Thesis for The Degree of Licentiate of Engineering

Enhancing the reliability of GNSS carrier phase measurements for precise positioning applications

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"This one's for you dad. Your memories will quietly reside in my heart forever...."

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Abstract

Global Navigation Satellite System's (GNSS) position, navigation and time (PNT) is used worldwide for numerous applications. With the advent of sophisticated techniques such as real time kinematic (RTK), precise point positioning (PPP) and the combination RTK-PPP, GNSS positioning using carrier phase data can now achieve centimetre to millimeter levels of accuracy in real time both in static or kinematic mode on land and decimeter to centimeter levels of positioning accuracy on the sea. In a post processing mode this accuracy can go down to sub-millimeter. However, the different error sources of GNSS continue to pose a hindrance to this. Even in a differential mode of operation, while error sources such as clocks and troposphere may cancel out for short baselines, rapid variations in ionosphere can cause loss of lock of the GNSS receiver, leading to cycle slips resulting in degraded position estimation. Also, local unmodelled error sources such as diffraction and multipath cannot be handled automatically by standard post processing software since they are dependent on the receiver environment. These error sources lead to large range errors which in turn impacts the position estimation accuracy. This work is a compilation of different studies on GNSS error sources and aims at enhancing the reliability of GNSS carrier phase measurements from a precise positioning perspective.

Keywords

GNSS, Satellite selection, network RTK (NRTK), PPP, Ionosphere, Multipath, Diffraction

List of Publications

Appended publications

This thesis is based on the following publications:

[**Paper I**] **Uttama Dutta**, Carsten Rieck, Martin Håkansson, Daniel Gerbeth, Samieh Alissa, Stefan Nord, *Satellite Selection in the Context of Network RTK for Limited Bandwidth Applications.*
Proceedings of the 34th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2021), 2474 - 2492, https://doi.org/10.33012/2021.17948 .

[**Paper II**] **Uttama Dutta**, Per Jarlemark, Carsten Rieck, Jan Johansson, *Ionospheric Effects on GNSS RTK.*
Proceedings of the 35th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2022), 1589-1598, https://doi.org/10.33012/2022.18297 .

[**Paper III**] **Uttama Dutta**, Jan Johansson, *Multi-Constellation/Multi-Frequency GNSS Signal Degradation Due to Foliage and Reflective Environments.*
Engineering Proceedings, 2023, 54(1):2, https://doi.org/10.3390/ENC2023-15454 .

[**Paper IV**] **Uttama Dutta**, Jan Johansson, Rüdiger Haas, *Investigating the impact of diffraction on GNSS carrier phase measurements.*
Submitted to Journal of Geodesy.

[**Paper V**] Samieh Alissa, Martin Håkansson, Carsten Rieck, **Uttama Dutta**, Stefan Nord, Peter Bergljung, Anders Bagge, *Distribution of the Adapted-NRTK Correction Data via VDES for the Shipping Navigation Safety.*
Proceedings of the 34th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2021), 521 - 534, https://doi.org/10.33012/2021.18142.

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Part I

Summary

Chapter 1

Introduction

Each winter, tens of thousands of Bar-tailed Godwits embark freely on a spectacular journey across the planet in pursuit of sunnier horizons. They navigate effortlessly through both day and night skies without the need for navigational aids or the requirement of permissions to cross man-made boundaries, which is quite a contrast to us, the supposedly "more intelligent species". While other challenges will continue to persist for us, our positioning, navigational and timing needs are thankfully fulfilled by the Global Navigation Satellite System (GNSS).

1.1 Global Navigation Satellite System (GNSS)

Navigation can be defined as the process by which a navigator determines it's position and direction relative to a reference point and target destination in space. It involves the integration of sensory information with internal representations of space to facilitate directed movement towards the target destination. In animals, navigation often relies on sensory cues like visual landmarks, magnetic fields, celestial cues, or odors. In contrast, human-made navigation systems utilize instruments such as compasses, gyroscopes, inertial navigation sensors and above all GNSS to determine position and to guide movement accurately. GNSS is a satellite based navigation system which provides accurate, continuous, all-weather, three-dimensional location for use in various applications such as disaster management, environmental monitoring, geomatics, precision agriculture, resource conservation, surveying, mapping, transport and timing etc. The GNSS service performance in terms of accuracy, integrity, continuity, and reliability has been improving in leaps and bounds over the past few decades. The purpose of a Global Navigation Satellite System is to have several satellite constellations operating together to provide better capabilities at the user level. With the availability of multiple global satellite navigation constellations (the American GPS, the European Galileo, the Chinese BeiDou, the Russian GLONASS) and a couple of regional systems (the Japanese QZSS, the Indian NavIC) a GNSS receiver should be capable of providing position information even in partially shadowed regions such as urban areas, forests, etc. However, as the GNSS signals travel from the satellite to the receiver they are affected by several error sources.

1.2 Significance of GNSS errors

The error sources and parameters discussed in this thesis are essential since the real-time GNSS-based techniques relying on carrier phase measurements are very vulnerable to errors arising from signal propagation delay in Earth atmosphere and in the local environment of the antennas. There are mainly two types of GNSS measurements used for positioning: the code-based pseudoranges and the carrier-phase measurements. The pseudorange to a satellite j from a receiver station A using code and carrier measurements is given by equations 1.1 and 1.2 respectively,

$$P_k^i = \rho_k^i + T_k^i + I_k^i + c\delta_k - c\delta^i + \nu_k^i. \tag{1.1}$$

$$L_{1k}^i = \rho_k^i + T_k^i - I_k^i + c\delta_k - c\delta^i + \lambda N_k^i + \nu_k^i, \tag{1.2}$$

where P or L is the pseudorange from code or carrier phase measurements respectively ρ_k^i is the true range to the satellite i from the receiver antenna k, T_k^i is the tropospheric error, I_k^i the ionospheric error, c the speed of light, δ_k the receiver clock correction, δ^i the satellite clock correction, λ the wavelength of the L_1 or L_2 carrier signal, N the respective carrier phase ambiguity and ν_k^i denotes the local effects influenced by the environment around the antenna such as multipath, diffraction and other biases such as receiver noise. Errors in the GNSS measurements are broadly classified as: satellite-based errors, propagation medium or atmospheric errors and receiver-based errors. Some errors can be removed, and some can be reduced. Understanding of the significance of these errors is important for applications especially requiring high accuracy measurements. *The discussions in this chapter focus on GPS information primarily.*

1.2.1 Satellite based errors

There are five major types of satellite-based errors. They are: clock errors due to instability of onboard atomic clocks, ephemeris errors due to errors in the estimated satellite positions, instrumental bias due to RF components of satellite and receiver, relativistic effects due to different gravitational potential experienced by satellite and receiver clocks and selective availability (if any) due to intentional degradation of the GPS signal in frequency and time domain. Satellite geometry is also crucial for accurate measurements. The general overall GPS design was for unaided code observations and was specified to a global coverage with at least four satellites in view above five degrees elevation at 99.9% of the time [1].

1.2.1.1 Ephemeris error

While the ephemeris data is transmitted every 30 seconds, the information itself may be up to two hours old. Variability in solar radiation pressure has an indirect effect on GPS accuracy due to its effect on ephemeris errors. The satellite ephemeris is required for both pseudo range and phase computations. The master control station is responsible for estimating and updating the satellites ephemeris via broadcasted navigation data which can be used by real-time applications.

1.2.1.2 Clock error

The satellite clock error is the difference between the true GPS time and the time maintained by a satellite. Though the satellite contains highly stable atomic clocks, they drift with time. This drift is closely monitored by the monitor stations. The master control station estimates the drift and transmits clock correction parameters to the satellite for rebroadcast in the navigation message, which is used to correct the time and measurements in a receiver [2].

1.2.2 Atmospheric errors

The satellite signals propagate through atmospheric layers as they travel from the satellite to the receiver. Two layers are generally considered when dealing with GPS: the ionosphere, which extends from a height of about 50 to 1000 km above the Earth, and the troposphere which stretches to about 16 km above the equator and 9 km above the poles from the surface of the earth.

1.2.2.1 Ionospheric error

The ionosphere is a region of ionized gases (free electrons and ions). The principal source of ionization in the ionosphere is the electromagnetic radiation from the sun. As the GPS signal travels from the satellite to the receiver, the presence of free electrons in the ionosphere changes the velocity (speed and direction) of propagation of the signals. The change in signal speed changes the travel time of the signal, and therefore the apparent range to the satellite. The ionosphere is not uniform in composition, and the refractive index changes all along the path of a signal. The effect of signal bending causes a range error, which is quite substantial at very low elevation angles less than $5°$. The ionosphere speeds up the propagation of the carrier phase beyond the speed of light, while it slows down the Pseudo Random Noise (PRN) code (and the navigation message) by the same amount. Therefore, the receiver-satellite distance will be too short if measured by the carrier phase and too long if measured by the code, as compared with the actual distance [3]. The ionospheric delay is proportional to the number of free electrons along the propagation path, which is known as the Total Electron Content (TEC). Further, this delay is dependent on three main factors: the geomagnetic latitude of the receiver, the time of day and the elevation of the satellite. A technique to remove a large part of the contribution from the ionosphere is to form a linear combination, L3, of the L1 and L_2 observables [4]

$$L_3 = 2.55L_1 - 1.55L_2. \tag{1.3}$$

It should be noted that due to such an approximation errors are introduced due to uncertainties involved in this computation. Paper-II discusses on the effects of ionospheric activity on RTK.

1.2.2.2 Tropospheric error

The troposphere is the lower part of the atmosphere that is non-dispersive for frequencies up to 15 GHz. The troposphere causes a delay in both the code and carrier observations. Since it is not frequency dependent (within the GPS L band range) it cannot be canceled out by using dual frequency measurements, but it can, however, be successfully modeled accurately. The troposphere can be split into two parts: the dry component, which constitutes about 90% of the total refraction, and the wet part, which constitutes the remaining 10%. Values for temperature, pressure and relative humidity are required to model the vertical delay due to the wet and dry part, along with the satellite elevation angle, which is used with an obliquity/mapping function. The tropospheric error is computed by calculating a product of the zenith total delay (ZTD) with $m(\epsilon)$ (the mapping function).

1.2.3 Receiver based and local sources of error

Receiver based errors could be receiver noise caused due to limitations of receiver electronics, receiver clock error due to use of inexpensive crystal clocks, which are less accurate than that of the satellite clocks and improperly modeled antenna phase center variations. Antenna phase center for a receiver varies with frequency, elevation and azimuth and is difficult to model. Moreover, other unmodeled local sources of error, such as those due to the antenna environment, such as multipath and diffraction pose a hindrance to optimum position estimation using GNSS [5]. Multipath error occurs due to multiple signals reaching the GPS antenna upon reflection from ground, nearby buildings and structures. Reflected signals reaching the antenna have a path difference and phase difference with respect to the direct signal. The superposition of the reflected and direct signal gives a composite signal which is different in phase and amplitudes with respect to the direct signals. After arriving at the receiver antenna, the multipath signals propagate into the receiver where they distort the correlation function of the tracking loop. Subsequently, they cause biases in range and carrier-phase estimations. These range errors are intolerant for high-precision applications, such as earthquake monitoring, crustal deformation monitoring, etc., which require millimeter-level precision. Multipath effect is environment dependent and not spatially correlated and hence cannot be removed by using differential techniques. Various pre-receiver, in-receiver and post-receiver approaches are followed to mitigate the code and carrier Multipath error. The code Multipath errors for each satellite for successive days can be isolated by calculating the Code-Minus-Carrier values [4][6]. Multipath error repeats itself with each passing sidereal day if the environment around the antenna remains the same for successive days. Effective signal processing using adaptive filters for two successive days can extract out multipath. The calculated Multipath error is smoothened with Carrier smoothing filter to remove the high frequency receiver noise. Diffraction occurs when radio waves bend around an object. This could be caused by either natural or man-made obstructions to the Line-of-sight path to the GNSS signal, such as hills or buildings. The work done in Paper-IV explains a knife-edge diffraction model for signal diffraction and the discusses the degradation in GNSS positioning due to signal bending.

1.3 Differential GPS (DGPS)

Most of the error sources in GNSS can be eliminated or reduced using Real time Kinematic (RTK) network where GNSS carrier phase signals received at a stationary reference with known position coordinates are used to correct position data at a rover receiver in another location. Differencing measurements of two receivers to the same satellite eliminates satellite-specific biases; differencing between two satellites and one receiver eliminates receiver-specific biases. As a consequence, double-difference pseudoranges (as in RTK) are, to a high degree, free of systematic errors originating from the satellites and from the receivers [7]:

$$\nabla\Delta L_{AB}^{ij} = \nabla\Delta\rho_{AB}^{ij} + \nabla\Delta T_{AB}^{ij} - \nabla\Delta I_{AB}^{ij} + \nabla\Delta\lambda N_{AB}^{ij} + \nabla\Delta\nu_{AB}^{ij}. \tag{1.4}$$

Double differencing technique is used for cancelling out clock biases and minimizing atmospheric errors for short baseline lengths as shown in Equation 1.4 in which two satellites i, j and two stations A, B are used to compute the double differencing. The true length is given as a sum of true baseline length, the atmospheric errors and the error due to integer cycle ambiguity. Integer phase ambiguity is computed by using the code phase as a reference to the carrier phase. Since the atmosphere does not vary much for short baseline lengths, their error contribution to Equation 1.4 is minimal.

1.4 Real Time Kinematic (RTK)

Real Time Kinematic (RTK) is a system that utilises Global Navigation Satellite Systems (GNSS) carrier phase measurements to provide accurate positioning in real time.

The general idea in RTK is to receive GNSS carrier phase signals at a stationary reference with known position coordinates and to use these to correct position data at a roving receiver in another location. The ideal signal is perturbed by ionosphere, troposphere and imperfections related to ephemerides, clocks and multipath and thus the calculated position coordinates differ from the known coordinates. By calculating corrections that mathematically “move” the reference to its known position and subsequently apply a similar set of corrections to the rover, the rover's position can also be determined very accurately. As the reference and rover are at different locations, the signals have been perturbed differently and the correction data are therefore affected by uncertainties that compromise the reliability of the rover's corrected position. The factors that affect the uncertainties can be classified in different ways, e.g. distance dependent, systematic, random, site specific, rapid, frequency dependent (dispersive).

With RTK it is also implicit that, in addition to the broadcast code signals that are handled by relatively cheap off-the-shelf products, the carrier phase of the signal is analysed with a geodetic receiver. With this technique it is possible to obtain position coordinates with accuracy of order 1 cm. The difference between RTK and Network RTK (NRTK) is that the latter combines data from several reference stations to provide the rover with corrections. With NRTK the distance dependent errors are interpolated between the reference stations, which allows for increased distance between reference stations without losing position accuracy.

One such NRTK method builds on the concept of Virtual Reference Station, VRS. At the VRS, the rover calculates a position from uncorrected code data like any off-the-shelf receiver and uploads this navigated solution to the central unit. The central software then deploys a virtual reference station at the coordinates of the initial navigated solution on the common phase ambiguity level that is calculated from data from an appropriate combination of the surrounding reference stations. From the synthetic data of the calculated surface, the VRS emulates a real reference receiver at the initial navigated coordinates. The rover receives the VRS data and makes a phase adjustment of its own position on the relatively short baseline.

The knowledge of error sources and parameters discussed in Section 1.2 are essential since real-time GNSS-based techniques are very vulnerable to errors arising from signal propagation delay in Earth atmosphere and in the local environment of the antennas. This is true both at the reference station and the rover. While the discussion on error sources in Section 1.2 are relevant for both code and carrier phase measurements, the primary focus of this work is using carrier phase measurements. This is because carrier phase measurements are often preferred over code measurements in precise positioning applications due to their improved signal resolution.

Chapter 2

Normal equation and position estimation using GNSS

2.1 Theory of least squares

Normal equations provide an analytic solution to least squares for optimization problems. Let us consider a system of equations with n parameters and m observations. Written in matrix form such an equation can be represented as

$$Ax = b. \tag{2.1}$$

Here, x is a vector of independent variables with n parameters. A is a design matrix of rank (r) and b is the matrix of observations, dependent on the values of x. Since x allows n degrees of freedom, Equation 2.1 can be uniquely solved when A^{-1} exists and $m = n = r$, such that $b - Ax = 0$. However, in most cases, the number of observations is much larger than the number of parameters needed to be estimated. Thus a minimization of the value of $b - Ax$ is aimed at. According to Gauss minimization of the square of the euclidean norm of $b - Ax$ provides an optimum estimate of x, $\hat{x}$. Thus for a least squares estimate,

$$\text{if} \quad L(\hat{x}) = (b - A\hat{x})^T(b - A\hat{x}) \quad \text{then} \quad \delta L(\hat{x}) = \delta(b - A\hat{x})^T(b - A\hat{x}) = 0 \tag{2.2}$$

Where δ is a partial derivative. Extending the rule for derivative of a product to a partial derivative,

$$\delta(b - A\hat{x})^T(b - A\hat{x}) + (b - A\hat{x})^T\delta((b - A\hat{x}) = 0 \tag{2.3}$$

Since the transpose of a product of two matrices will be equal to the product

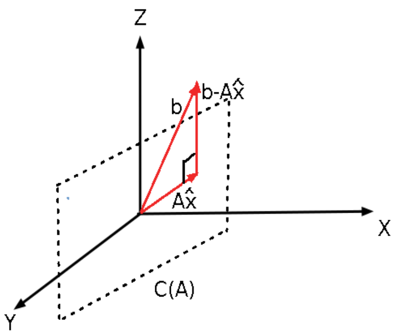

Figure 2.1: Geometrical interpretation of normal equation in the 3 dimensional position domain

of the transpose of individual matrices in reverse order,

$$\begin{aligned}&(-A\delta\hat{x})^T(b-A\hat{x})+(b-A\hat{x})^T(-A\delta\hat{x})=0\\&(-2A\delta\hat{x})^T(b-A\hat{x})=0\\&((\delta\hat{x})^TA^T)(b-A\hat{x})=0\\&(\delta\hat{x}^T)(A^Tb-A^TA\hat{x})=0\end{aligned} \tag{2.4}$$

since $(\delta\hat{x}^T)$ can never be equal to zero,

$$A^Tb=A^TA\hat{x} \quad\implies\quad \hat{x}=(A^TA)^{-1}A^Tb \tag{2.5}$$

Equation 2.5 gives the normal equation and its solution.

2.2 Geometric interpretation of normal equation

Figure 2.1 shows the geometrical interpretation of a normal equation in the 3 dimensional position domain. Vector $A\hat{x}$ is $\hat{x}$ as mapped to the planar column space of A, $C(A)$. Thus the error vector $b-A\hat{x}$ is minimum when it is perpendicular to $A\hat{x}$. Therefore the dot product

$$(A\hat{x})^T\cdot(b-A\hat{x})=0, \tag{2.6}$$

which leads us to the solution presented in Eq. 2.5.

2.3 Position estimation using GNSS data

A linearised model is assumed where the actual observation is a sum of modeled observations and noise (ν). Next using apriori values for estimated parameters, the model is expanded about the apriori using Taylor series expansion. The second and higher order terms are ignored. Typically for a set of 4 parameters (3 coordinates x, y, z and time τ) an equation can be built for each satellite in view that epoch of data. For m such satellites, the equation in matrix form is as follows,

$$\begin{bmatrix} \Delta P^1 \\ \Delta P^2 \\ . \\ . \\ \Delta P^m \end{bmatrix} = \begin{bmatrix} \partial P^1/\partial x & \partial P^1/\partial y & \partial P^1/\partial z & \partial P^1/\partial \tau \\ \partial P^2/\partial x & \partial P^2/\partial y & \partial P^2/\partial z & \partial P^2/\partial \tau \\ . & & & \\ . & & & \\ \partial P^m/\partial x & \partial P^m/\partial y & \partial P^m/\partial z & \partial P^m/\delta \tau \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \\ \Delta \tau \end{bmatrix} + \begin{bmatrix} \nu^1 \\ \nu^1 \\ . \\ . \\ \nu^m \end{bmatrix}, \tag{2.7}$$

where the superscript in Equation 2.7 is the satellite number.

2.3.1 Co-variance and co-factor matrices

Equation 2.7 is often written as

$$\mathbf{b} = \mathbf{A}\mathbf{x} + \nu \ , \tag{2.8}$$

where **A** is the design matrix and can be rewritten using apriori coordinates (x_o, y_o, z_o) and substituting time of travel as the ratio of speed of light (c) to the true range (ρ) as

$$\mathbf{A} = \begin{bmatrix} \frac{x_o - x^1}{\rho} & \frac{y_o - y^1}{\rho} & \frac{z_o - z^1}{\rho} & c \\ \frac{x_o - x^2}{\rho} & \frac{y_o - y^2}{\rho} & \frac{z_o - z^2}{\rho} & c \\ . & & & \\ . & & & \\ . & & & \\ \frac{x_o - x^m}{\rho} & \frac{y_o - y^m}{\rho} & \frac{z_o - z^m}{\rho} & c \end{bmatrix} \tag{2.9}$$

A is purely dependent on the direction to each of the satellites as observed from the receiver. The term $(A^T A)^{-1}$ is also known as the "cofactor matrix" and is also referred as the "covariance matrix," when scaled by the variance of the input observation errors. The cofactor matrix is used to assess the relative strength of the observing geometry, and to quantify how the level of errors in the measurements can be related to the expected level of errors in the position estimates as is shown in Paper-I. The least squares approach is modified as weighted least squares (WLS) for double differences given in Eq. 1.4 because of correlations in double differenced data.

Chapter 3

GNSS post-processing software

Post-processing of GNSS carrier phase data helps in precise estimation of position. Scientific software commonly used for GNSS post-processing such as GipsyX software [8], Bernese GNSS software [9] and RTKLib [10] are discussed here. It also provides information on external sources of data required to achieve high precision.

3.1 External information required in high precision applications and their sources

High-precision post-processing applications of GNSS data require accurate information about the GNSS satellite orbits and clocks. Since the accuracy of the broadcast orbit information is at meter-level this study utilizes final orbit and clock products from the International GNSS service (IGS) [11] which has uncertainties on the order of 1-2 cm. The orbit and clock products are calculated at the IGS analysis center. The final products can only be used for post-processing, since they have a latency of approximately 14 days. The precise final products for the satellites' orbits and clocks are downloaded from the IGS, together with the other products needed to reach sub-centimeter precision.

The second source of external information comes from International Earth Rotation and Reference System Service (IERS) [12] which provides information about the solid earth tides, ocean tide loading and the Earth Orientation Parameters (EOP). In geodesy, EOP illustrate irregularities in the rotation of planet Earth. EOP provides the rotational transform from the International Terrestrial Reference System (ITRS) to the International Celestial Reference System (ICRS), or vice versa, as a function of time. Solid earth tides are the displacement of the earth's surface due to the influence of the Sun's and the Moon's gravitational forces. Displacements are also caused by ocean tidal loading. Internationally agreed models for reference frames, EOP, solid earth

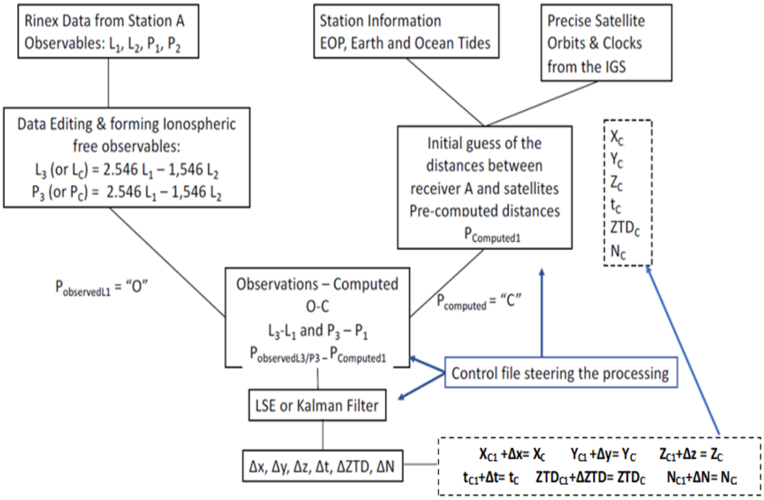

Figure 3.1: Flowchart for the GipsyX software

tides, and ocean tide loading are implemented in all high-precision geodetic software packages. These models are constantly revised and update by the IERS, in the so called IERS conventions [13]. Software packages like the Bernese Software and GipsyX have the same and latest IERS models implemented.

3.2 Precise point positioning (PPP) using GipsyX software

The workflow using GipsyX software has been illustrated in Figure 3.1. Raw data files logged in GNSS receiver in RINEX (Receiver Independent Exchange) format, are fed to GipsyX. Most geodetic processing software for GNSS data use a well-defined set of observables as shown in Figure 3.1:

- the carrier-phase measurement at one or both carriers seen as L_1 and L_2
- the pseudorange (code) measurements P_1 and P_2 (for L_1 and L_2 respectively)
- the observation time

The observation time is valid for both the phase and the code measurements, and for all satellites observed. Apart from the observations on code and carrier phase, information such as station-related information like station name, antenna height, etc. are obtained from the RINEX file. Each individual station, designated as A in Figure 3.1 is processed one at a time to obtain the observables L_1, L_2, P_1, P_2. The data is then edited to from linear combinations for L_3 and P_3 which are ionosphere free observables using equations shown in Figure 3.1. As stated earlier in Equation 1.3, such editing involves error inclusion due to approximations. Coordinates from RINEX header are used as an initial guess for the station position. Since we process 24 hour data, during which the station moves due to earth's rotation, effects of different geophysical phenomena (such as earth and ocean tides, etc.) and earth orientation parameters will change during the day. GipsyX uses standard models to eliminate these effects. IGS product files such as precise orbits and clocks are also used as inputs for computation. Using all these inputs, pseudorange distances based on code and carrier phase measurements between receiver A and satellites are computed. Such a computation also involves computing initial guesses of all the parameters of interest namely the co-ordinates (X_{C1}, Y_{C1}, Z_{C1}), the time information ($t_C 1$), the Zenith Tropospheric Delay (ZTD_{C1}) and the integer ambiguity for carrier phase data (N_{C1}). The pre-computed values(¨C¨) are then subtracted out of the observables (¨O¨). These differences are then processed in Least square estimator (LSE) or a Kalman filter. The filter uses a user defined input control file to understand the parameters of interest. Thus, the outputs of the filter are the changes in parameters of interest namely Δx, Δy, Δz, Δt, ΔZTD, ΔN. These changes are then used to update the initial guesses to form freshly computed values (so X_{C1} modifies to X_{C2} and so on) and with every iteration the computed values get closer to the true values. The process is repeated until the statistics around the computed solution X_C, Y_C, Z_C, t_C, ZTD_C, N_C is satisfactory enough. Papers II, III and IV use GipsyX position estimates to understand the impact of different error sources.

3.3 Network solution using Bernese GNSS software

Figure 3.2 shows the flow chart for processing using Bernese GNSS software (BSW). While the precise point positioning (PPP) algorithm is similar to that of GipsyX, BSW also provides the possibility to estimate a network solution using single frequency data which is advantageous for isolating local unmodeled effects such as multipath and diffraction using a double difference solution of colocated stations. This is made use of in Paper-IV to study diffraction effects in GNSS signals.

3.4 Post processing using RTKLib

Finally, RTKLib is an open source software and provides the posibility of estimating position solution using PPP and also network solution both in post-processing but also real time (RTK) for both static and dynamic applications. Paper-I and Paper-V use RTKLib as a postprocessing tool for demonstrating satellite selection.

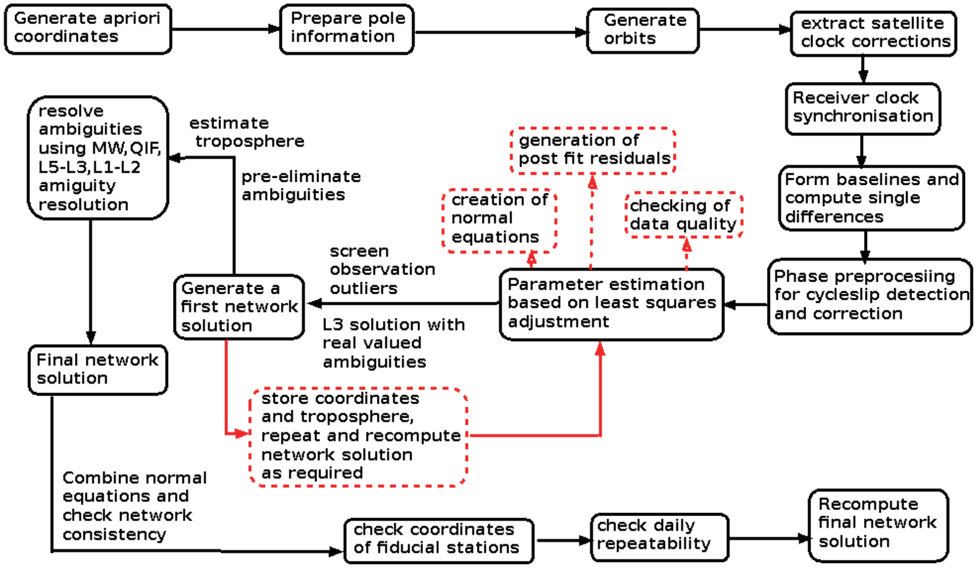

Figure 3.2: Flowchart for the Bernese GNSS software

Chapter 4

Summary of Included Papers

4.1 Paper-I: Satellite Selection in the Context of Network RTK for Limited Bandwidth Applications

This paper is based on the work conducted in the project PREParE SHIPS [14] funded by the European Union Agency for the Space Programme (EUSPA) on the specific application of Maritime Navigation using Network Real Time Kinematic (NRTK) and focuses on the satellite selection algorithms of the Prepare Ships dissemination solution. This study is motivated by data rate requirements and restrictions of the VDES (VHF Data Exchange System) that provides a net-bandwidth of 650 bytes/s. This strict bandwidth limitation is the main driver to optimize the reference data that is broadcasted to the user. Therefore, there is a need for optimal selection of satellite/signal subsets from the set of the available GNSS provided by the NRTK service. For this, multiple algorithms were developed and tested in static and dynamic scenarios. Optimization techniques for height (for vertical position), two and three dimensions were examined. Different weighting schemes were used that employed signal to noise ratio and elevation.

During the studies conducted in Paper-I, it was realised that in order to arrive at optimum weighting schemes, there is a need for a better insight into atmospheric and local errors (multipath and diffraction) and how they would impact position solutions obtained. Therefore the following 3 papers focus on investigations on ionospheric error and local unmodeled error sources of GNSS and their impact on RTK and PPP.

4.2 Paper-II: Ionospheric Effects on GNSS RTK

GNSS signals are influenced by free electrons as they propagate through the ionosphere. Studies have shown how the spatial variations of electron density in the ionosphere, affects measurements with network-Real Time Kinematic (NRTK) [1]. This paper predicts what can be expected from measurements during the next solar maximum that is expected to occur around 2025 and discusses how it would affect RTK. The ionospheric activity and its impact on positioning in the coming solar cycle maximum is discussed. This study focuses on data from Kiruna in northern Sweden (67.8N), mainly captured in January 2014 – in the middle of the most active time during the last cycle. Based on the data, it was concluded that there is a risk of occasions with simultaneous signal slips on several satellites caused by the ionosphere which could cause temporary (minutes) loss of positioning ability for the RTK equipment. It is expected to occur a couple of times per month during the most active months of the solar cycle.

4.3 Paper-III: Multi-Constellation/Multi-Frequency GNSS Signal Degradation Due to Foliage and Reflective Environments

This paper studies the impact of foliage and reflective environments on the various signals of multi-constellation GNSS with a focus on GPS and Galileo. Signal strength indicators have been used as a measure to understand the shadowing environment around a stationary GNSS antenna mounted on an excavator. The effect of signal degradation due to bending over sharp metallic edges is also discussed. Skyplots obtained during the stationary period show that satellites in the NW direction of the excavator during a certain period of time face signal degradation due to a possible obstruction from a tree. GNSS signal degradation is also possible due to reflections and bending over sharp metallic edges due to diffraction. A geometric model for signal diffraction is presented in the paper.

4.4 Paper-IV: Investigating the impact of diffraction on GNSS carrier phase measurements

This paper is an extension to the work presented in Paper-III and studies the impact of local un-modeled sources of error on GNSS. GNSS carrier phase measurements are often preferred over code measurements due to their improved signal resolution. They are therefore very useful in precise positioning applications. Commercially available post-processing software packages makes use of these measurements to provide precise positions of GNSS stations with sub-dm level accuracies. While other major error sources of GNSS such as the atmosphere, orbits, clocks, ambiguities etc. are modelled and taken care of by these software, local un-modeled effects such as multipath and diffraction continue to pose a hindrance to the achievement of desired level of positioning accuracies. Single frequency post-fit carrier phase residuals generated using the Bernese GNSS software are used to demonstrate the presence of unwanted signals in shadowed region due to signal bending caused by diffraction.

4.5 Paper-V: Distribution of the Adapted-NRTK Correction Data via VDES for the Shipping Navigation Safety

This paper is an application of the work done in Paper-I using satellite selection algorithms. The Lantmäteriet Adjustment Solution (LAS) for GNSS correction data adjustment was developed based on the satellite selection algorithms and is tested in real time on a pilot boat and a car and the test results are presented in this paper. The responsibility of this solution is to produce a correction data stream that complies with the bandwidth limitation of 650 bytes/s. To provide corrections for a potentially large number of users, dissemination is done by broadcasting corrections for a grid of Virtual Reference Stations (VRSs). The objective is to achieve optimal performance in terms of accuracy for the ship's differential positioning solution, while at the same time adhering to constraints that might locally apply for individual transmitters.

Chapter 5

Future Work

A future paper will be a continuation to the work carried out in Paper-IV and would focus on mitigation of the impact of diffraction on GNSS shown in the paper. GNSS in the recent times has also been quite vulnerable to interferences both intentional (in the form of spoofing/jamming) but also unintentional due to receiver environment and this will be investigated as well.

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