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Precipitable water vapour estimation using GPS in Uganda

A study on obtaining the Zenith Wet Delay



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A study on obtaining the zenith tropospheric wet delay

By

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Preface

This additional thesis is written as part of the master of science track "Geoscience and Remote Sensing". I chose to write an additional thesis instead of doing more courses to develop more experience in fieldwork, in scientific thinking and writing. This project also gave opportunity to do research abroad and to experience living in another country and culture. In the time given to fulfil the thesis, a feasibility study is done on using a network of single and dual frequency GPS receivers to estimate the precipitable water vapour in Africa. Thereto, the theory behind this principle will be explained, the GPS network will be designed and the obtained data from the resulting measurements will be analysed.

The research is split up in two parts. I will do the research together with Eva Stierman, but because the additional thesis requires us to deliver an individual report, we divided the research. This part of the research is about finding the Zenith Total (Tropospheric) Delay (ZTD) and to this purpose, the possibilities to estimate the ZTD using single frequency receivers in combination with dual frequency receivers will be investigated. In the second part of this research, the precipitable water vapour will be obtained from the Zenith Total (Tropospheric) Delay. The reports are of interest to those who like to know more about GPS and to those who are especially interested in using the errors in GPS for analysing the precipitable water vapour.

I would like to thank Nick van de Giesen and Florence D'ujanga for giving us the opportunity to experience living abroad in Kampala, Uganda, and for the support during the project. I would like to thank Sandra Verhagen for being our supervisor from Geoscience and Remote Sensing and I would like to thank Hans van der Marel for always being available for any question we had about GPS. In addition, I would like to thank Richard Cliffe for making time to help us and do research with us during our stay in Kampala. I would like to thank Erik Oudejans, who wrote the script on a raspberry-pi for logging the single frequency data and who helped us with using the raspberry-pi as a logging. Last but not least, I would like to thank Eva Stierman, for doing this project together.

*A.M. Koning
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Abstract

To improve weather monitoring, local near-real time weather forecasts and climate monitoring, a dense network of sensors should be set up. As shown already in the 1990s, GPS is a promising measurement device to form a dense network for meteorology observation. Because of economic reasons, a network of dual frequency GPS receivers is densified using low-cost single frequency GPS receivers.

In this thesis and the complementary thesis written by E.M.J. Stierman (2016), respectively, the quality of the Tropospheric Zenith delay and the Precipitable Water Vapour recordings that are estimated using the single frequency receivers in the network are investigated. To do this, two networks of small ($<10\text{km}$) spacing and large (30-90 km) spacing have been set-up. After this, a L2- and C2-measurement is generated for the single frequency receivers, using epoch-differenced ionospheric delay for L2 and regular ionospheric delay for the C2 measurement together with the L1 and C1 observations of the single frequency receiver. This is done to be able to use web-based PPP processing software of NRCan, that estimates the ZTD for dual frequency data.

The single frequency GPS show a ZTD that is much more variable in time than the ZTD found by dual frequency measurements. Secondly, the standard deviation to which the single frequency measurements converge is about 5 cm. It takes about half a day to obtain this precision. For comparison; the dual frequency receivers obtain a standard deviation well below 1 cm in less than 2.5 hours.

The results show this processing method for single frequency receivers is not good enough to obtain an accurate and precise measurement of the ZTD. Further research could be done on taking the correlation between the made observation and generated observations into account, using other processing methods, for instance double differences, or improving this processing method.

1 Introduction

According to the Report on Climate Change 2014 of the IPCC, an increase in surface temperature of approximately 4° Celsius during the 21st century, would likely cause more rainfall in areas that are already wet and less rainfall in dry areas. In regions where extreme rainfall is experienced, for instance in the mid-latitude land masses and over wet tropical regions, the rainfall will likely become more frequent and intense. In most developed countries there are resources and knowledge to protect us from these problems. However, places that will be mostly affected are those countries that are more vulnerable, such as African countries. Therefore, a network of weather stations that are equipped with GPS to keep track of temperature, pressure, water vapour content, could be of great help in monitoring the climate change in these countries. Temperature and water vapour content are namely reflecting the changes in climate. In addition, the knowledge of the precipitable water vapour is essential for short-term local weather forecasts (Shrestha 2003) that can be of great help for farmers.

This research is a feasibility study for the Trans African HydroMeteorological Observatory (TAHMO n.d.). A network of both single and dual frequency GPS receivers was set up to test u-blox single frequency receivers on their ability to estimate the precipitable water vapour in the atmosphere, using the results of the dual frequency Trimble 5700 receivers. This part only contains the estimation of the total tropospheric delay. All error sources in the GPS signal are discussed to get better insight in the precise point position (PPP) processing. The thesis of Eva Stierman, that forms the entire research together with this thesis, contains the part of estimating the precipitable water vapour from the tropospheric delay (Stierman 2016). At last, a conclusion is formulated about whether this is possible using the configurations tested in the research.

Recent development of affordable single GNSS receivers and further view on development of affordable dual frequency GNSS receivers, have made the project of TAHMO an interesting subject to study. With accurate dual frequency GPS receivers, the goals of weather monitoring is already been achieved in the Netherlands (Bender et al. 2009)(Baltink et al. 2002) and other parts of Europe (Geodetic observatory Pecny 2012). However, in Uganda, there are more severe storms and the ionosphere is much more dynamic due to the location of Uganda near and on the equator. The research question of this part of the project will mainly be:

“What accuracy and which precision can be obtained in the estimated tropospheric delay above Uganda when measurements are taken in an area of maximally 1200 km² using 3 dual frequency GPS receivers and at most 6 single frequency GPS receivers together in one network?”

The choice for three dual frequency GPS receivers originates from the interpolation minimum for a triangle. The triangle is formed by schools that already have a TAHMO weather station and the physics department of the Makerere University. Two of the most nearby TAHMO schools are chosen to set up the dual frequency receivers. There are maximally 6 single frequency receivers, because we want to test how the distance between the single frequency receivers with respect to the dual frequency receivers will influence the results of the single frequency receiver. On top of this, there must be time to place them all at the same day, which poses a restriction on the number of receivers. This is done to be able to have similar circumstances at all places, at least for the ionosphere.

In order to answer this question, several sub-questions have been formulated:

- Using PPP web-processing, the ZTD is given for the dual frequency receivers. How is this obtained and which accuracy is reached?
- What will be the main problem in estimating the ZTD using PPP processing for single frequency GPS receivers?
- What can be done in order to make PPP processing feasible for single frequency GPS receivers?
- How much is the difference between the ZTD obtained with the single frequency and the ZTD obtained with the dual frequency when measuring at the same location?
- How much does the accuracy improve when a longer time is measured?

Using the outcome of this research question and sub-questions, we can see if the desired accuracy for the precipitable water vapour content can be obtained. This will be the main interest of the complementary thesis by E.M.J Stierman, that answers the following research question:

“What accuracy and which precision can be obtained in the precipitable water vapour above Uganda when measurements are taken in an area of maximally 1200 km² using dual frequency GPS receivers and at most 6 single frequency GPS receivers together in one network?”

And the sub-questions are as follows:

- How is the precipitable water vapour determined using the ZTD?
- Which models are available for the estimation of the zenith hydrostatic delay and which one is the most suitable for this thesis?
- How does the distance between the GPS receivers influence the accuracy of the determined precipitable water vapour (Stierman 2016)?

The research is carried out between 11 September to 7 November 2016 in the vicinity of Kampala, Uganda, in collaboration with the Makerere University. Especially Florence Mutonyi d'Ujanga and Ssenyunzi Richard Cliffe have been working with Eva Stierman and me on the project. First a small network (~3-5 km between dual frequency GPSs) was set up, to see if everything works properly and to see the accuracy on small scale. Then a larger network (~30km between dual frequency GPSs) has been set up to meet the goals of TAHMO's view. The research is mostly carried out during the raining season (Information World Weather & Climate 2016), accordingly we can expect a lot of rainfall that will influence the tropospheric delay as experienced by GPS. In addition, we must consider that there are many regions that have a different type of weather in Uganda as there are many different geographic regions (Worldatlas.com 2016). As we are not going very far away (<90 km) from Kampala, the weather conditions will not differ extensively for the researched areas.

This report consists of a theoretical background, in which the basic principles of the origin of the delays in GPS and the methods to estimate the magnitude of the delays will be discussed. Thereafter, the set-up of the GPS will be given and how the theory is applied to the configuration to find the wanted values. Then we naturally arrive at the result section, where the results will be shown and discussed. At last, there will be a conclusion and advice about the usage of the used GPS configurations to estimate the ionospheric and tropospheric delay and indications for further research.

2 GPS: errors and processing techniques

In this chapter, the measurement types and the origin of the delays will be explained. Moreover, the Precise Point Position will be elaborated on to see which models and algorithms are used to determine the precise position and the zenith tropospheric delay. First, the errors in the space control segment will be discussed, followed by an explanation of the errors in the user control segment and at last, the errors in the atmosphere are discussed. This is where our focus will be. At last processing techniques and optimal network design will be addressed.

2.1. GPS measurement types

There are two kinds of measurements: Pseudorange code measurements and carrier phase measurements. Both will be discussed below and their positive and negative aspects are discussed accordingly. The pseudorange code measurements are less precise, but unambiguous, whereas the carrier phase measurements are very precise but ambiguous.

2.1.1 Pseudorange code measurements

The GPS receiver measures the time between the emission of the signal by the satellite and the reception at the receiver. The time of emission of the signal according to the satellite clock is imprinted on the code part of the signal and the time of reception is recorded by the receiver clock. The receiver generates the same code as sent by the satellite and measures the amount of time shift that is required to align the C/A-code replica with the original. The measured apparent range, known as pseudorange, can be written as:

$$\rho(t) = c[t_u(t) - t^s(t - \tau)] = c\tau + c[\delta t_u(t) - \delta t^s(t - \tau)] + \varepsilon_\rho(t) \quad (1)$$

In this formula $\rho(t)$ is the pseudorange in metres as measured at time t , c is the speed of light in m/s, $t_u(t)$ is the time of reception as recorded by the receiver clock and $t^s(t - \tau)$ is the time of emission as recorded by the satellite. So τ is the true travel time that would be experienced without any error. The $\delta t_u(t)$ and $\delta t^s(t - \tau)$ are the clock errors of the receiver and the satellite, respectively. The clock errors will be discussed shortly. At last, $\varepsilon_\rho(t)$, is used to denote un-modelled effects, modelling errors and measurement errors (Misra & Enge 2001). Writing it more explicitly, we will obtain:

$$\rho_{C_i}(t) = c\tau + \frac{f_1^2}{f_i^2} D_{C1} + T + c\delta t_u(t) - c\delta t^s(t - \tau) + \varepsilon_{\rho_{C_i}}(t) \quad (2)$$

Where $\rho_{L_i}(t)$ is the frequency dependent pseudorange, $c\tau$ is the true range, $\frac{f_1^2}{f_i^2} D_{C1}$ is the frequency dependent ionospheric delay, T is the tropospheric delay. All terms are to be calculated in metres.

2.1.2 Carrier phase measurements

The carrier-phase measurements are measured in the following way. The carrier signal originating from the satellite is multiplied with the replica that is generated by the receiver. This will result in a fast oscillation on top of a low frequency oscillation. This is illustrated in Figure 1.

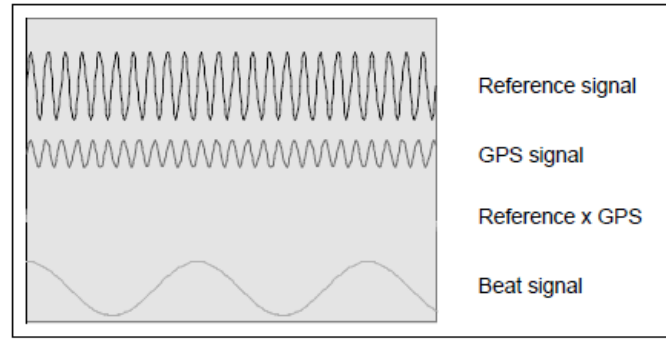


Figure 1 Multiplication of the reference signal (replica generated by the receiver) and the GPS signal resulting in the beat signal. It is not shown well, but the beat signal should have high frequency oscillations on top of the base frequency. Figure obtained from (Blewitt 1997).

The low oscillation is called beat signal and it can be obtained by filtering out the high frequency component. The phase of the carrier beat signal is defined equal to the difference in phase between the satellite signal and the receiver replica.

$$\begin{aligned} B(t) &= B_0 \cos(2\pi\phi_B(t)) \\ \phi_B(t) &\equiv \phi_R(t) - \phi_G(t) \end{aligned} \quad (3)$$

In this formula $B(t)$ is the beat signal, B_0 is the amplitude of the signal, $\phi_B(t)$ is the phase of the beat signal, $\phi_R(t)$ is the phase of the reference signal, and $\phi_G(t)$ is the phase of the GPS signal. The phases are measured in terms of cycles and the amplitude in terms of strength of the electric field, as it represents a radio wave (Blewitt 1997). The observation equation for the frequency dependent carrier phase measurements is defined as:

$$\phi_{L_i}(t) = c\tau - \frac{f_1^2}{f_i^2} D_{L1} + T + c\delta t_u(t) - c\delta t^s(t - \tau) + \lambda N + \varepsilon_{\phi_{L_i}}(t) \quad (4)$$

A new term has shown up in this formula: λN . This term represents the ambiguity. Using the phase measurement, the range can be estimated on part of the wavelength scale, but the amount of integer wavelengths that are completed (N) is not exactly known. Between the phase and code measurement we can make the following analogy: suppose you want to measure the distance between the earth and the moon. You have a very long measuring tape to do so. For the code measurement the measuring tape only has the meter scale, so the last part of a metre must be estimated. The phase measurement has only mm scale, where the start of a centimetre is there, but the number is absent. So the part of the cm can be viewed very accurately, but the moon could be any integer cm distance away. This is called ambiguity (Misra & Enge 2001).

2.1.3 Position estimate

When we have done the measurements, we know the satellites' positions and the satellite clock bias from the navigation message and the pseudorange. Then we will be able to calculate our own position using linearized pseudorange (equation (1)):

$$\rho(t) = \sqrt{(x^s(t - \tau) - x_r(t))^2 + (y^s(t - \tau) - y(t))^2 + (z^s(t - \tau) - z_r(t))^2} + c(\delta t_u(t) - \delta t^s(t - \tau)) + \varepsilon_\rho(t) \quad (5)$$

Then we are left with four unknowns: the three coordinates and the clock bias of the receiver. However, a lot of errors are still inside of this pseudorange. These are represented by ε . Now, the most important error sources that can occur in the GPS measurement will be described.

2.2. Errors in the space control segment

The Control Segment computes the ephemeris and clock parameter values that the satellites will put on the signal using measurements of GPS monitor stations on Earth. The states of the satellites, its position and velocity, are obtained, as well as the states of the clocks, such as the phase bias, frequency bias and frequency drift rate. Every parameter is predicted in advance, to enable the satellites to broadcast these parameters in real time. The prediction error grows with the time that it is predicted in advance (Misra & Enge 2001).

2.2.1. Ephemeris error

The ephemeris gives the position of the satellite. The ephemeris at time of broadcast is part of the navigation message that is sent to the receiver. It includes the square root of the semi-major axis (with respect to Earth's centre), eccentricity, argument of perigee and the mean anomaly, inclination angle, right ascension. The mean anomaly, inclination angle, right ascension are given at the reference time of the satellite. The master control station of the ground-based monitor stations computes the ephemeris based on the observations of all monitor stations. Every hour, they produce a broadcast ephemeris and the error of this first computed ephemeris is in the order of 3m.

For precise positioning, the accuracy of the broadcast ephemeris is not sufficient. Orbit products from IGS, among others, provide corrections to increase the accuracy. Corrections are made in three degrees: Ultra-rapid orbits are generated twice each day and have a precision of approximately 20cm. Rapid orbits are available after one or two days of data collection and they have an accuracy of approximately 10cm. The final orbits are most accurate with a precision of less than 5 cm. However, you have to wait for two weeks to obtain them. It is calculated among others by the International GPS Service (IGS) (Shrestha 2003).

2.2.2 Satellite clock error

The satellite contains very precise atomic clocks, with which it keeps track of time. However, still errors occur in these times because of drift of the atomic clocks that are caused by instabilities in the oscillators of the satellite. The clock error can be estimated using the information of the satellite navigation message, but these computed errors are not very precise. The clock error of the satellite will of course be the same for every measurement of different receivers that take place simultaneously. Therefore, using single or double differences in the GPS processing, these errors are removed. Another option is using the products from IGS in which also the precise clocks are provided (Shrestha 2003).

2.2.3 Satellite hardware delay

The time delay that is introduced by all kinds of electronics before the signal leaves the satellite is due to hardware delay. This can be found in the length of cables, filters, analogue to digital converters and so more.

2.3. Delays in the user control segment

2.3.1. Receiver clock error

The receiver clock is just a regular quartz clock. Of course, we could reduce the clock error by taking an atomic clock for the receiver clock, but, in that case, it would be unaffordable and very unpractical to move around. Therefore the receiver clock error is estimated together with the coordinates of the antenna. Because now there are four unknowns, at least four different satellite signals should be received in order to estimate the position (Blewitt 1997).

2.3.2 Multipath error

Typically, a direct in line-of-sight measurement is received. However, the signal can also go via multiple paths, having reflected on surrounding objects or via the ground to the receiver. A multipath is longer than the direct line-of-sight to the satellite and therefore introduces a delay in both the code and phase

measurements (Misra & Enge 2001). The multipath signals can be characterized by their amplitude, the signal is usually weaker than the direct signal, the delay of the signal, its phase and phase rate of the reflected signal with respect to the direct signal. When multiple waves coming in simultaneously, interference will occur and the multipath signals will thus distort the direct signal. There are ways to reduce the presence of multipath interference by eliminating the low-magnitude signals (Satya Srinivas 2011), but this will not be done in this report.

2.3.3. *Phase wind-up*

As GPS signals consist of right circularly polarized radio waves, the observed carrier-phase depends on the common orientation of the satellite and receiver antennas. The carrier-phase is changed when either of the antennas is rotated along its bore axis. This change is maximally for 1 full rotation that corresponds to one wavelength. As the receiver antenna is fixed, no rotation should take place there. However, the satellite antennas rotate slowly as their solar panels must be rotated towards the Sun continuously and the station-satellite geometry changes. In differential positioning, it is quite negligible for baselines up to a few hundred kilometres. For PPP on the other hand, this effect is quite significant: neglecting phase wind-up and fixing IGS orbits/clock will result in a position and clock errors at the dm-level. For the receiver antenna, the rotations are estimated together with the station clock solutions (H  roux et al. 1999).

2.3.4. *Receiver hardware delay*

From the antenna, the signal has to travel to the receiver. The length of the data cable, analogue to digital converters and possible filters that are applied to the signal cause a delay between time of arrival and the time of storage in the CF-card of the receiver.

2.4. *Atmospheric delays*

Other than in vacuum, the GPS signal can be reflected on the particles that are present in the atmosphere. This causes a delay in the signal. There are two main parts in the atmosphere that cause delays in the signal: the ionosphere, which is between ~50 km and ~1000km above the Earth's surface and the troposphere that extends from the Earth's surface to about 15 km height. These two layers and their effect on the signal will be discussed shortly.

2.4.1. *Ionospheric delay*

The ionosphere obtained its name because it is a spherical shell that contains ionised gas (free electrons and ions). Due to the Sun's (UV) radiation, molecules, such as H₂, O₂ and N₂, are broken up into ions and electrons. The free electron density is mainly responsible for the attenuation of the signal. As could be imagined, this density is closely related to day and night patterns in which the electron density can vary by two orders of magnitudes. During the day, more and more molecules will be broken up, as in the night, there is no UV radiation and the electrons and ions will recombine. The speed of propagation of a radio wave in the ionosphere depends on the amount of electrons it encounters on its way down. This is expressed as the total electron content (TEC) [$\# / \text{m}^3$], which is the amount of electrons in a tube of a radius of 1 m around the entire path of the signal (Misra & Enge 2001).

The ionosphere is very different in Uganda from the part above the Netherlands (or more general; the ionosphere around the equator behaves different from the part above mid-latitudes). The one at mid-latitudes behaves calmly and therefore satellite signals can be measured easily, even when the satellites are low above the horizon. Using dual frequency GPS receivers, as will be discussed shortly, the ionospheric delay in the pseudorange and carrier phase measurement can be removed. However, above the equator, the ionosphere is untamed and sometimes it is hard to measure accurately using GPS because this trick only works with an undisturbed ionosphere. In the polar and equatorial regions, there can be large disturbances that have close relation with magnetic activity and solar activity. The highest TEC values and disturbances can be found between 0° and 30° North and South from the equator, which covers about 50% of the Earth's surface area. The strongest effects are at approximately at 10° North and South. Irregularities in the TEC with spatial distances from a few meters to several kilometres can produce scintillation (e.g. refraction and diffraction effects on the GPS signal). The severest effects of small-scale

irregularities in the atmosphere is attenuation of the signal so that the threshold of the receiver is not reached (Wanninger 1993).

Ionised gas is dispersive to radio waves, so different frequencies will have a different refractive index. Therefore, when using dual frequency GPS receivers, the ionospheric delay can be estimated using the difference in arrival time of the two signals. The estimate of the ionospheric group delay of the code pseudorange observation is expressed as:

$$\begin{aligned} D_{C1} &= \frac{f_{L2}^2}{f_{L1}^2 - f_{L2}^2} (\rho_{C2} - \rho_{C1}) \\ D_{C2} &= \frac{f_{L1}^2}{f_{L1}^2 - f_{L2}^2} (\rho_{C2} - \rho_{C1}) \end{aligned} \quad (6)$$

The ionospheric delay in the carrier phase measurement is formulated as:

$$\begin{aligned} D_{L1} &= \frac{f_{L2}^2}{f_{L1}^2 - f_{L2}^2} [\lambda_{L1}(\phi_{L1} - N_{L1}) - \lambda_{L2}(\phi_{L2} - N_{L2})] \\ D_{L2} &= \frac{f_{L1}^2}{f_{L1}^2 - f_{L2}^2} [\lambda_{L1}(\phi_{L1} - N_{L1}) - \lambda_{L2}(\phi_{L2} - N_{L2})] \end{aligned} \quad (7)$$

In these equation, f_{L1} is the L1 frequency in Hz, f_{L2} is the L2 frequency in Hz, ρ_{L1} is the pseudorange in m as measured using the L1 frequency and ρ_{L2} is the pseudorange in as measured using the L2 frequency. ϕ_{L1} and ϕ_{L2} are the carrier phase measurements on L1 and L2 frequency, respectively, N is the ambiguity of the carrier-phase and lambda is the carrier wavelength (Misra & Enge 2001)(Deng et al. 2009).

2.4.2 Tropospheric delay

The GPS signal is not only refracted in the dispersive ionosphere, but also in the (for GPS frequencies non-dispersive) troposphere that consists mainly of O₂, N₂ and water vapour. The tropospheric delay is induced because the signal travels slower in the atmosphere than in free space. This causes an addition of 2.5-25m in pseudorange, depending on elevation angle. The delay cannot be estimated from GPS measurements if the position is not exactly known. In that case, a model must be used to correct for this error. Typically, the tropospheric delay is split in two parts:

1. Tropospheric dry delay
2. Tropospheric wet delay

This is done because the refractive index, which determines the amount of delay, is dependent on the density of the air. The density of the 'dry' troposphere is related to latitude, season and altitude, but it is fairly stable and it is responsible for about 90% of the delay. The water vapour content is for 90% contained in the first 4-5 km (Wolfe & Gutman 2000) and varies with the weather and therefore it is very dynamic. The tropospheric wet delay is mainly responsible for the changes in the total tropospheric delay (Misra & Enge 2001). 90% Of the water vapour is contained in the first 4-5 km.

2.5. Un-differenced PPP model

2.5.1 General description of PPP

The precise point positioning is used as a post-processing method for determining the absolute position using stand-alone (thus un-differenced) GPS receivers. The parameters that commonly have to be estimated by the model are the position of the receiver (in our case in static mode), the station-clock states, local zenith delays and carrier-phase ambiguities. The input parameters to this method are precise satellite orbits, precise satellite clocks and for every physical phenomenon that the signal can undergo, a model for

this phenomenon should be used (Mireault et al. 2008). The basis for this processing method in kinematic mode, multi-satellite, single epoch will now be explained.

Using the GPS receivers, a measurement of the pseudorange and a code-phase measurement is recorded. To shorten notation, $c\delta t_u$ will be used for $c\delta t_r(t)$ and $c\delta t^s$ to represent $c\delta t^s(t - \tau)$.

$$\begin{aligned}\rho_{Ci} &= \|\mathbf{x}^k - \mathbf{x}\| + \frac{f_1^2}{f_i^2} D_{C1} + T + c\delta t_u - c\delta t^s + \varepsilon_{\rho_{Ci}} \\ \phi_{Li} &= \|\mathbf{x}^k - \mathbf{x}\| - \frac{f_1^2}{f_i^2} D_{L1} + T + c\delta t_r - c\delta t^s + \lambda_{Li} N_{Li} + \varepsilon_{\phi_{Li}}\end{aligned}\quad (8)$$

In these formulae, every term changes in time, except for the ambiguity N . The code observation are linearized around the a-priori parameters and observations ($\mathbf{v}_0$) for every observation to every satellite in view. Thereto we take the difference between the observed and computed pseudorange:

$$\delta\rho^k = (-\mathbf{1}^k)^T \delta\mathbf{x} + \delta b + \frac{f_1^2}{f_i^2} \delta D_{C1} + m_w \delta T + \widetilde{\varepsilon}_\rho^k \quad (9)$$

$$\delta\rho_{Ci} = \begin{bmatrix} \delta\rho^1 \\ \delta\rho^2 \\ \vdots \\ \delta\rho^m \end{bmatrix} = \begin{bmatrix} (-\mathbf{1}^1)^T & 1 & f_1^2/f_i^2 & m_w^1 \\ (-\mathbf{1}^2)^T & 1 & f_1^2/f_i^2 & m_w^2 \\ \vdots & \vdots & \vdots & \vdots \\ (-\mathbf{1}^m)^T & 1 & f_1^2/f_i^2 & m_w^m \end{bmatrix} \begin{bmatrix} \delta\mathbf{x} \\ \delta b \\ \delta D_{Ci} \\ \delta T \end{bmatrix} + \widetilde{\varepsilon}_\rho^k \quad (10)$$

In which $\delta\mathbf{x} = \begin{bmatrix} x - x_0 \\ y - y_0 \\ z - z_0 \end{bmatrix}$ and $\delta b = b - b_0 = c(\delta t_r - \delta t^s) - c(\delta t_{r,0} - \delta t_0^s)$, m_w denotes a mapping function between slant and zenith direction as δT is calculated for the zenith direction.

The same is done for the carrier-phase:

$$\delta\phi^k = (-\mathbf{1}^k)^T \delta\mathbf{x} + \delta b - \frac{f_1^2}{f_i^2} \delta D_{L1} + m_w^k \delta T + \lambda_{Li} N_{Li}^k + \widetilde{\varepsilon}_\phi^k \quad (11)$$

$$\delta\phi = \begin{bmatrix} \delta\phi^1 \\ \delta\phi^2 \\ \vdots \\ \delta\phi^m \end{bmatrix} = \begin{bmatrix} (-\mathbf{1}^1)^T & 1 & -f_1^2/f_i^2 & m_w^1 \\ (-\mathbf{1}^2)^T & 1 & f_1^2/f_i^2 & m_w^2 \\ \vdots & \vdots & \vdots & \vdots \\ (-\mathbf{1}^m)^T & 1 & f_1^2/f_i^2 & m_w^m \end{bmatrix} \begin{bmatrix} \delta\mathbf{x} \\ \delta b + \lambda_{Li} N_{Li}^1 \\ \delta D_{L1} \\ \delta T \\ N_{Li}^2 - N_{Li}^1 \\ \vdots \\ N_{Li}^m - N_{Li}^1 \end{bmatrix} + \widetilde{\varepsilon}_\phi^k \quad (12)$$

The equation is solved using least squares estimation. When more epochs are considered, we can put the similar design matrices below each other as well as the vectors (van der Marel 2016b) (H  roux et al. 1999). This approach is simplified. As described by (H  roux et al. 1999), there are many other errors that should be mitigated to obtain a precise point positioning, such as satellite attitude effects, site displacement effects, antenna phase centre variations as a function of azimuth and elevation.

There should be noted that there are many models exist for obtaining the total tropospheric delay, as well as for estimating the dry and wet delays. When using PPP processing, the ZTD is estimated for the dual frequency receivers using least squares estimation and equation (12). However, the total tropospheric delay is fixed by models for the single frequency receivers.

In the NRCan PPP web-processing, surface meteorological data that is extracted from the Global Pressure and Temperature (GPT) model are used as input for the models and a default value of 50% relative

humidity is assumed. (NRCAN .sum file) However, as we want to measure the ZTD, this will not be discussed any further.

2.5.2. PPP processing of single frequency observations

GPS PPP processing uses the ionosphere-free combinations of dual-frequency pseudorange and carrier-phase observations. When using PPP for single frequency GPS we have to resort to TEC maps or correct for the ionospheric delay in alternative way. To obtain the best result possible, PPP involves the extraction of error sources from the signal, that include antenna phase offsets, variations of satellites and receivers, phase wind-up, solid-Earth tides, ocean loading (which will not be very important as we are far away from the ocean), Earth rotation, relativistic effects and multipath. The preference for PPP instead of DD processing arises from the benefit of processing each GPS station independently and that simultaneous observations of the same satellite of the two stations are not needed (Yuan et al. 2014). In this way, no data is rejected from processing for dual frequency receivers (this is not true for the single frequency data in the way we will use them). Other than the carrier phase and the pseudorange observations, the PPP processing also uses external GNSS satellite orbit and clock products, such as IGS products (van der Marel 2016b).

The Natural Resources Canada (NRCAN) online web-processing has 2 approaches:

1. Dual frequency approach: when it recognises that there is a L1&L2 Code & Phase combination of the observations, PPP recognised that the precision is good enough to estimate the Zenith Total Delay.
2. Single frequency approach: when it recognises that there is a L1 CODE observation only, the precision is in orders of decimetres for higher-end receivers, which is insufficient for tropospheric delay estimation. Therefore a model for tropospheric delay is used, along with default (GPT) meteorological data and elevation mapping function to correct the delay along the line of sight to the satellite (Natural Resources Canada n.d.).

2.5.3 Solution for single frequency observations with PPP

A method to pre-process the single frequency measurements should be found to be able to use the online PPP processing for estimating the ZTD using single frequency receivers. The solution to this problem is introduced by (Deng et al. 2009): Generate observations for the second frequency using the observations of the first frequency and the data of the dual frequency receivers. (Deng et al. 2009) states that phase centre corrections must be applied in advance, because the same non-dispersive delay is used for the different frequencies. We have not applied this correction, which will cause a larger error in the PPP output.

For the carrier phase measurements, an epoch-differenced delay will be applied. It is important that this delay is calculated for each individual satellite at every epoch, as the path through the atmosphere will be different for each satellite-receiver path and therefore the delay will be different. The difference in ionospheric delay between the epoch in which the satellite is first tracked (j_0) and k epochs after the first tracked epoch can be expressed as:

$$\delta D_{Li}(j_0, j_0 + k) = D_{Li}(j_0 + k) - D_{Li}(j_0) \quad (13)$$

In this equation, the i represents the frequency index. $D_{Li}(j_0)$ will never be a known value. We will take zero for this parameter, but any value will do. Applying the correction to the delay observation of the (j_0+k) th epoch, this can be written as:

$$L_i(j_0 + k) + \frac{f_i^2}{f_1^2} \delta D_{Li}(j_0, j_0 + k) = \rho(j_0 + k) - D_{Li}(j_0) + \lambda_i N_i \quad (14)$$

In this equation, ρ represents the non-dispersive delay: the geometric, tropospheric delays and the clock biases. The wavelength is represented by λ and the ambiguity by N . The last two terms of this equation will be merged together to form an ionosphere-free observation equivalent.

The ionospheric observation L_4 that is used for constructing the ionospheric model, is proposed to be:

$$L_4 = L_1 - L_2 = \lambda_1 N_1 - \lambda_2 N_2 - (D_{L1} - D_{L2}) \quad (15)$$

Using epoch-differencing, we will obtain the epoch-differenced ionospheric delay:

$$\delta L_4(j, j+1) = \delta D_{L1}(j, j+1) - \delta D_{L2}(j, j+1) = \frac{f_1^2 - f_2^2}{f_1^2} \delta D_{L1}(j, j+1) \quad (16)$$

This delay is calculated using the dual frequency receivers, as these receivers also contain a L2 measurement. After determining the ionospheric delay for the three dual frequency receivers, this will be interpolated to the location of the single frequency receivers using inverse distance interpolation, $p=2$. The generated model will thus result in a epoch-differenced ionospheric correction of any single frequency receiver contained by the network of both dual and single frequency receivers. The correction that will be applied to epoch k will be the sum of the epoch differenced corrections between epoch k and the start of the tracking at epoch j_0 :

$$\widetilde{L}_4(j_0, k) = \sum_{j_0}^{k-1} \delta \widetilde{L}_4(j, j+1) \quad (17)$$

To generate the carrier phase observation for the single frequency receiver, this delay is added to the corresponding L1 observation:

$$\widetilde{L}_2(k) = L_1(k) - \widetilde{L}_4(j_0, k) \quad (18)$$

In which L2 is exactly the same observation as L1, only corrected for the ionospheric delay of the second frequency. For the pseudorange code measurement, no epoch-differenced method has to be used; there we determined the ionospheric delay on the L1 and L2 frequency, interpolated this using the same interpolation method as for the carrier phase subtracted the ionospheric delay of the first frequency from the observation and the ionospheric delay of the second observation is added.

$$\widetilde{C}_2(k) = C_1(k) - D_{C1}(k) + D_{C2}(k) \quad (19)$$

After the generation of the L2 and C2 observation, the adjusted RINEX file is submitted to the PPP online web-processing of NRCAN. According to (Deng 2012), usage of PPP requires a long observation time, as the ionospheric-free linear combination is not based on integer ambiguities.

Of course, the measurements on the L1 frequency will be correlated to the generated observations on the L2 frequency. This is not taken into account by PPP, nor by our generation. As the eventual goal will be to estimate the precipitable water vapour, a flow chart of the processing steps is presented in Figure 2. In this thesis, we will focus on the part that is indicated inside the red rectangle, the other part will be focused on in the thesis of E.M.J. Stierman.

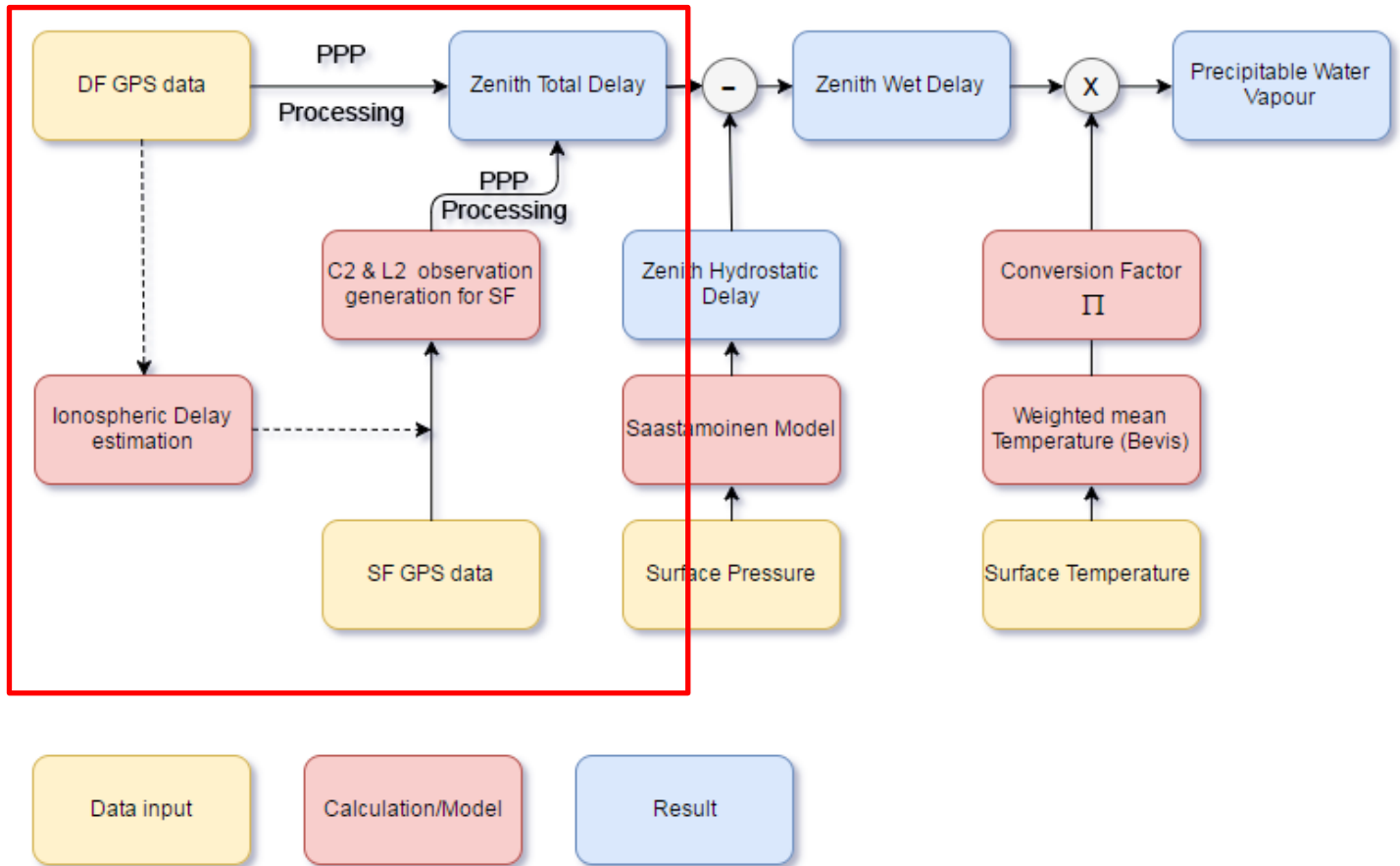


Figure 2 The full process to obtain the precipitable water vapour from both dual- and single-frequency GPS measurements is shown in this flow chart. The focus of this thesis is indicated by the red rectangle, the other part will be the focus of the thesis of E.M.J. Stierman.

2.6. Ideal network design

The GPS network of dual and single frequency receivers will be used for weather forecast (improvement). The usage of single frequency GPS receivers to densify the network is formerly because of economic reasons. In order to obtain the ZTD of high spatial resolution that is required for regional and short-term forecasts, an ideal network would have a separation of maximally several kilometres between the stations (Deng et al. 2009). Temporal variations in the number of visible GPS satellites and the position of the satellites in the sky causes a variation in the available data in a given period. The network design of the GPS receivers is very important for the quality of the data in a certain region: if some parts have closer spaced receivers, the resulting estimation will become better (Bender et al. 2009). In northern Oklahoma, a spacing between 35-150km between the dual frequency receivers is enough to interpolate ionospheric corrections of L1 at mm-level to each L1 receiver site (Rocken et al. 2000). However, this should be still investigated in the equatorial regions, as the ionosphere behaves differently near the equator than in higher latitudes. Each GPS receiver experiences influences of the atmosphere within a radius of maximally 22 km at a height of 4 km (as 90% of the water vapour is contained in the first 4-5km above the Earth's surface) and using a cut-off angle of 10° (Wolfe & Gutman 2000). Keeping this in mind, the receivers can be placed 20 km apart, to have half of the distance an overlap hence most of the vertical atmosphere covered.

3 Experimental Set-up

In this section, the experimental set-up of both measuring rounds will be given and the reasoning behind this set-up will be provided. There will be a discussion of the problems we faced in the experimental set-up during the project. To answer the research questions, the GPS dual frequency stations (Trimble 5700 receiver and Zephyr Geodetic Trimble antenna) will be first distributed in a triangle in Kampala, and the single frequency GPS (u-blox M8T) receivers will act in between or around these stations to densify the network. Every time we measure, the dual frequency GPS receivers need 20 to 40 minutes to reach centimetre accuracy (de Bakker 2012). We had the dual frequency receivers running for already one day before setting up the single frequency GPS receivers. The single frequency receivers will not be able to remain for 3 days, as the power banks will not contain enough energy to do this (they provide energy for about 36 hours).

Measuring round 1

In the first measuring round, the objective was to test the configuration on a small distance of less than 10 km apart. In case something went wrong, it would have been possible to be there soon. In addition, the precision and accuracy in a smaller network is interesting to compare to those that can be obtained in a larger network, especially in the case of interpolation of the ionospheric and tropospheric delays. This is because the eventual TAHMO network would have weather stations, on which also a GPS is mounted, would be 30km apart.

In order to find suitable locations, some schools in Kampala were asked to provide a secure, yet open place to set up the GPS there. However, no response was received, apart from one rejection. The Dutch embassy provided a location on top of a guardhouse of two of their employees. For the set up on 20 September, a construction to put the GPS on the sloped roof had to be made. At the pick up on 30 September, it turned out that the antenna's stability had not been ideal. Although the tilt could barely be seen by eye, it was not leveled anymore. The tilt was oriented to the South and is estimated to be less than 10 degrees.

The second GPS dual frequency receiver is set up at the Makerere University on 19 September. They had a platform on a room that had a clear view to the sky. There we cannot look to the horizon in the north side. Multipath can occur due to the rooftop and the platform the GPS is standing on.

The third and last GPS dual frequency receiver was located on the roof of the flat in which the TAHMO guesthouse is situated on 21 September. Also there, there is a water tank in the view to a certain direction, which makes it impossible to view the satellites from there. Multipath can occur due to the ladder, the water tank and the rooftop. 29 September the receiver is picked up.

The locations that are chosen to be a GPS location were selected on basis of best location that can be found within a reasonable time, in our case that is one week.

At 27/28 September, 5 single frequency receivers are out in the field collecting data. We selected areas in which we would like to have a single frequency receiver and went to all kinds of buildings to ask whether we could place the single frequency receivers there for one day. The first one is situated on a roof, however, there is a flat standing nearby that could make it a bit harder to view satellites in this direction. Unfortunately, due to the heavy rains, this receiver recorded only for 1 minute. The other one is situated on the roof of the guardhouse of IITA and this one was still working well at pick up. The third is put on top of the Arcadia Suites hotel, which was the best location of all: It had a clear view in all directions and it was put after the rain. Another receiver is put on the Makerere university again, to find out the difference between dual GPS and single GPS/GLONASS. However, the building blocked a great part of the sight and we will have many multipath signals. The last one is put at our house, where multipath and block of sight can be dominant as well. In Figure 3, the locations of all GNSS receivers are shown on a map.

Overview set up measurement round 1

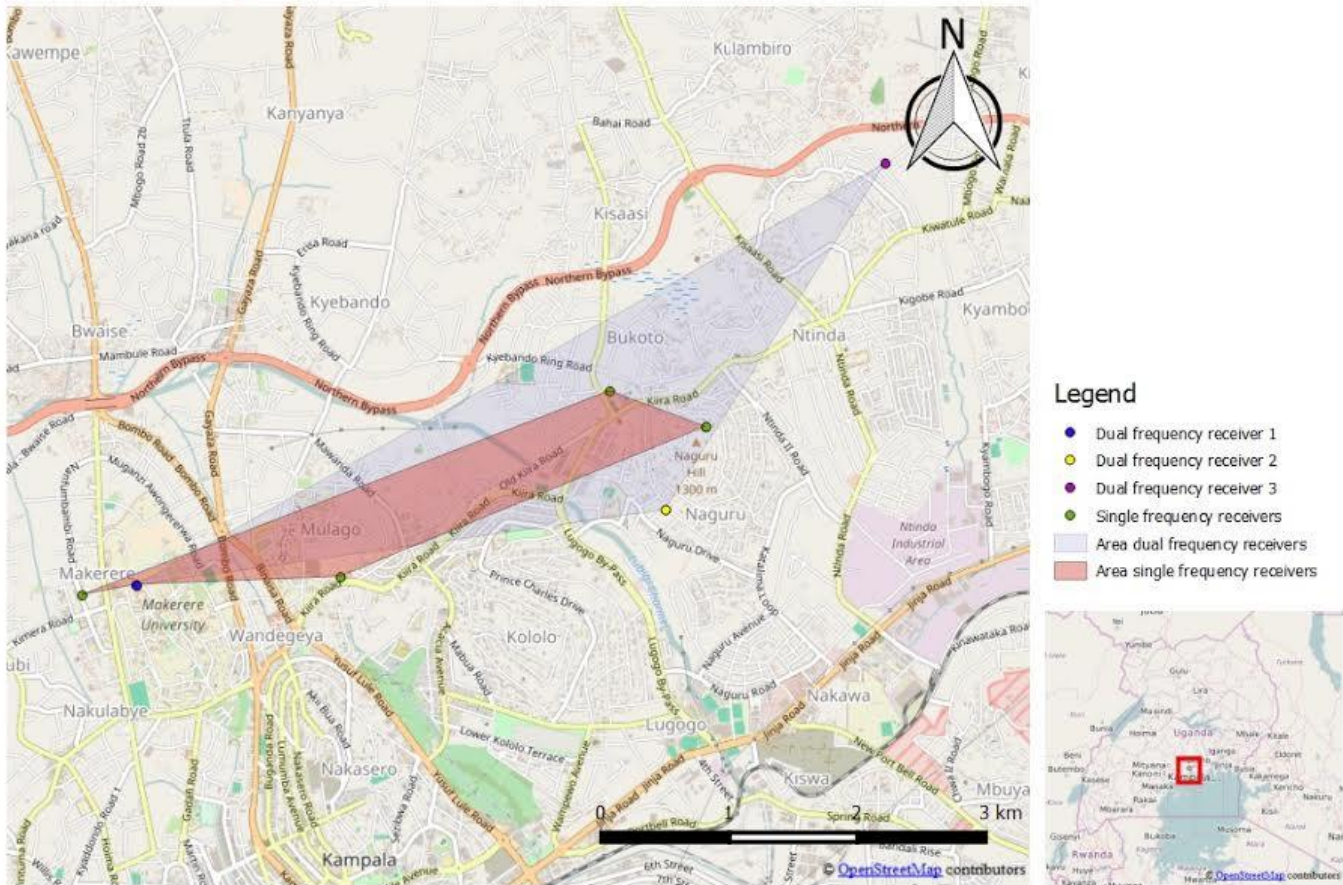


Figure 3 A map showing a part of Kampala. The first dual frequency GPS receiver is located on top of the roof of the physics department of the Makerere University (indicated using a blue dot). The Second dual frequency GPS receiver is located at the house of Dutch diplomats of Uganda (yellow dot) and the last one is located at the TAHMO guesthouse (purple dot). This forms an almost isosceles triangle in which or in the vicinity of which the single frequency GPS/GLONASS receivers are located (green dots).

Measuring round 2

During the second measuring round, the distance between the GPS locations is increased. The precision that is obtained using this configuration will be compared to the precision that is observed in the first measuring round. Using this information, the ideal distance between the GPS location is thought to be deduced.

In this round, the dual frequency GPS receivers are set-up at schools where also a TAHMO weather station is situated. In this way, accurate temperature and pressure levels can be used as input for the tropospheric delay models. The GPS receiver stood at Ndejje Senior School between 3 October 2016 and 12 October 2016, where it was set-up on a flat roof that has a clear view to the sky. Multipath can occur only via the floor and some metal sticking out of the concrete. The other dual frequency GPS receiver was located at Mityana Secondary School, where it is standing next to a water reservoir, but it is put up on 5 October 2016 and removed on 13 October 2016. The last one remained at the Makerere University.

After they ran for a couple of days, the single frequency GNSS receivers are set-up in the field (on 10 October 2016). They are set-up at Richard's house which is situated between Kampala and Mityana, and at the Modern Primary School, which is situated in Jezza: between Richard's house and Mityana. Another is placed at the Makerere High School, between Ndejje and Kampala and one in the middle of the triangle of the dual frequency receivers, in the Water Recourses ministry. The last one is placed at the Makerere University because the measurement that was done in the first measuring round failed. The complete overview of the setup can be seen in Figure 4.

Overview set up measurement round 2

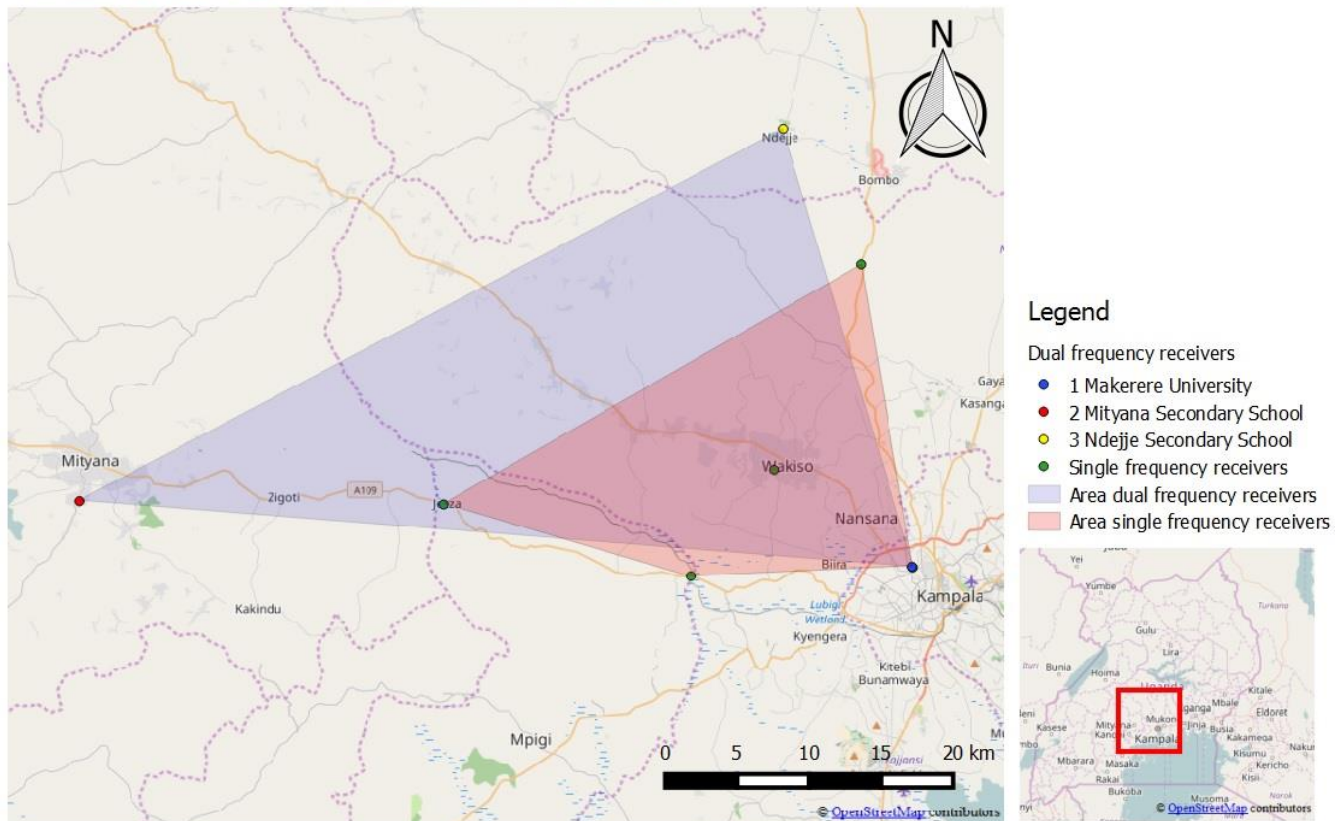


Figure 4 A map showing a part of Uganda. The first dual frequency GPS receiver is still located on top of the roof of the physics department of the Makerere University (blue dot). The Second dual frequency GPS receiver is located at Mityana Secondary School (red dot), but unfortunately it failed, and the last one is located at Ndejje Secondary School (yellow dot). As can be seen, the single frequency receivers (green dots) are placed in between Kampala and Mityana (two receivers), between Kampala and Ndejje (one receiver) and one between Ndejje and Mityana (Wakiso).

Measuring round 3

The third measurement round is done because of a failure in the dual frequency GPS receiver at Mityana Secondary School during the second measuring round. As the problem of the GPS failure was not entirely clear, we decided to put this receiver at the Makerere University as it can be frequently monitored there. The well working other two GPS receivers, are set up at Ndejje Secondary School again and at a new location: Wanyange Girls School. The latter one was chosen to make sure that if the problem was caused by the electricity network of the school in Mityana, it would not fail again.

At Ndejje Secondary School, the dual frequency GPS is set up on 17 October 2016. The same location as last time is used. At Wanyange Girls School, the GPS receiver is set up on Tuesday 18 October 2016. Wanyange Girls school is situated on top of a hill and the receiver is placed on the roof of the guard house at the entrance of the school. Unfortunately there is a tree nearby and the gate will also block a part of the sight. However, this was the most suitable location, as it is not blocked by large buildings or multiple trees, it is not on the ground where students can come and disturb the signal and it is situated near a power supply.

Single frequency receivers are set up on Tuesday 25 October 2016. One is again set up at the same place in Makerere High school in Migadde. A new school in this track is added: the World Ahead Secondary School. There the single frequency receiver is also put on a high open place on a water tank. Then there is put one on the rooftop of the Colline hotel in Mukono, which is situated between Wanyange and Kampala. There were many multipath objects and the signal could also be blocked by parts of the building. The other one in between Kampala and Wanyange was located at the Homeland Secondary School, where it was put on top of the entrance gate. There was one tree standing nearby, furthermore it had a clear sight. The last one in the middle of the network, was set-up on top of a water tank at the African Village Hotel. There it had a quite good sight, as it was approximately as high as the top of the surrounding trees. The overview of this measuring round is presented in the map of Figure 5.

Overview set up measurement round 3

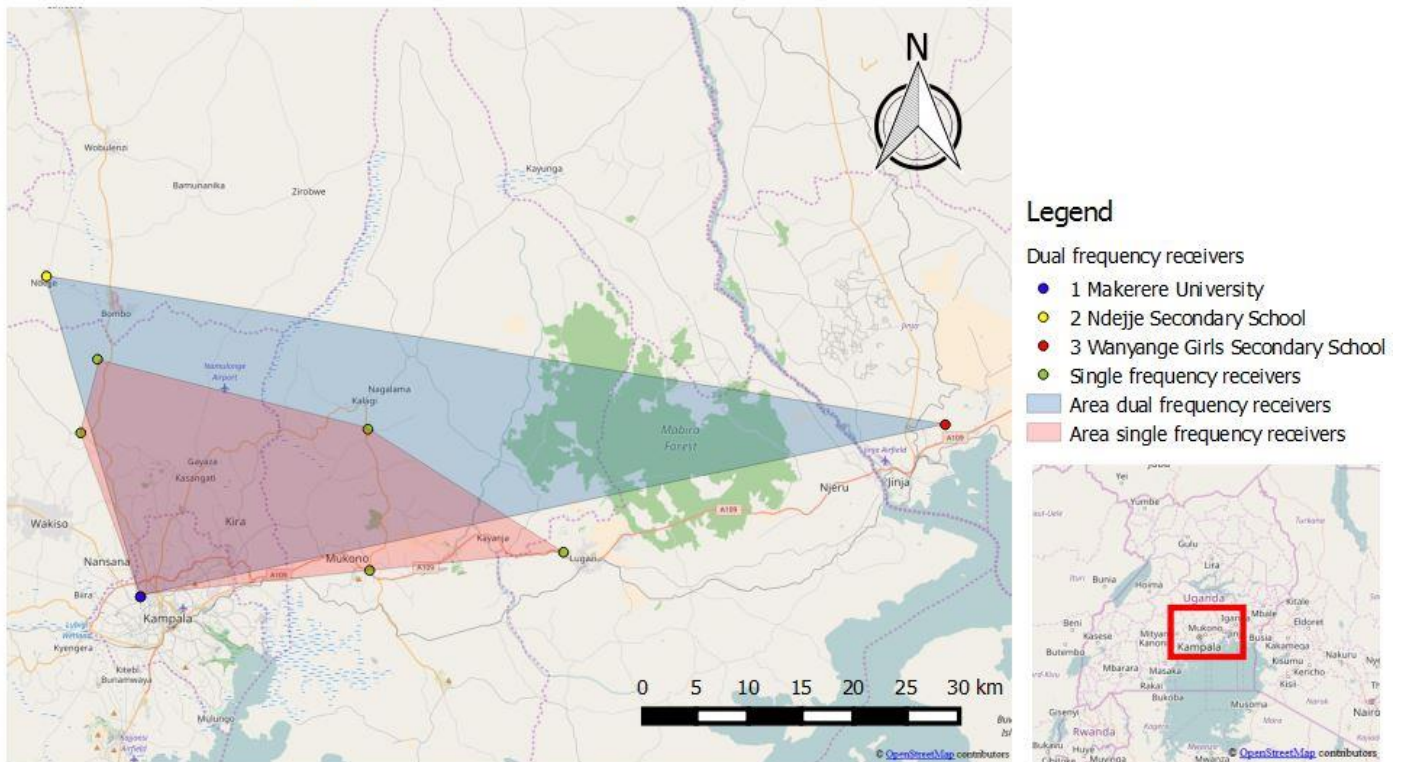


Figure 5 A map showing a part of Uganda. The first dual frequency GPS receiver is still located on top of the roof of the physics department of the Makerere University (blue dot). The Second dual frequency GPS receiver is located at Ndejje Secondary School (yellow dot) and the last one is set up at Wanyange Girls School, indicated by the red dot. As can be seen, the single frequency receivers (green dots) are placed in between Kampala and Wanyange (two receivers), between Kampala and Ndejje (two receivers) and one between Ndejje and Wanyange.

4 Results & Discussion

It is ideal to station the GPS receivers at location for about one day in order to let the standard deviation converge to the lowest possible value. For the dual frequency receivers this is not a problem, as they run continuously. For the single frequency receivers it is much more difficult, as it depends on how long the batteries will provide power to the antenna and raspberry-pi. Therefore we should have a look at the standard deviation that is given by the NRCan Processing software: the standard deviation of the ZTD should at least reach 1 cm (Marel 2016). To analyse this effect, the standard deviation of the ZTD for different time durations will be analysed. Another quick check on the quality of the ZTD is to view the quality (standard deviation) of the height estimation, as the ZTD is also highly correlated with the height estimation, as they are estimated in the same direction (van der Marel 2016a). In this section, the ZTD output and its standard deviation of each of the receivers will be presented.

To make a statement about the precision of the single frequency measurements that have a generated L2- and C2- observation, there will be a comparison between these two at the same location. Furthermore, we will give some attention to the accuracy of the interpolation of the ionosphere to generate the L2- and C2- observations for the single frequency receiver.

To make a statement about the accuracy of the measurements, other measurement method should be used. However, in this timeframe, it was not possible to do this as insufficient weather data is available for Uganda and processing satellite data would be too much to process in such a short time.

Measuring round 1

For the dual frequency receivers, the zenith total delay (also called tropospheric zenith delay), is in the order of 2.2 m and its standard deviation decreases rapidly after the start of the logging: in one hour it decreased from more than 0.1m to well below 0.01m. Therefore, these measurements are sufficiently well to use for PWV determination. An example of one of the dual frequency receivers can be viewed in Figure 6.

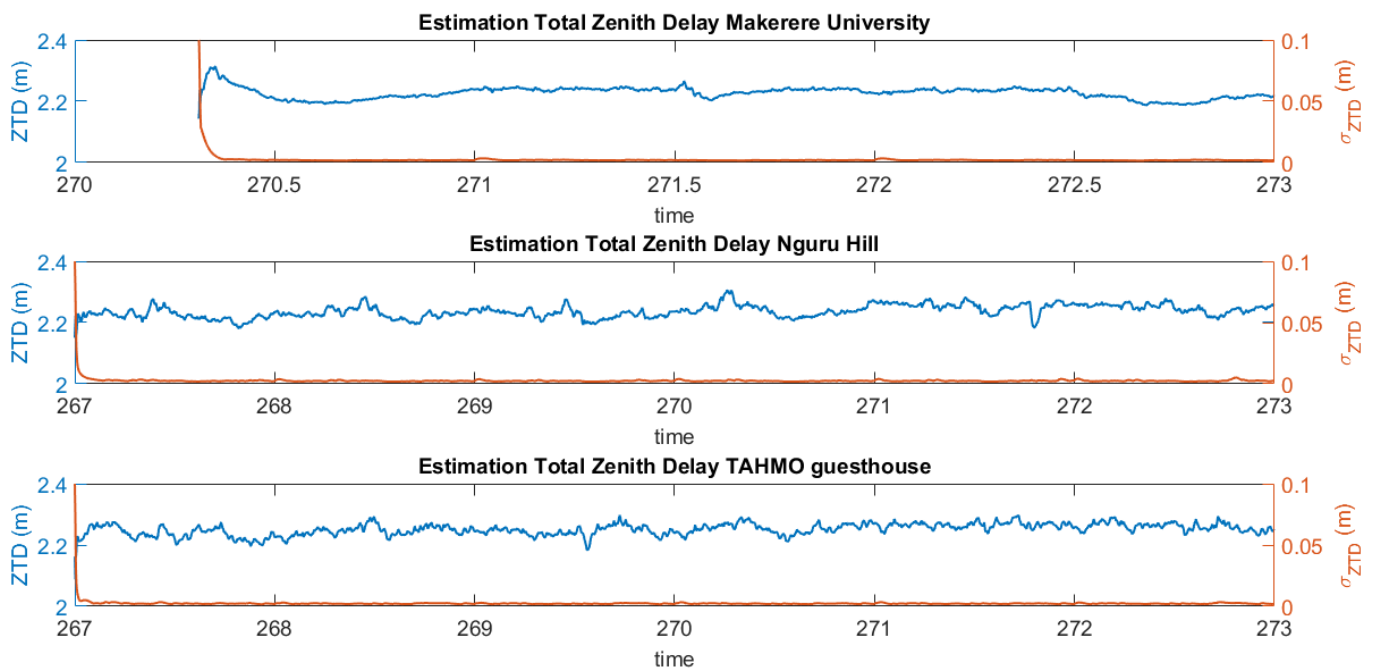


Figure 6 The ZTD (blue) and its standard deviation (red) are show for the dual frequency GPS receivers at Makerere University, Nguru hill and the TAHMO guesthouse, respectively. As can be seen, the standard deviation reduces quickly in time; in less than 2.5 hours from the beginning of the measurements it reduced to less than 0.005m.

The standard deviation of the single frequency receivers is a factor 10 higher than in the dual frequency receiver. In addition, the time needed to converge to this level is also longer. This could be due to several things. Firstly, PPP processing sends a warning about the antenna type, which was not given in into the newly formed RINEX file, which will cause a larger error in the height estimation. Therefore, we wanted to find these entries to solve this problem, as the height estimation is essential for ZTD estimation. While looking for the antenna type, we found out that a patched T0002 antenna is used, however, this type was not recognised by the NRCan website and therefore it was not able to correct for this antenna type. Secondly, there are many more ambiguity resets in the single frequency PPP output than in the one of the dual frequency receiver.

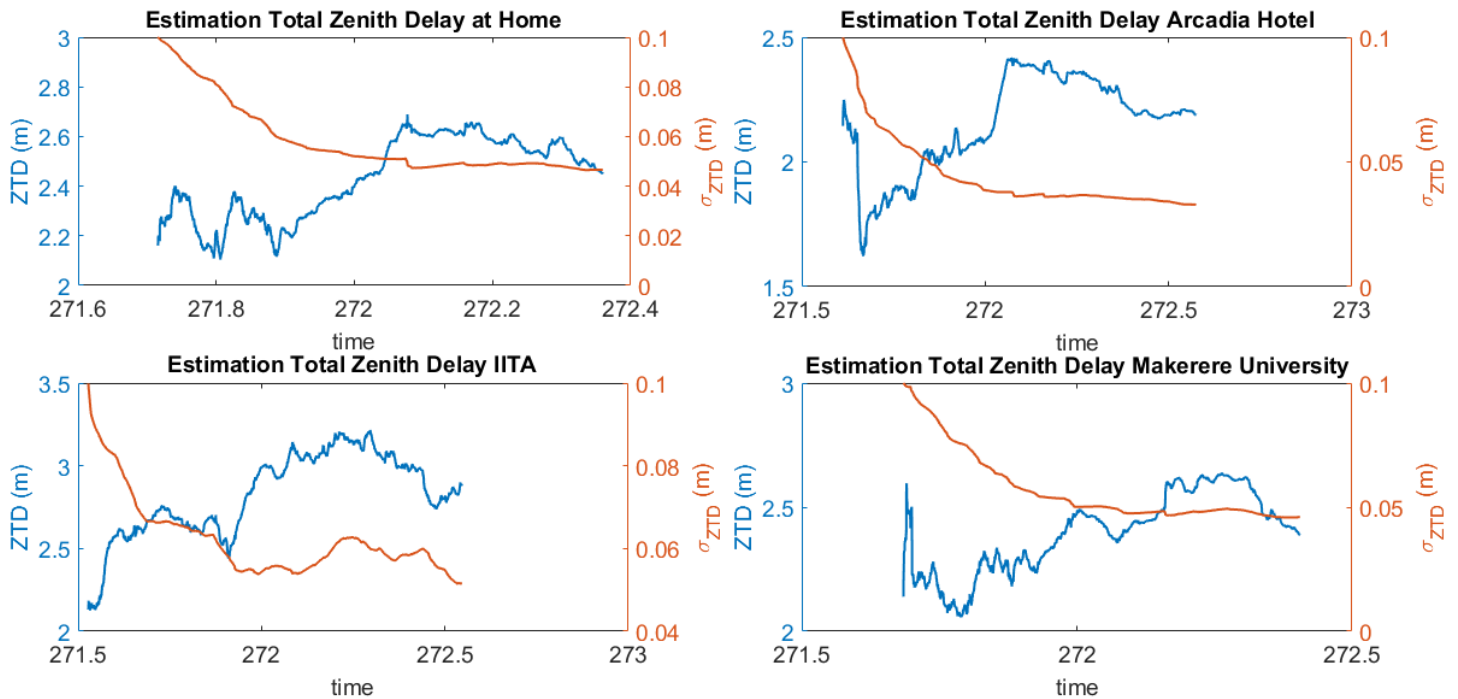


Figure 7 The ZTD (blue) and its standard deviation (red) are show for the single frequency GPS receivers at Makerere Kikioni (Home), the Arcadia hotel, IITA and Makerere University. Mind the different scales on the axis. As can be seen, the standard deviation reduces less quickly in time than in the dual frequency diagrams; instead of less than 2.5 hours from the beginning of the measurements to reduce to less than 0.005m, it needs about half a day to reduce to only 0.05m or 0.04m.

Measuring Round 3

The results of the dual frequency receivers that are far apart now (<90km), are presented in Figure 8. As can be seen, a different ZTD is measured at each location, as was expected for this configuration of the dual frequency receivers. The standard deviation of the measurements went down quickly, as was also seen in the first measuring round.

The single frequency receiver results for the ZTD (blue) and the standard deviation in the ZTD (red) are shown in these figures. Note the different scales for each receiver. As can be seen, the estimated ZTD varies significantly for the different receivers, as was expected. The standard deviation of all receivers goes down, but seems to level off near 0.05m. This is too much for using as good input for PVW estimation.

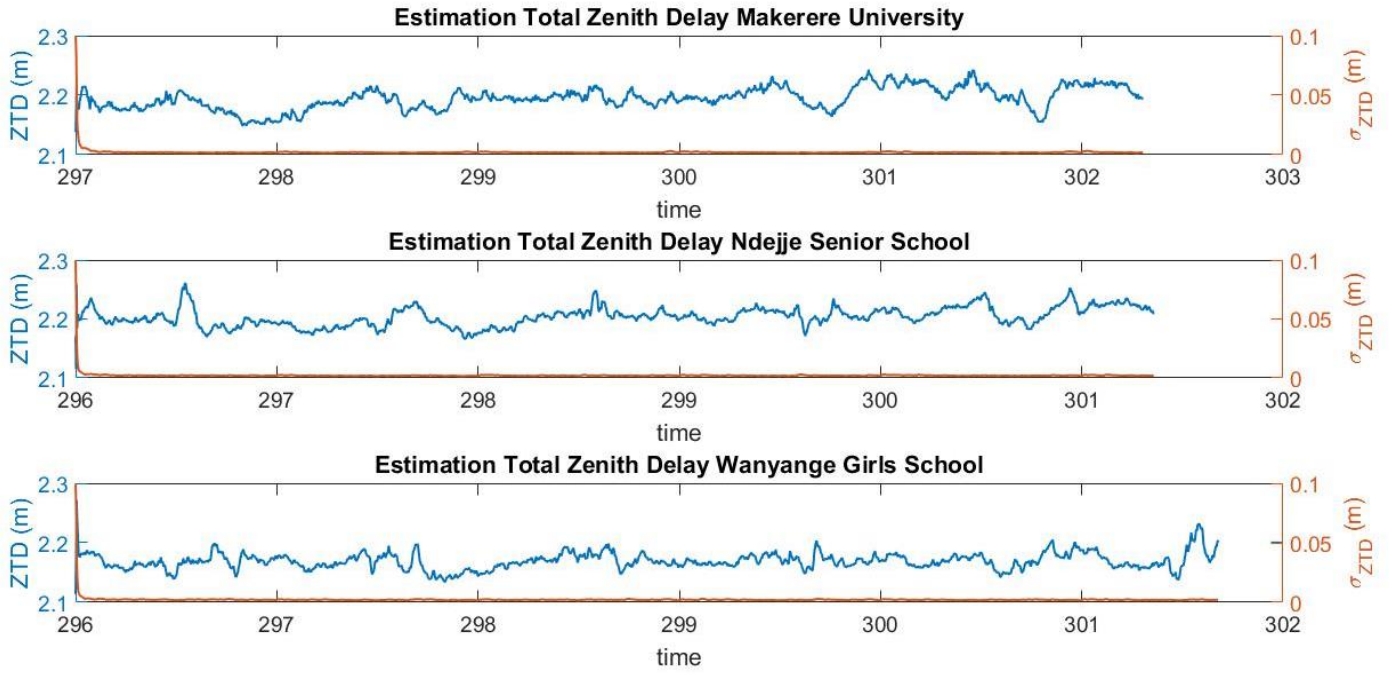


Figure 8 The ZTD and its standard deviation are shown in blue and red, respectively. As can be seen, the standard deviation reduces quickly in time, as was also seen in the first measuring round. The values and especially the shape of the estimation is different, which was expected as the ZTD is also expected to be different if the measurement locations are far apart.

The single frequency receivers have the same convergence velocity in the standard deviation as in the first measuring round. On top of this, they converge to the same level as in the first measuring round, even though the distance between the single frequency receivers and the dual frequency receivers increased much. This is an indication that the interpolation scheme is working equally well with increasing distance.

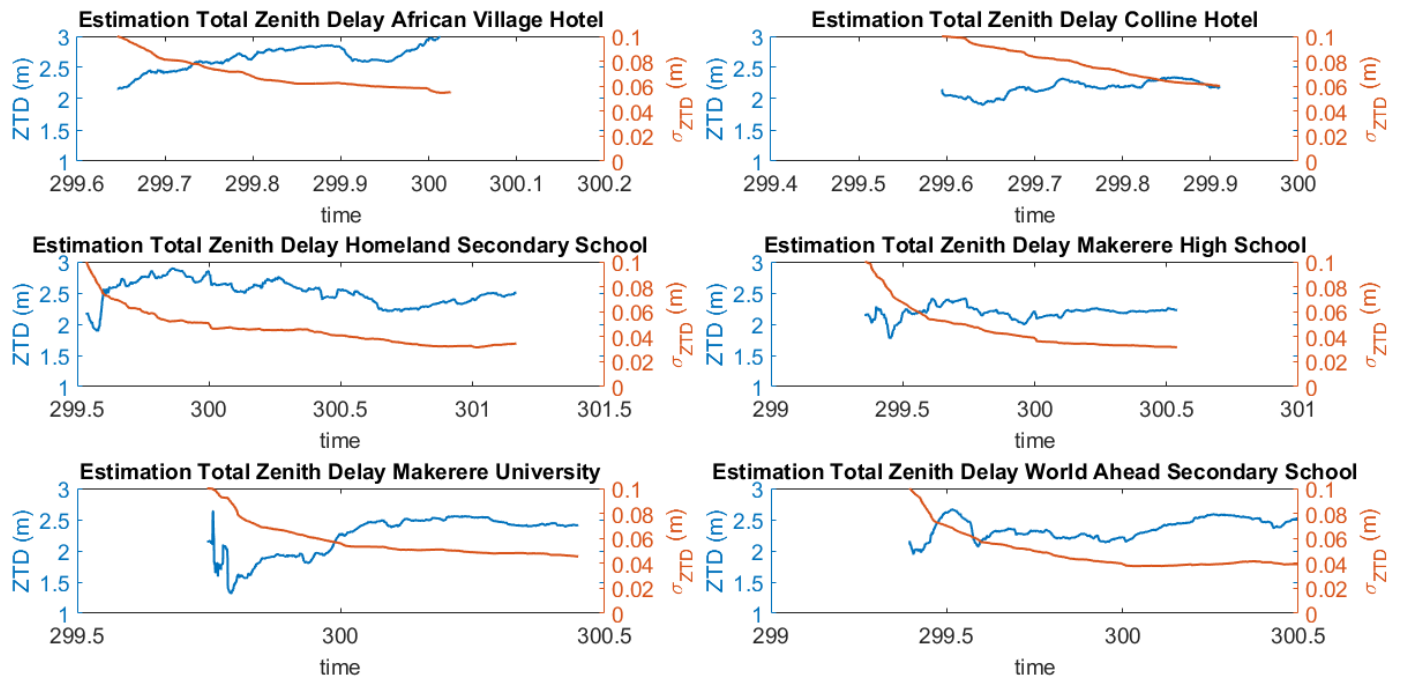


Figure 9 The ZTD (blue) and its standard deviation (red) are shown for the single frequency GPS receivers. As can be seen, the standard deviation reduces in about half a day to only 0.06m or at best 0.03m. This is consistent with the observation in the first measurement round.

Ionospheric delay

The ionospheric delay needed to be estimated for both frequencies of every dual frequency receiver. When estimated, the ionospheric delay was interpolated to obtain the ionospheric delay at the two frequencies at the single frequency GPS receivers. Here, the ionospheric delay plot has been given in Figure 10 to show that the three dual frequency receivers exhibit similar behaviour and to confirm that the shape of the graph is logical in time. In Uganda, the Sun is at its highest point right above us at one in the afternoon, local time. Local time differs 3 hours from local time, as Kampala uses the UTC+3 zone. The maximum ionospheric delay is expected a bit later than solar noon: at this time there is the solar maximum, so most electrons will form during this time and built up, until solar induction will decrease and electrons can recombine with their atoms again after some time. This is what is seen in the graph. The maximum is at around 11 or 12 AM, therefore the time in Uganda will be at 2 or 3 PM, a bit later than the solar maximum. This is an indication that the calculation is done correctly. According to (Misra & Enge 2001), the ionospheric delay (mapped to the zenith direction) can be in the order of 10m or more, which is also seen in the graph.

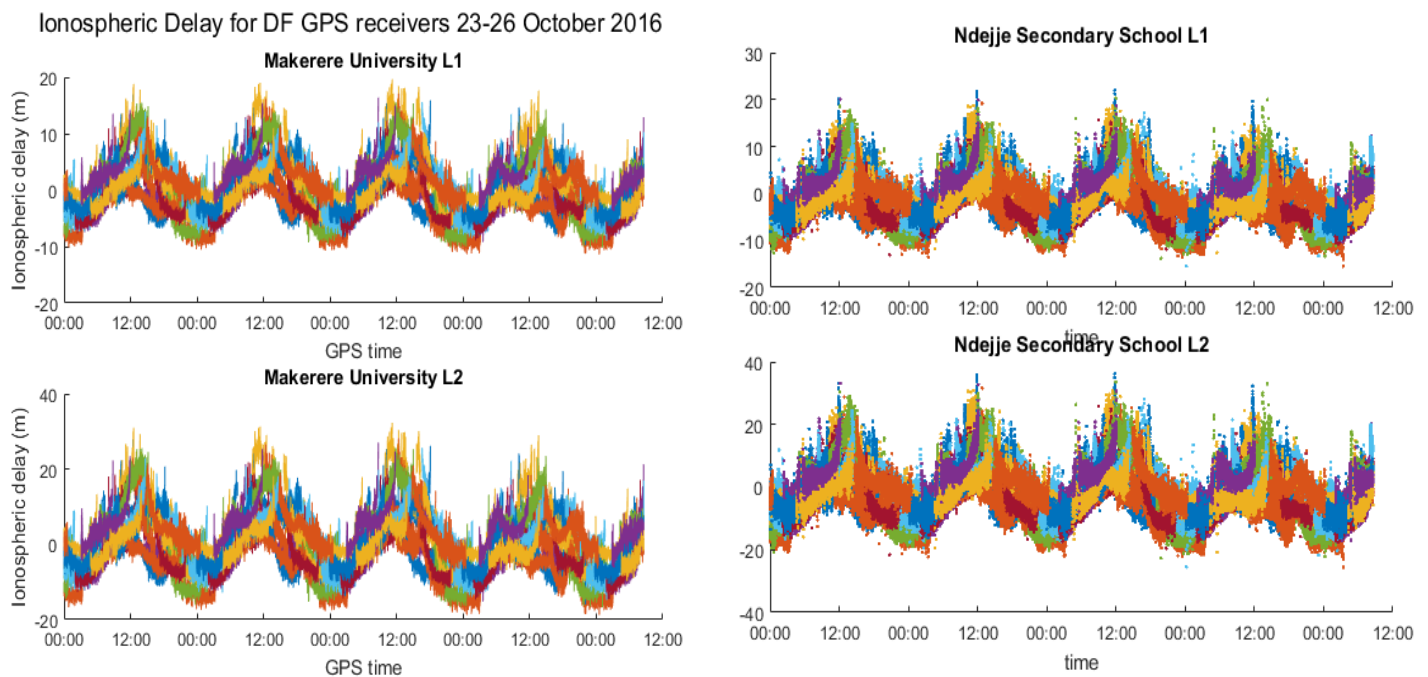


Figure 10 For two of the stations, the ionospheric delay at each frequency is shown. The different colours represent the different 32 satellites. There can be seen that the maximum ionospheric delay occurs at around noon, depending on the path of the signal. This is an indication that the ionospheric delay is calculated correctly.

Comparison Single- and Dual frequency simultaneous observations

In the third measurement round, the single frequency receiver ran together with the dual frequency receiver at Makerere University. This is done to view the difference between these two receiver types. In Figure 11 the ZTD and the standard deviation of the ZTD for both receivers are shown. The precision of the dual frequency receiver is much higher than that of the single frequency receiver. In addition, the estimated ZTD is much more constant for the dual frequency receiver. As there is already shown that a good ZTD estimation is possible using double frequency receivers (Bevis et al. 1992; Bevis et al. 1994; King 1995), we assume this signal is closest to the truth. The cause could be that in the single frequency receiver PPP, there are more ambiguity resets. This reduces the precision of the ZTD measurement, as it introduces also an error spike in the height estimation (Shen 2002). Secondly, there was no antenna correction possible for the single frequency receivers, causing a larger error in the height estimation and accordingly in the ZTD estimation. At last, there is probably a high correlation between the measurement on the first frequency and

the measurement on the second frequency. PPP processing does not correct for this correlation; it assumes that the measurements at the different frequencies are measured independently.

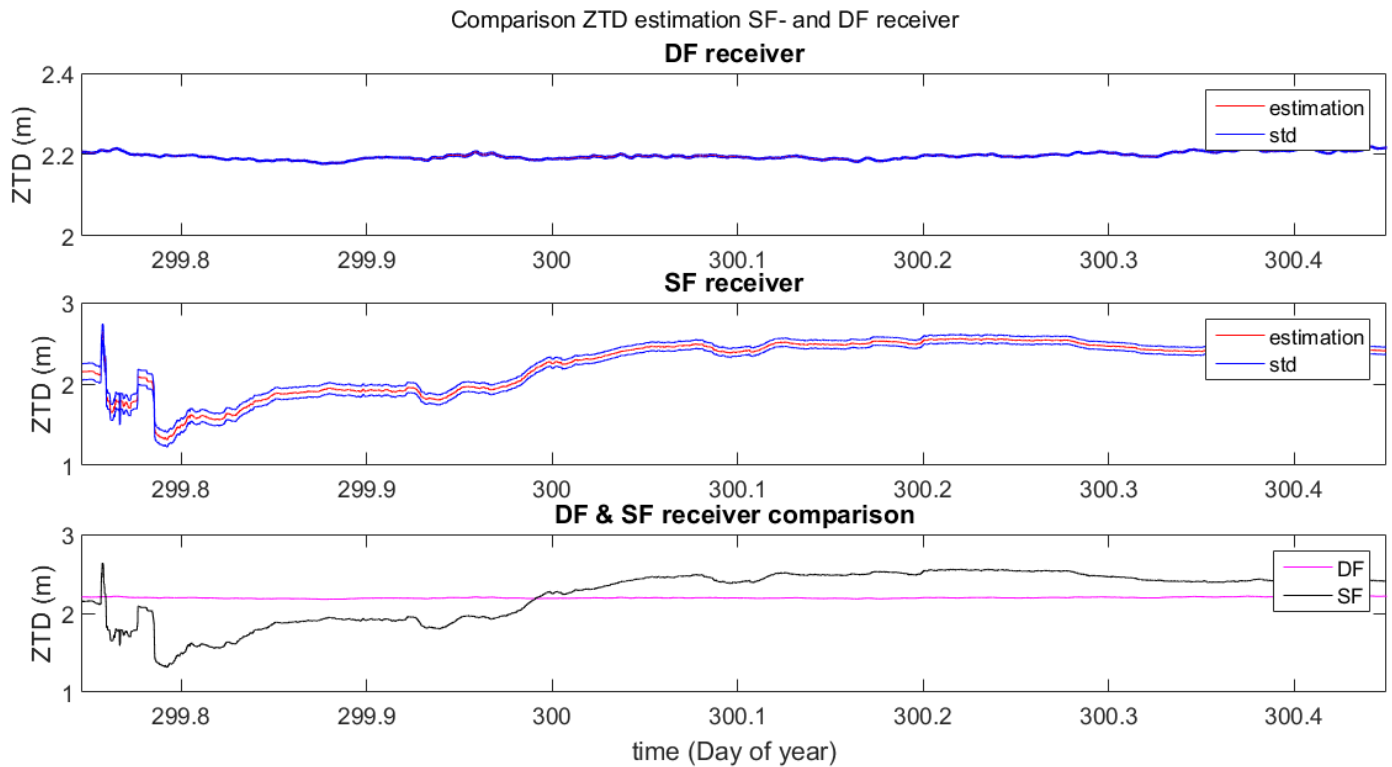


Figure 11 The comparison between a dual frequency receiver at (almost) the same location is made in three different ways. The first panel shows the estimation and standard deviation for the dual frequency receiver. There, the standard deviation lies upon the estimated value and the ZTD does not differ very much according to the measurements. In the second panel, the estimation and standard deviation of the single frequency receiver is shown. There, the deviation is much larger, and also the variation in the estimated ZTD is larger. In the last panel, the estimation of the dual and single frequency receiver are shown together. Combining the three windows, we can state that the single frequency measurements are not very accurate. Hereby is assumed that the dual frequency receiver is more reliable, as it is already shown that the ZTD can be well estimated using dual frequency receivers (Bevis et al. 1992; Bevis et al. 1994; Duan et al. 1995).

5 Conclusion

The measurements done with the u-blox M8T were not precise nor accurate enough for estimating a good ZTD. This is thought to be due to the very frequent ambiguity resets and a lack of information on the antenna for PPP processing and the correlation between the measurements on the first and second frequency. Measuring for a longer time will not decrease the standard deviation as it seems to level off at 3-5cm, whereas we need at maximum a standard deviation of 1cm.

Further research

To continue this research more, we would advise to think of a continuous power supply to provide the single frequency antenna and raspberry-pi with power to be able to run even longer than 24 hours. This would help save a lot of time to obtain a longer time series.

To reduce ambiguity reset, there could be looked into methods to use former estimations of the ambiguity when there was a loss of an in-between epoch. Another approach is to use the code estimations for the ionospheric delay and level them with the phase-measurement estimations. This could give an indication of the ambiguity already (van der Marel et al. 2016). Another approach is an enhancement of the ambiguity resolution (Jokinen 2014).

Validating the accuracy of the ZTD and PWV has not been possible in the time frame of this research; the single frequency data is only compared to the dual frequency data. The latter is assumed to be the best data available. If available for this period of time, it is suggested to do the validation using satellite weather data.

If the dual frequency u-blox receivers come available, it is advised to test these receivers as well, for they are much less expensive than usual dual frequency receivers and it is thought these will be able to estimate the ZTD better as they have independent measurements on the two different frequencies.

If everything is working properly, one could think of looking into real-time estimation of the ZTD. Another follow-up research could be found in obtaining a vertical PWV profile as input to numerical weather models, as is done in (Troller 2002).

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Appendix

Read out Trimble 5700 with DataTransfer programme

Makerere University location is called m1 (Eva)

1. Turn off the data logging by pressing the data button for 3 seconds.
2. Disconnect the power supply from the cable and connect the middle output with the VGA to USB and put in computer
3. Start DataTransfer software and press devices.
4. Press new and select the GPS Receiver (R/SPS/ 5000 series).
5. For the port, select the COM6 port.
6. In the COM6 port menu every setting is left untouched.
7. Click in the window part of 'Files to Receive' on Add
8. Select all the files you want to transfer and put a directory to transfer to.
9. Click transfer all
10. When the transfer has taken place, you have both the .T01 and .DAT files, that still need to be converted. Use the programme 'Convert to RINEX' to do this.

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.

Read a RINEX file

C1 – pseudorange from C/A-code on L1 (m)
L1 – L1 carrier cycles (number of L1 cycles)
L2 - L2 carrier cycles (number of L2 cycles)
P1 – pseudorange from P-code on L1 (m)
P2 – pseudorange from P-code on L2 (m)
D1 – Doppler on L1 (Hz)
D2 – Doppler on L2 (Hz)
S1 – Raw signal strength values L1
S2 – Raw signal strength values L2

U-blox receiver

Board features:

Ublox **NEO-M8T**

HMC5983 magnetometer

Patch antenna (GPS + GLONASS + BEIDOU) T0002

Power supply: **3.3V or 5V**

Rechargeable battery for faster startup

Filter on power supply lines

EMI Shielding

USB micro connector

Default configuration: 9600Baud & 1 Hz (can be changed easily with the U-center software)

Dimensions: **80*80mm**

Hole distance: 70mm

Personal correspondence with Hans van der Marel

Hallo Mariska en Eva,

Er komt in ieder geval geen onzin uit, maar de periode is veel te kort om er iets zinnigs over te zeggen. Voor PPP is het noodzakelijk data van 24 uur te verwerken, jullie hebben 30 minuten verwerkt. Je ziet dit terug in de geschatte positie die een standaard afwijking van meters heeft (en ook de hoogte die zwaar correleert met de geschatte ZTD), en de standaard afwijking voor de geschatte ZTD parameters van 0.1 meter. De 0.1 meter st.dev. voor ZTD lijkt op eerste gezicht misschien goed, maar dit is absoluut niet zo: a) je verwacht een waarde van beter dan 1 cm om enige betekenis te hebben, b) de PPP verwerking wordt van een a-priori model uitgegaan (zie de summary file) die als pseudo-waarneming wordt toegevoegd met een standaard afwijking van 10 centimeter.

Je kan een eenvoudige test doen om te zien of jullie procedure werkt: pas jullie procedure toe op de data van een 2^e dual frequency ontvanger (als ware het een single frequency ontvanger), verwerk de data van deze 2^e dual frequency ontvanger een keer met en een keer zonder correcties. Analyseer de verschillen. Je kan verschillende tests doen met verschillende afstanden tussen de ontvangers. Je kan ook een opstelling maken met twee ontvangers vlak bij elkaar . Verwerk altijd 24 uur data tegelijkertijd.

Een andere goede test is om een dual frequency en single frequency ontvanger op dezelfde locatie te gebruiken.

Dat jullie RINEX file positieve waarden bevat is om de reden die jullie noemen (negatieve waarden hebben te maken met de fase meerduidigheid).

Groeten,

Hans