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Analysis of Zenith Path Delay in Dynamically Changing Environment

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ABSTRACT

Many studies have been conducted for evaluating the tropospheric effect on GPS signals. Among many troposphere models, Saastamoinen's and Neill's models have been widely used. The troposphere's zenith path delay in GPS signals can be estimated by the hydrostatic component of the Saastamoinen model and then the delay can be mapped with the dry Niell mapping function in order to obtain the slant path delay. This paper aims to identify and analyse the characteristics of the tropospheric delay associated with an aircraft's flight trajectory using the aforementioned troposphere models. The test data consists of the kinematic data observed during a 700km-long flight at the maximum elevation of 3,300m and the static data observed at seven reference stations distributed across the study area. The data was processed on an epoch-by-epoch basis in the double-differenced mode with mixed, kinematic and static stations. The correlation between the delay and the flight height is addressed as a result of the analysis. Since the estimation can be affected by the data quality, the baseline length and other factors, it is necessary to cross-verify the estimation. Hence the expected accuracy of the estimation is also provided along the flight trajectory.

KEYWORDS: Tropospheric effect, Zenith Path Delay, Slant Path Delay, Saastamoinen model, Niell model.

1. INTRODUCTION

Global Positioning System (GPS) as well as Russia's Global Navigation Satellite System (GLONASS) are currently operational Global Navigation Satellite Systems (GNSS) and play an important role as space-based geospatial infrastructure. GNSS provides accurate positioning and timing information, as a result of the availability of user equipment capable of real-time tracking, receiver portability and operational flexibility. In addition to GNSS being used for navigational purposes, it is also becoming common to use it for atmospheric sciences and various other fields. The advent of new generation GNSS and space-borne technologies coupled with recent development of Continuously Operating Reference Stations (CORS) infrastructure, have ushered in a new era of reliable, timely acquisition of critical weather information.

In recent years GNSS has been used increasingly for remote sensing of the Earth’s atmosphere. There are two approaches: ground-based atmospheric sounding and GNSS radio occultation (RO). This paper concentrates on ground-based atmospheric sounding and kinematic atmospheric sounding. This paper shows how better tropospheric values for kinematic stations can be derived with dual-frequency GNSS measurements over a CORS network as a reference. Once better tropospheric/slant path delays are determined, it can be processed to obtain the Zenith path delays (ZPD) by applying mapping functions e.g. Niell mapping function. If additional meteorological data are available, the slant Integrated Water Vapours (IWVs) along the paths from the GPS satellites to the receivers or the vertical IWVs over the CORS stations with an accuracy at the millimetre level (Bevis et al., 1992; Morland et al., 2006) can be processed for the assimilation into Numerical Weather Prediction (NWP) models (Guerova et al., 2004).

The ZPD can be divided into two parts, a *dry* and a *wet* part. The *dry* part contains nitrogen (78%), oxygen (20%) and 1% other gases which are almost uniformly distributed. The *dry* part of the ZPD can be modelled accurately by the model of Saastamoinen.

The *wet* part contains 1% water vapour and shows highly temporal and spatial variability. Seidel, 2002 describes that nearly half of the total water vapour in the air is below an altitude of about 1.5km and less than 5% is in the upper troposphere above 5 km. In this paper it is investigated to determine whether it is possible to obtain more details of the water vapour distribution and to what extend it is possible to find the correlation between the GPS-based ZPD and the GPS receiver´s height.

2. PROCESSING OF KINEMATIC DATA

2.1 Data Processing Strategy

In this study, a flight trajectory was being analysed over which GNSS observation was made. The flight was flown for a distance of 700 kms from Bathurst to Coffs Harbour. For processing such kinematic data in a dynamic environment, seven static reference stations were selected to observe GNSS simultaneously. These stations are part of a CORS network, located at Bathurst (BATH), Mudgee (MUDG), Putty (PUTY), Singleton (SNGO), Taree (TARE), Port Macqaurie (PMAC), and Coffs Harbour (COFF) as shown in Figure 1. The data are processed in post-processing mode. Final kinematic coordinates at 1-second interval and ZPD at 1-minute interval are computed.

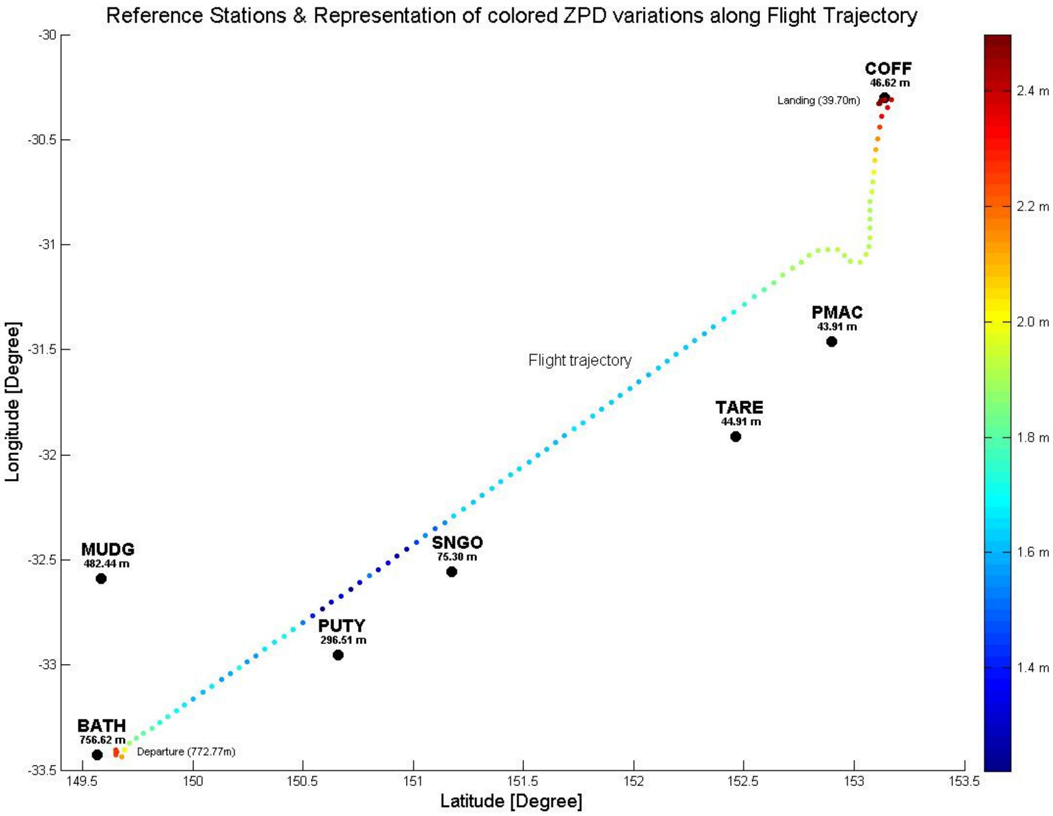

Figure 1. Flight Trajectory and Stations Location

For efficiency, it is better to resolve the ambiguities in the baseline mode (i.e. processing each baseline separately) and then introduce the resolved ambiguities as known quantities into the subsequent session processing. There are several aspects in determining the optimal ambiguity resolution strategy. Before selecting the strategy the following questions should be answered:

1. Are phase measurements available on both carriers? If yes, are there high quality code measurements on both carriers, too?
2. How long is the baseline?
3. How long is the session?

If only single frequency data are processed, there are not many possibilities how to resolve the ambiguities. Either the SEARCH algorithm (for short sessions) or the SIGMA algorithm (for long sessions) must be used in Bernese software based processing. If both frequencies are available, the following options are available:

1. For very short baselines (up to several kilometers) the ambiguities may be resolved independently on L1 and L2 using the SIGMA algorithm. This case is similar to processing single frequency data.
2. For longer baselines (up to approximately 2000 km) it is possible to process both carriers together and resolve both (L1 and L2) ambiguities in the same run. The recommended strategy is applying Quasi Ionosphere-Free (QIF) algorithm to long

sessions and baselines of almost arbitrary length, and applying SEARCH to short sessions and short baselines.
3. Using the so-called wide-laning technique, each baseline is processed twice. Firstly the wide-lane ambiguities are obtained. In the subsequent run, the wide-lane ambiguities are introduced as known, and then the narrow-lane ambiguities are resolved.

Using the resolved wide-lane ambiguities, satisfactory results are expected up to baseline lengths of about 100 km (or longer if a good a priori ionosphere model is used). In this case the processing steps are:

- Ionosphere-free Code solution to get a priori coordinates for the trajectory
- L3 (i.e. L1-L2) float solution saving the coordinate results to get improved a priori coordinates for the ambiguity solution.
- Wide-lane ambiguity solution with SIGMA strategy
- Introducing the resolved wide-lane ambiguities to resolve the narrow-lane ambiguities. In the third step the estimation of station-specific troposphere parameters is highly recommended to be accurately obtained, considering the small wavelength.

For the flight of 700-km long attaining maximum height of approximately 3,000m and having seven base stations observing simultaneously, approximately 70-80% ambiguities were resolved with a priori sigma of nearly 1mm and Root Mean Squared Errors (RMSE) of nearly 1.5mm in the narrow-lane ambiguity resolution, while in the wide-lane ambiguity resolution, approximately 90-95% ambiguities were resolved with a priori sigma of nearly 1mm and RMSE of nearly 3.5mm.

2.2 Kinematic Processing

For this type of study, it is ideal to examine a flight trajectory from the departure to the landing because of its height variations. In such dynamically changing environment, selection of appropriate ambiguity resolution strategy is important. In order to resolve the ambiguities and get better a-priori coordinates, the data is processed iteratively using wide lane and narrow lane combinations. However, since the flight trajectory is 700-km long, the aforementioned strategy needs some modifications for processing the kinematic data to achieve cm-accuracy.

In total, the data from eight stations are used in this study. In other words, one station is continuously moving and other seven stations are stationary. The kinematic station is assigned to be FLGT while processing. As a first step, the data from FLGT is processed iteratively with various baselines in L3 solutions to obtain the best a priori values and thereby the final solution.

In the next step, the combination of FLGT and a static station TARE, is processed using the wide-lane ambiguity resolution and SIGMA strategy which also enables ambiguity resolution for GLONASS in a phase-only mode because inter-frequency code biases caused by the FDMA technology of GLONASS ([Dach et al., 2006a]) are not handled by Bernese. It has to be noted here that in case of combined GPS/GLONASS data processing, one has to make sure that no ambiguities between the different GNSS are resolved. In this step, resolved ambiguities were saved in order to be introduced later into the narrow-lane solutions for efficiency. The output of kinematic coordinates should be used as an input for narrow-lane solutions in next step.

In a subsequent run, the same combination is processed using the narrow-lane ambiguity resolution. In this step, kinematic coordinates obtained from wide-lane solutions previously, is used as an input to the process and the saved ambiguities are introduced as known quantities and narrow-lane ambiguities are resolved in order to produce the final solution.

As a final step, combination of all seven stationary GPS stations and one kinematic station (FLGT) are processed. As a final output, kinematic coordinates and tropospheric delay values for FLGT at every 1 minute are obtained.

3. ANALYSIS AND INTERPRETATION

Figure 2 illustrates the ZPD variations along the flight trajectory. Depending on the current position and altitude, the tropospheric delays vary during the two hour test flight between ~1.2m and ~2.5m. Figure 3 shows the ZPD as a function of the ellipsoid height. The minimum ZPD of 1.25 +/- 0.012m is estimated during the flight when the plane reaches its maximum height at ~3200 m. The maximum ZPD of 2.50 +/- 0.003 m occurs at the minimum ellipsoid height of 40m shortly after arrival near Coffs Harbour. This result agrees with the assumed strong correlation between ZPD and altitude. Another effect which can be seen in the data is that the tropospheric delay is not only a function of altitude. During the 50min in which the plane stays at a constant ellipsoid height of 3200 +/- 2 m, the ZDP varies between 1.35m and 1.66 +/- 0.07 m. If the tropospheric delay would be only a function of altitude, the ZPD should stay nearly constant but during this 50min period, the ZPD varies by more than 30cm. As mentioned in Section 1, the ZPD can be split into two parts: the stable *dry* or hydrostatic part (ZHD) and the *wet* part (ZWD) which shows highly temporal and spatial variability. Due to the limited size of the project area and the constant flight height during the 50min, the effect of h and Φ (Eq. 1-1) on the ZHD variations is small, and it is mainly dependent on the changes in air pressure p_o at the antenna.

Unfortunately no pressure data at the antenna was available; hence the maximum change in air pressure of 20 hPa is taken into account. A change of 20 hPa would result in a change of the ZHD of ~6 cm. That means the ZPD variation of 30cm can be mainly the estimation errors.

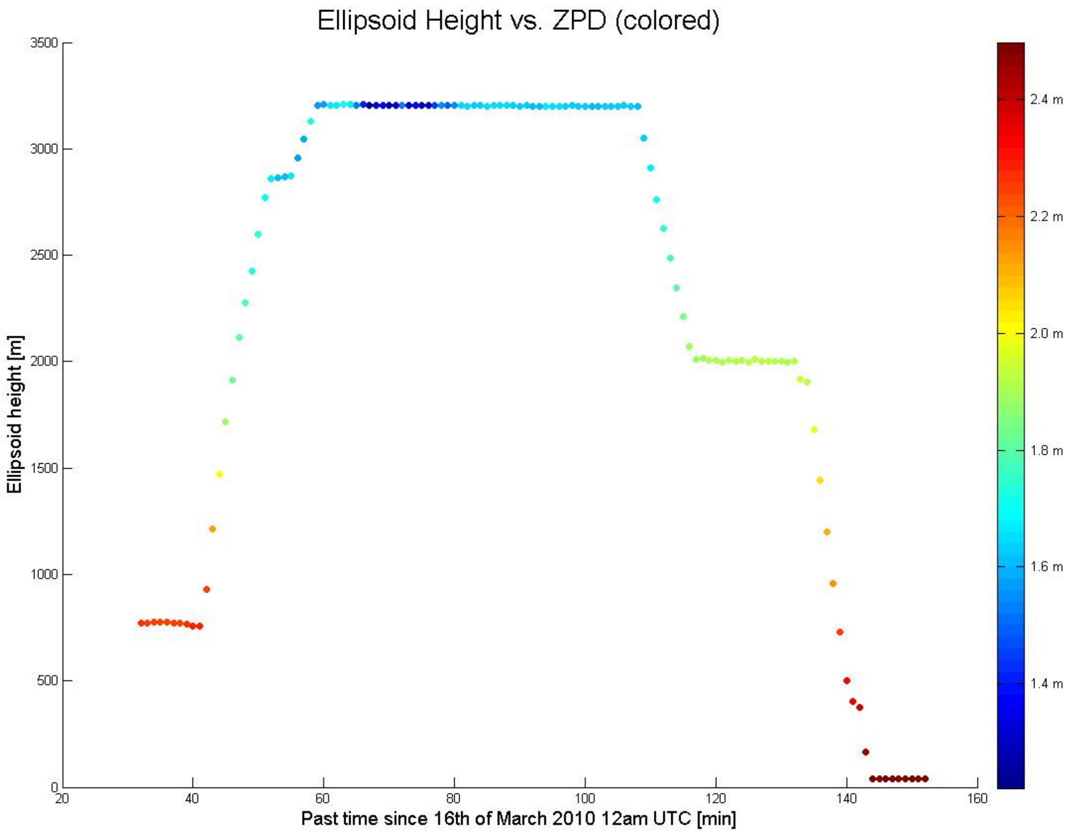

Figure 2. ZPD Vs Height

The ZPD estimation errors shown in Figure 3 vary between 1.5mm and 13mm, and are mostly smaller than 5mm. It can be treated as the theoretical error, resulting from the least squares adjustment. Due to the high correlation between subsequent GPS observations, the error of 5mm is usually too optimistic. Under the assumption of accurate orbits, the realistic ZPD estimation error in static processing is roughly five times the theoretical error. In kinematic processing it probably is higher than that. As shown in Figure 3, only between the 40^{th} minute and the 80^{th} minute during the test flight, the ZPD estimation error is bigger than 1cm.

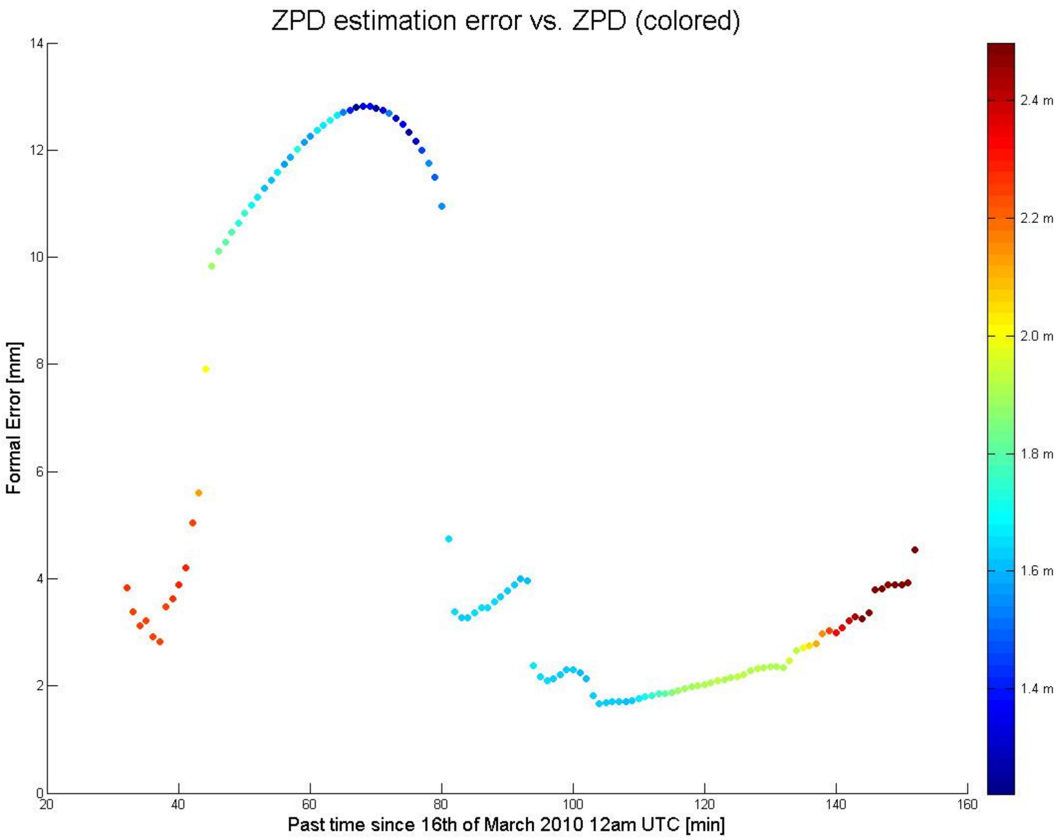

Figure 3. ZPD Estimation Error

4. CONCLUDING REMARKS

Within the achieved accuracy range it is possible to detect only serious changes in the water vapour content and its extensive spatial distribution in the atmosphere. This information would be useful for climate monitoring and large scale weather forecasting. Therefore not only the ZPD but also the ZWD would be needed. To estimate absolute ZWD values and to convert them into IWV, at first the ZHD must been known. It can be calculated on the assumption of a standard atmosphere. Due to the unavailability of the meteorological data, it was not possible to report the outcome of this task in this paper.

The main disadvantage of using flight data is that they are not continuously available and therefore not suitable for climate monitoring and weather forecasting, however, this work should be seen as a feasibility study to show that it is possible to estimate the path delay in the troposphere based on kinematic data with suitable accuracy.

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