figure 5.1: Example of SNR and precipitation graph, with SNR, precipitation, elevation and relative humidity.

As mentioned before, if any relationship exists between SNR and precipitation, the expectation is that if precipitation occurs, the SNR will drop. In the rest of this section several of the generated graphs will be evaluated.

In figures 5.2 and 5.3, the same elements occur as in figure 5.1. Immediately, the largest issue which will reoccur throughout this chapter, the differentiation between the effect of the SNR being related to a multitude of GPS characteristics, like elevation, or atmospheric conditions, such as precipitation.

One thing to take notice of is the unusual shape of the elevation curve in most of the figures. A typical elevation curve would have a ∩ shape, the satellite climbing higher in the sky throughout the day and later in the day the satellite descending in height. In the figures in this chapter, the elevation angle has more of an M shape, so the satellite going up-down-up-down in elevation, this is because the earth rotates in intertial space under the circular path of the satellite. This pattern has both been verified as correct and the reasoning has been provided by Dr.ir. H. van der Marel at the TU Delft.

In figure 5.2 fluctuation occur in the moving average SNR (black line) before and after the precipitation (orange line). The moving average seems more related to the elevation (light blue line), however. From this graph alone, the relationship between precipitation and SNR could not be confirmed, much less the the expectation that if precipitation occurs, the SNR will drop.

A different conclusion can be reached from figure 5.3, where the moving average considerably drops during precipitation. However, during the precipitation occurrence the elevation of the satellite also drops. Contrasting this with the elevation drop in figure 5.2, which is of a similar nature, that do not cause the same drop in SNR. This could be a potential indication that the SNR drop in figure 5.3 is due to the precipitation, however, the location and days are different, so it is not a robust statement.

Looking at figure 5.4, during the precipitation the SNR does not seem that impacted, however, two hours after the precipitation a SNR drop is present, although it seems more related to the following of the elevation drop by the SNR curve. Nonetheless, in figure 5.5 the SNR curve exhibits opposite behaviour, while the elevation of the satellite increases a drop in SNR occurs which coincides very well with the precipitation occurrence. However, it is counter intuitive that with the smallest absolute amount of precipitation has the largest effect on the SNR. This leads to the conclusion that the drop in SNR in figure 5.5 is most likely still largely due to the elevation variations over time or another unknown effect.

Note however, that the precipitation scale difference between figures 5.4 and 5.5. With all of the GPS and atmospheric graphs the maximum precipitation axis is kept constant at 1 mm. This is done to keep the precipitation amount in perspective, so as not to compare minuscule amounts of rainfall with large amounts. Since this expectation is that the SNR will be influenced more by larger precipitation quantities, than smaller precipitation quantities.

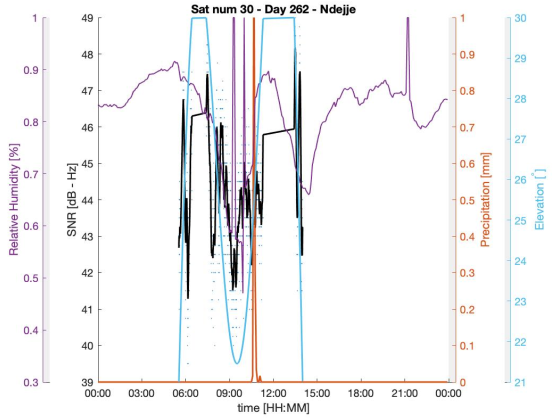

Figure 5.2: GPS and precipitation graph, day 262, Ndejje, sat. 30

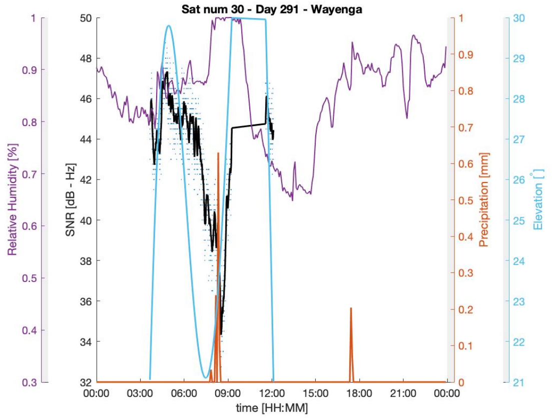

Figure 5.3: GPS and precipitation graph, day 291, Wayenga, sat. 30

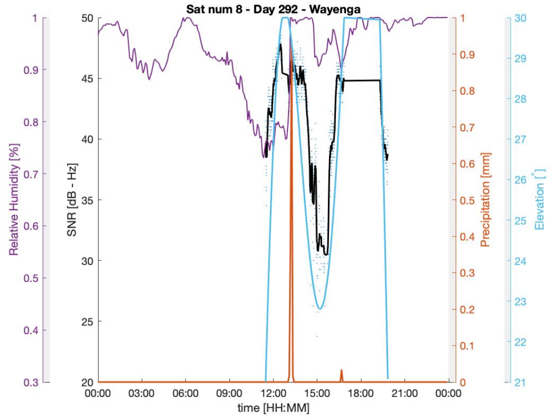

Figure 5.4: GPS and precipitation graph, day 266, Ndejje, sat. 4

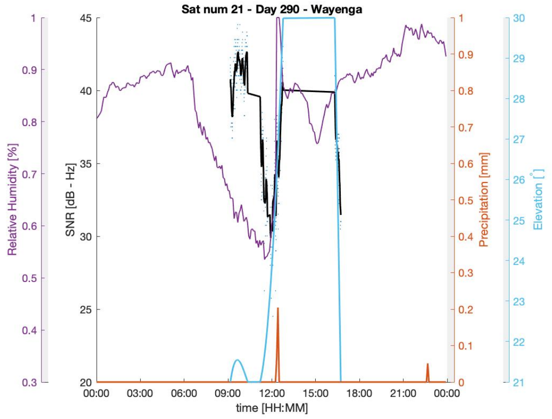

Figure 5.5: GPS and precipitation graph, day 290, Makerere, sat. 4

The 1 mm scale is based on the maximum amount of precipitation that occurred during the whole experimentation period. However, 1 mm rainfall is not very much, especially considering the field work was performed during the rainy season, in which the average rainfall is around 150 mm per month during the rainy season [13]. This averages to around 5 mm per day, which in practice should be more since the bulk of the precipitation falls on a day, followed by several days of drought, followed by a large quantity of rain again. To put this precipitation amount in perspective, in the Netherlands during the wettest month, December, the rainfall is approximately 100 mm per month [14].

This little amount of rainfall was unexpected and to compensate for this lower data quality, data from the Netherlands (Cabauw) was analyzed. Four dates with rainfall in January and February of 2019, 13$^{\text{th}}$ of January, 17th of January, 6th of February and 10th of February 2019, were selected, based on the relatively large amount of precipitation on these days.

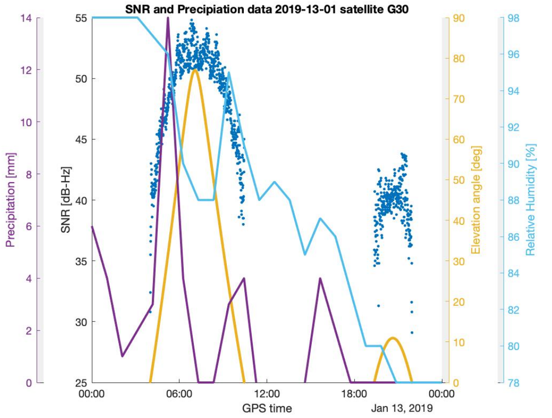

Figure 5.6: GPS and precipitation graph, day 262, Ndejje, sat. 30

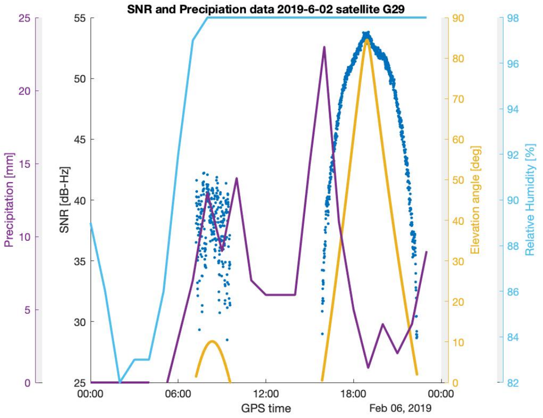

Figure 5.7: GPS and precipitation graph, day 291, Wayenga, sat. 30

For both figures 5.6 and 5.7, the precipitation does not seem to have much effect on the SNR, and as noted before, the SNR seems mostly to follow the elevation of the GPS, even more so than the Ugandan data from figures 5.2, 5.3, 5.4 and 5.5. The large precipitation peaks in figures 5.6 and 5.7 do not cause visible fluctuations in the SNR. Comparing figures 5.6 and 5.7 the SNR around the precipitation seems more scattered in figure 5.6, it could be due to the precipitation but similar precipitation shapes do not cause the scattered property of the SNR. The same satellite (31) flies over during two separate days in figures 5.8 and 5.9, the precipitation alterations do not have an effect on the SNR in this case.

Considering both the Ugandan and the Dutch data the conclusion is that the precipitation does not have effect on the SNR. However, it is still difficult to separate the effects of the various variables, especially from a visual analysis. In order to deal with this problem a correlation matrix will be used in the following subsection.

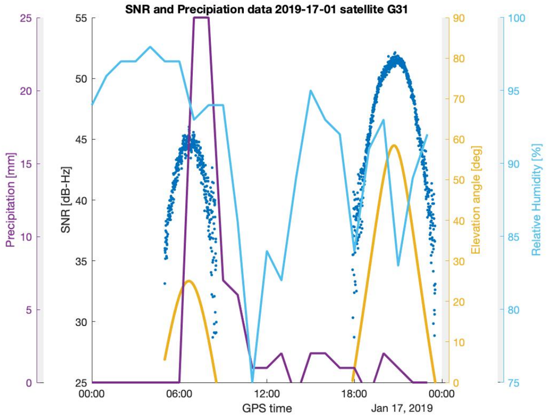

Figure 5.8: GPS and precipitation graph, day 266, Ndejje, sat. 4

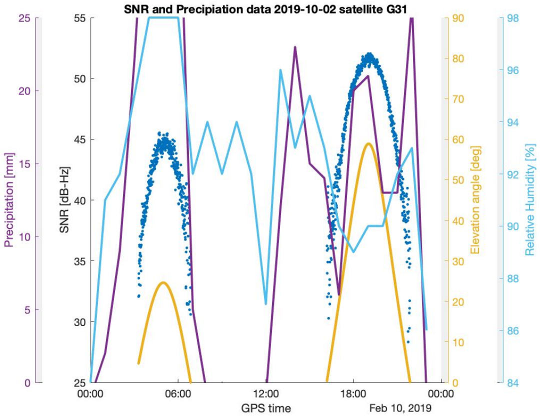

Figure 5.9: GPS and precipitation graph, day 290, Makerere, sat. 4

5.3. Correlation Matrix Analysis

An effective and efficient way of showing relationships between multiple variables is a correlation matrix, in which each cell in the matrix shows the correlation between two variables.

Using the Matlab function `corrplot` [12] figure 5.10 was generated from 7915 time elements, in which a matrix of 5 by 5 shows the correlations between pairs of the variables SNR, Elevation, precipitation, relative humidity and a randomly generated variable (with a normal distribution). Along the matrix diagonal histograms of the variables are visible, and scatter plots of variable pairs appear in the off diagonal. The slopes

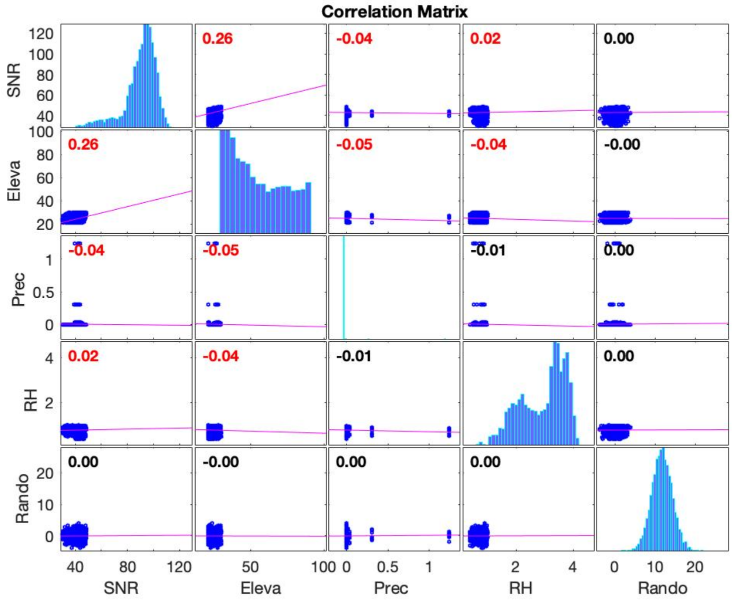

Figure 5.10: Example of SNR and precipitation graph, with SNR, precipitation, elevation and relative humidity of Ugandan Data.

of the least-squares reference lines in the scatter plots are the displayed correlation coefficients. When the variable pairs are uncorrelated, the line will have a slope close to zero. The closer the slope or correlation coefficient is to either 1 or 1, the stronger the correlation between the variables. The randomly generated variable was used to illustrate this effect, since the correlation with the random variable is always 0, by definition.

The problems encountered with the visual inspection of the relationship between SNR and precipitation using the graphs like in figure 5.1, are not present with a correlation matrix, since here the variables can be looked at in pairs and not as quadruplets.

Looking at figure 5.10, the correlations of none of the variables pairs is particularly high. The strongest correlation relationship is between the elevation and the SNR, which was seen in the visual analysis section as well. As described in chapter 2 Theoretical Background this relationship was expected. However, this seems to be the strongest relationship between all variable pairs.

Relative humidity is both a precursor and a result of rain and when it rains, the relative humidity will increase to 100٪. Yet, from correlation matrix in figure 5.10, this correlation between precipitation and relative humidity is not present. This correlation is not very obvious or clear in figure used in the visual inspection process either (figures like 5.1).

A correlation matrix was also made from the Netherlands data, and can be found in figure 5.11 in which the same variables SNR, Elevation, precipitation, relative humidity and the random variable were used. Comparing figure 5.11 to figure 5.10 the SNR and the elevation are most strongly correlated of all the variables, just like with the Ugandan data, moreover, the correlation is even stronger (0.82 compared to 0.26). This strong relationship is also visible in the figures 5.6, 5.7,5.8, 5.9. This is mostly because there is less noise in the data. The precipitation and relative humidity correlation for the Dutch data is also larger than the Ugandan data, however, still not large enough to be significant, and similar to the random generated variable.

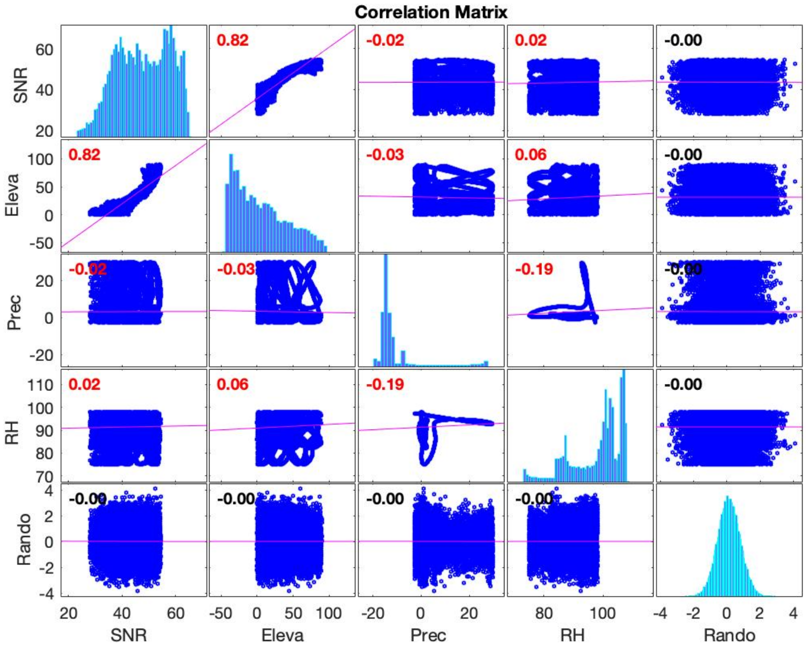

Figure 5.11: Example of SNR and precipitation graph, with SNR, precipitation, elevation and relative humidity of Netherlands Data.

6

Conclusions and Recommendations

In the previous chapters the research questions *Can GPS used reliably for precipitation data?*, has been systematically answered following the structure of the sub-questions provided in the Chapter 1. In this chapter the conclusion and recommendations will be given.

6.1. Conclusions

From observing the generated graphs (figures 5.2, 5.3, 5.4 and 5.5) with SNR and precipitation, no clear correlation or relationship was found between the two variables. From these graphs it was unclear if the relationship was 'purely' dependent on precipitation or that the elevation of the satellite was a stronger effect.
In order to make this less ambiguous, a correlation matrix was created, which showed small correlations between all the variables, but the strongest relationship is between the SNR and the elevation. However, little correlation exists between precipitation and SNR variables according to the correlation matrix, seeing as SNR has similar correlations with a randomly generated variable, precipitation and relative humidity.
To compensate for the relatively small amount of precipitation that fell during the field work, data from some rainy days in the Netherlands were analyzed. This was in order to ensure that the precipitation effect was strong enough to make a impact on the SNR. The same analysis method of visual inspection and a correlation matrix were performed as in the Ugandan data case. Just like with the Ugandan data the correlation between the SNR and the evaluation angle is the strongest.
Once again, however, little correlation exists between precipitation and SNR variables according to the correlation matrix generated from Dutch data (figure 5.11), although the correlation is stronger than the random variable and stronger than the Ugandan correlation matrix (figure 5.10). Just like with the Ugandan data the correlation is present, in fact even stronger. This strong relationship is also visible in the figures 5.6, 5.7,5.8, 5.9 and is is mostly because there is less noise in the Dutch GPS data. The precipitation and relative humidity correlation for the Dutch data is also larger than the Ugandan data, however, still not large enough to be usable as a predictor of rainfall.
So, from the measurements gathered in Uganda and the data used from the Netherlands, no strong correlation or relationship was found between SNR and precipitation from either visual examination of graphs and conclusions from correlation matrices. Further research could improve the result, and is therefore recommended, as will be discussed in the next subsection.

6.2. Recommendations

The biggest obstacle during the project was the locating of suitable measurement site, which took up a majority of time during the field campaign. Building trust and acceptance with decision makers of these sites was difficult, mostly due to misinformation, fears and bureaucracy. Because of the limited amount of time available for this project and the difficulty locating suitable measurement sites, only two measurement round were performed. Preferably, more rain-day data would be collected in further research.
Another difficulty during the project were the lengthy travel times from location to location. This played a part in the scheduling for setting up of the equipment and caused limitations distance wise for measurement locations. This also met that checking up on the dual-frequency receivers, to see if power supply was still sufficient and the storage card has sufficient space on it, was not possible as much as would have been

preferred. Ideally, the dual-frequency receiver set up would be monitored once a week. This way the defect that cause a problem in the second measurement round, would have been avoided.

Moreover the precipitation amounts which occurred during the measurement campaign was not of a caliber that it could sufficiently disrupt the SNR. If the measurement campaign were longer, the chance that more excessive and intense rainfall would be measured is higher and the chance of identifying a relationship between SNR and rainfall.

Additionally, the precipitation from the School-2-School [5] is on a 5 minutes scale, while the SNR data is on a 30 second time scale. Ideally, these time frames would be the same, to get better correlation results. The Dutch KNMI results are even more sparse, being hourly data, this data should also be more frequent.

Another issue related to the precipitation is that is is unknown how accurate the precipitation measurement from the School-2-School [5] network was. From observational and personal experience the rainfall occurred with a larger frequency and intensity than is reflected in the School-2-School data. In further research a more exact and dependable rain measurement device should be placed near the GPS equipment.

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7

Appendix

7.1. Convert T01 data to RINEX

Use the programme ‘Convert to RINEX’

1. Click on the dropdown menu ‘file’ and press ‘open’.
2. Select the files you want to convert.
3. Again, click on the dropdown menu ‘file’ and press ‘convert files’.
4. The converted files can be found in the same folder as the original files.

7.2. Ugandan data script

```
%% Script to plot SNR as function of time with elevation and precipitation
% Uganda
%%
clear all
close all

%% Select Location and Round
loc_all = ['mak'; 'way';'ndj'];
loc_sel = loc_all(3,:); %CHANGE HERE
doy_sel = 267;

%% GOOD DAYS
% mak_1 = 262, 264, 265, 266, 290, 292, 293, 294, 296
% way_2 = 290, 291, 292, 294, 296
% ndj_1 = 263,265,267

%% Importing the TAHMO Precipitation file
filename = sprintf('/Users/estherroosenbrand/Desktop/5_minutes_data/tahmo_%s_5minutes.csv',loc_sel);
delimiter = ',';
startRow = 2;
formatSpec = '%s%f%f%f%f%f%f%f%f%f%[^\n\r]';
fileID = fopen(filename,'r');
dataArray = textscan(fileID, formatSpec, 'Delimiter', delimiter, 'TextType', 'string', 'EmptyValue', NaN, 'HeaderLines' ,startRow-1, 'ReturnOnError', false, 'EndOfLine', '\r\n');
fclose(fileID);
```

```
table_data = table(dataArray{1:end-1}, 'VariableNames', {'timestamp','radiation','precipitation','lightningevents','lightningdistance','winddirection','windspeed','windgusts','temperature','relativehumidity','atmosphericpressure'});
clearvars filename delimiter startRow formatSpec fileID dataArray ans;

%% Select date
date_time = table_data{:,1};
date = datetime(strtok(date_time,' '));
doy_prec = day(date,'dayofyear');
table_data = [table_data table(doy_prec)];
index_find = find(doy_prec == doy_sel);
data_prec = table2array(table_data(index_find,3));
data_RH = table2array(table_data(index_find,10));
data_date = date_time(index_find);
prec_time = split(data_date,' ');
prec_time_plot = datenum(cellstr(data_date),'yyyy-mm-dd HH:MM');

%% Importing SNR_DATA
filename = sprintf('/Users/estherroosenbrand/Desktop/SNR_DATA/%s/%d_%s.txt',loc_sel,doy_sel,loc_sel);
formatSpec = '%3f%10f%10f%10f%7f%7f%7f%f%[^\n\r]';
fileID = fopen(filename,'r');
SNR_SCAN = textscan(fileID, formatSpec, 'Delimiter', '', 'WhiteSpace', '', 'TextType', 'string',  'ReturnOnError', false);
fclose(fileID);
SNR_DATA = table(SNR_SCAN{1:end-1}, 'VariableNames', {'VarName1','VarName2','VarName3','VarName4','VarName5','VarName6','VarName7','VarName8'});
clearvars filename formatSpec fileID dataArray ans;
SNR_DATA = table2array(SNR_DATA);

%% Remove sat's with elevation lower that threshold
threshold_elevation = 21;
elevation_find = find(SNR_DATA(:,2) > threshold_elevation);
SNR_DATA = SNR_DATA(elevation_find,:);

%% Filter SNR data on satellite number
SNR_SATS = unique(SNR_DATA(:,1));
%SAT_SEL = SNR_SATS(1);
for i = 1:length(SNR_SATS)
    FIND_SNR_SAT{:,i} = find(SNR_DATA(:,1) == SNR_SATS(i));
    SNR_sec{:,i} = SNR_DATA(FIND_SNR_SAT{:,i},4);
    elevation{:,i} = SNR_DATA(FIND_SNR_SAT{:,i},2);
    S1{:,i} = SNR_DATA(FIND_SNR_SAT{:,i},7);
    S2{:,i} = SNR_DATA(FIND_SNR_SAT{:,i},8);
    SNR_time{:,i} = datestr(seconds(SNR_sec{:,i}),'HH:MM:SS');
    SNR_plot_merge{:,i} = strcat(prec_time(1,1),{' '},SNR_time{:,i});
    SNR_time_plot{:,i} = datenum(cellstr(SNR_plot_merge{:,i}),'yyyy-mm-dd HH:MM:SS');
end

%% Calcuate Moving Average of SNR DATA for plot
mov_av = 22;
for i = 1:length(SNR_SATS)
    S1_mov{:,i} = movmean(S1{:,i},mov_av);
end
data_RH(isnan(data_RH))=1;
```

```

%% Figure Precipitation and SNR Values per sat
for i = 1:length(SNR_SATS)
    figure()
    scatter(SNR_time_plot{:,i},S1{:,i},1,'filled')
    hold on
    plot(SNR_time_plot{:,i},S1_mov{:,i},'-k','LineWidth',1.5)
    ylabel('SNR [dB - Hz]')
    addaxis(prec_time_plot,data_prec,[0,1],'LineWidth',1.5)
    addaxis(prec_time_plot,data_RH,[0.3,1],'-','Color',[0.4940 0.1840 0.5560],'
        LineWidth',1)
    addaxis(SNR_time_plot{:,i},elevation{:,i},'LineWidth',1.5)
    xlabel('time [HH:MM]')
    ylabel('Precipitation [mm]')
    addaxislabel(1,'SNR [dB - Hz]')
    addaxislabel(2,'Precipitation [mm]')
    addaxislabel(3,'Relative Humidity [%]')
    addaxislabel(4,'Elevation [^{\circ}]','Interpreter','tex')
    datetick('x','HH:MM')
    title(sprintf('Sat num %d',i));
end
```

7.3. Netherlands data script

```
%% Script to plot SNR as function of time with elevation and precipitation
% Netherlands
%%
clear all
close all

%% IMPORT Cabauw DATA
opts = delimitedTextImportOptions("NumVariables", 6);
opts.DataLines = [16, Inf];
opts.Delimiter = ",";
opts.VariableTypes = ["double", "double", "double", "double", "double", "double"];
KNMIhourly = readtable("/Users/estherroosenbrand/Desktop/NL_DATA/
    KNMI_20190424_hourly.txt.tsv", opts);
data = table2array(KNMIhourly);
clear opts delimiter fileID filename formatSpec startRow

%% Data interesting dates
date_interest = [20190113,20190117,20190206,20190210];
data_date = data(find(data(:,2) == date_interest(3)),:); % CHANGE HERE
time= datetime(2019,2,6,0,0,0):hours(1):datetime(2019,2,6,23,0,0);%%

%% Load the RINEX-3 observation file
filename='CAB200NLD_R_20190370000_01D_30S_MO.rnx';
if ~exist('rnx','var') || ~strcmp(rnx.filename,filename)
    rnx=myrnxread(filename);
end
[staname,xyz]=rxheader(char(rnx.header),'stainfo'); % extract station name and
    approximate position
orb=rxnav(strrep(filename,'_30S_MO','_MN')); % Load RINEX-3 navigation file

%%
for i = 1:length(rnx.satid)
    k{:,i} = strfind(rnx.satid(i,:),'G');
```

```
end
sat_G = find(~cellfun(@isempty,k));
A = string(rnx.satid(sat_G,:));
unique_G = char(unique(A))

%% Select a satellite, extract observations and observation types
satid = 'G29';                          % GPS satellite 1
[epoch,obs,obstype] = myrnxgets(rnx,satid);
seltype= 'S1C'; % SNR of the L1CA signal
[types,idx] = intersect(obstype,seltype);
[epoch,obs,obstype]=myrnxgets(rnx,satid);
[types,idx]=intersect(obstype,seltype);
[gpssec,gpsweek] = date2gps(epoch);
xsat=rxsatpos(satid,gpssec,gpsweek,orb); % compute satellite positions
[z,a,s]=xyz2zas(xsat,xyz,'xr'); % compute the zenith angle and azimuth angle
epoch1 = datestr(epoch);

%% Plot SNR and Precipiation Graph
figure;
plot(datetime(epoch1),obs(:,idx),'.')
ylabel('SNR [dB-Hz]')
addaxis(datetime(epoch1),90-z*180/pi,[0,90],'.')
addaxislabel(2,'Elevation angle [deg]')
addaxis(datetime(datestr(time)),data_date(:,4),[0,25],'LineWidth',2);
addaxislabel(3,'Precipitation [mm]')
addaxis(datetime(datestr(time)),data_date(:,5),'LineWidth',2);
addaxislabel(4,'Relative Humidity [%]')
xlabel('GPS time')
title(sprintf('SNR and Precipiation data 2019-6-02 satellite %s',satid))
```