TROPOSPHERIC DELAY EFFECTS ON RELATIVE GPS HEIGHT DETERMINATION

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Abstract

In the global positioning system (GPS) surveying for point positioning, one of the principal limiting error source is incorrect modeling of the delay experienced by GPS signal propagating through the electrically neutral atmosphere, usually referred to as the tropospheric delay. This paper concentrates on showing the result of an experimental work that has been conducted by integrating the Malaysian Active GPS Station (MASS) data and ground meteorological observations to analyze the variation occur to the GPS height determination due to the tropospheric delay. Four individual satellites are selected to assist the analysis due to their availability during the observations period. The result of introducing a Saastamoinen tropospheric model to the data shows a delay variation for up to 20 meter in pseudorange which causes an error up to 5 meter of height component. This paper verify that the integration of ground meteorological observations and GPS lead to a better understanding of the tropospheric delay to the GPS signal and improve the GPS height accuracy.

1.0 INTRODUCTION

The troposphere is a part of the earth atmosphere which is situated in its lower region. It is where all weather occurs, electrically neutral and non-dispersive for frequencies as high as about 15GHz. In the global positioning system (GPS) surveying, the principal limiting error source is incorrect modeling of the delay experienced by GPS signal propagating through the troposphere, usually referred to as the tropospheric delay.

Within this medium, group and phase velocities of the GPS signal on both L1 and L2 frequencies are equally reduced. The resulting delay is a function of atmospheric temperature, pressure, and moisture content represented by relative humidity. Without appropriate compensation, tropospheric delay will induce pseudorange and carrier- phase errors that vary from roughly 2 meters for a satellite at zenith to more than 20 meters for a low-elevation- angle satellite (Hay.C and Wong, 2000). This delay affects mainly the height component of position and constitutes therefore a matter of concern in space geodesy applications (Mendes and Langley, 1998).

1.1 GPS Observations

The GPS consists of 24 satellites. These satellites are distributed in six orbital planes inclined at 55°, with a nodal separation of 60°. The orbits are circular with 12 hour period. Each satellite broadcasts navigation signals on two L band frequencies: 1.57542 GHz (L1) and 1.2276 GHz (L2) carrier phase observations that are used to form ionospheric-free double differences (Gutman et al., 2003). Sources of initial measurement error include receiver noise, site-dependant multipath, and antenna phase delays.

1.2 GPS Error Budget

There are several sources of error in GPS and can be classified into three major groups which are satellite, signal propagation and receiver as shown in table 2-1.

Table 2-1: Satellite error propagation

Source	Effect
Satellite	Clock bias Orbital errors
Signal propagation	Ionospheric refraction Tropospheric refraction
Receiver	Antenna phase center variation Clock bias Multipath

In this experiment, both satellite and receiver clock bias is eliminated by applying double differencing during the processing. Since the measurements are taken on both the L1 and L2 frequencies, an ionosphere-free (IF) double difference observable can be obtained by combining the observations. Using this observation during positioning removes the first-order effects of the ionosphere (99% of this error source), allowing for the removal of this error to the centimetre-level even with low elevation observations and high atmospheric electron content (*Brunner and Gu*, 1991). Multipath effect is minimize by a long hours observations, in this case is 3 hours for each session and the antenna phase center variation can be neglected as long as the system is well maintain and calibrated. The remaining bias is the tropospheric refraction which value can be estimated and corrected using existing empirical models such as Saastamoinen, Hopfield, Black and others.

1.3 Surface Meteorological Observations

Surface observations are required to parse the tropospheric signal delay into its wet and dry components. Surface temperature measurements can be used to estimate the mean temperature of the atmosphere with an error of about 2%. In general, surface pressure measurements with accuracy of about 0.5 hPa, and surface temperature measurements with accuracy of about 2 degrees are sufficient (Saastamoinen, 1972). A Real time surface meteorological sensor (Davis GroWeather^{TM} System) is stationed nearby the MASS Station to collect the meteorological parameters needed in the tropospheric model correction algorithm. Parameters taken are surface temperature, pressure and relative humidity. These surface values of meteorological data were taken within a 10 minutes interval from 9am to 5pm to identify the variations.

1.4 Satellite Orbit Accuracy

IGS precise final orbits are adopt to achieve cm level of accuracy and to give the exact location of the satellite at any given time. This is to ensure the value of azimuth and elevation angle of the satellite is corrected before the delay of each satellite can be determined. Precise orbits are available with about 13 days latency, and are determined from hundreds of ground tracking stations' measurements. The accuracy of precise orbits is <5 cm [*IGS*, 2005]. If the application permits, most processing is done with precise orbits due to the fact that it provides very complete ephemeris (if a certain satellite ephemeris is not available at the time the rapid orbit is available, an effort is made to make it available in the precise ephemeris) and there is enough time to correct blunders which may have made their way into other orbital products.

2.0 EFFECTS ON GPS SIGNALS

In this paper, GPS data are used to estimate the tropospheric delay from measurement of the delay from each GPS satellite in view from a ground station. Typically four to six GPS satellites are in view at any given time over the study area.

GPS signals are affected while being transmitted through the ionosphere and troposphere (the neutral atmosphere). Normally, the global atmospheric models are use to correct for the atmospheric effect and these models are suitable for most GPS positioning. For high accuracy static and kinematic applications the global models are, however not sufficiently accurate (Jensen, 2002).

2.1 Residual Tropospheric Effects

Tropospheric layer is the most dynamic among other atmospheric layer because of the high variation of its water vapor content. This is a major task and an appropriate model has not yet found.

When the satellite signals are transmitted through the troposphere they are refracted, and the refraction is a function of meteorological conditions. The refraction causes a signal delay has a size of 2-3 meters in zenith depending on meteorological conditions and the altitude of the GPS receiver.

Within the tropospheric layer, group and phase velocities of the GPS signal on both L1 and L2 frequencies are equally reduced. Without appropriate compensation, tropospheric delay will induce pseudorange and carrier phase errors that vary from roughly 2 meters for a satellite at zenith to more than 20 meters for a low elevation angle satellite (Hay.C and Wong, 2000).

2.2 Delay Estimation

The tropospheric delay is actually composed by two components; one is the dry part and the other is the wet part. The wet component is more difficult to model because of the heterogeneous distribution of the water vapor.

The dry component correction is usually carried out using some atmospheric model. The surface pressure and temperature data are used to compute the dry component delay. In this experiment, an equation given by Saastamoinen's (Saastamoinen, 1973) is use to compute the tropospheric delay including the wet component.

Saastamoinen has refined this model by adding two correction terms, one being dependent on the height of the observing site and the other on the height and on the zenith angle. The refine formula is as follows (Hofmann-Wellenhof, 1994):

The equation is given below:

$$\Delta^{Trop} = \frac{0.002277}{\cos z}\left[P + \left(\frac{1255}{T} + 0.05\right)e - B\tan^2 z\right] + \delta R$$

where Δ^{trop} is propagation delay in terms of range,

z is zenith angle of the satellite,
P is the pressure at the site in milibar,
T is temperature in Kelvin and,
e is the partial pressure of water vapor in milibar.
B, δR is the correction term for height and zenith angle (Hofmann-Wellenhof, 1994).

In the above equation, partial pressure of water vapor is computed from the relative humidity as a fractional of 1. RH and the temperature, T measured at the surface. The following equation is used to calculate the partial pressure of water vapor (Murakami, 1989).

$$e = 6.108RH \times \exp\left[\frac{17.15T - 4684}{T - 38.45}\right]$$

RH is relative humidity at site

The pressure P at height above sea level h (in kilometers) is given in terms of the surface pressure Ps, and temperature Ts as mention by Murakami, 1989 as:

$$P = Ps\left[\left(\frac{Ts - 4.5h}{Ts}\right)\right]^{7.58}$$

The dry model is accurate to better than 1 cm (King et al 1985). This is more than sufficient for the purpose of the orbit determination.
The radio signal delay through the tropospheric is dependent on the total amount of the water vapor existent along the path. It means that the delay depends on the distribution of water vapor. The geographical distribution of the clouds is difficult to model. As a result, a wet component correction using a model is less effective. Fortunately, the total magnitude of this effect is less than a meter in normal cases.

3.0 DATA ANALYSIS

The data use this experiment is a relative positioning connecting UTMJ and INSTUN within 300km baseline. The data processing is done in Trimble Geomatic Office (TGO) v1.6. During baseline processing, errors such as clock biases, orbital errors, ionospheric refraction, cycle slips and multipath were eliminated and leave out the tropospheric refraction alone to be fix.

3.1 The Models

A refined Saastamoinen model is used in this experiment to estimate the tropospheric delay in the study area. This has to do with the good reputation of the model (Saastamoinen) which is widely used for high accuracy GPS positioning (Jensen, 2002). The accuracy of the Saastamoinen model was estimated to be about 3cm in zenith (Mendes, 1999).

The ionospheric free solution uses a combination of L1 and L2 carrier phases to model and remove effects of the ionosphere on the GPS signals. This type of solution is often used for high-order control surveying, particularly when observing long baselines.

The azimuth and elevation of the satellite after the use of precise ephemeris is derived from the skyplot function in TGO. These are essential parameters to determine the zenith angle of the satellite to be use in the Saastamoinen algorithm to estimate the signal delay. Figure 4-1 shows the azimuth and elevation of each single satellite due to time variation.

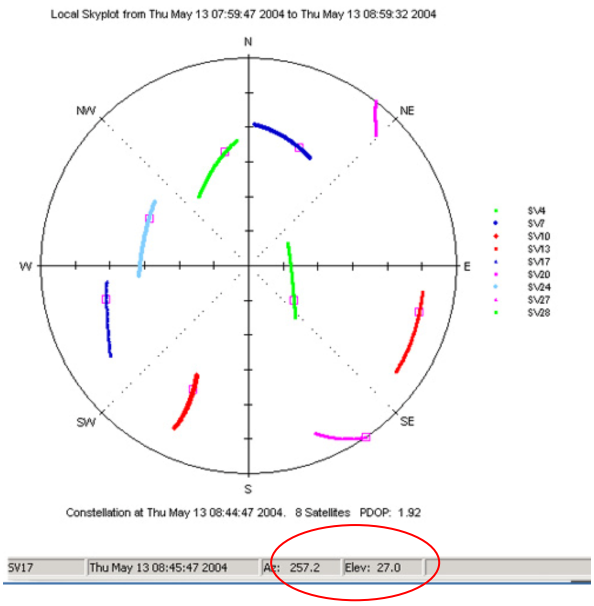


Figure 3-1: Satellite elevation and azimuth in the Trimble Geomatic Office's Skyplot function.

Four satellites has been chosen to represent the observations. The satellites are PRN05, PRN09, PRN17 and PRN24. The most critical parameters to be analyzed in this experiment is the elevation height, *h* of the observed point since the tropospheric delay mainly effected this components. Figure 3-2 below shows the variations of the height components:-

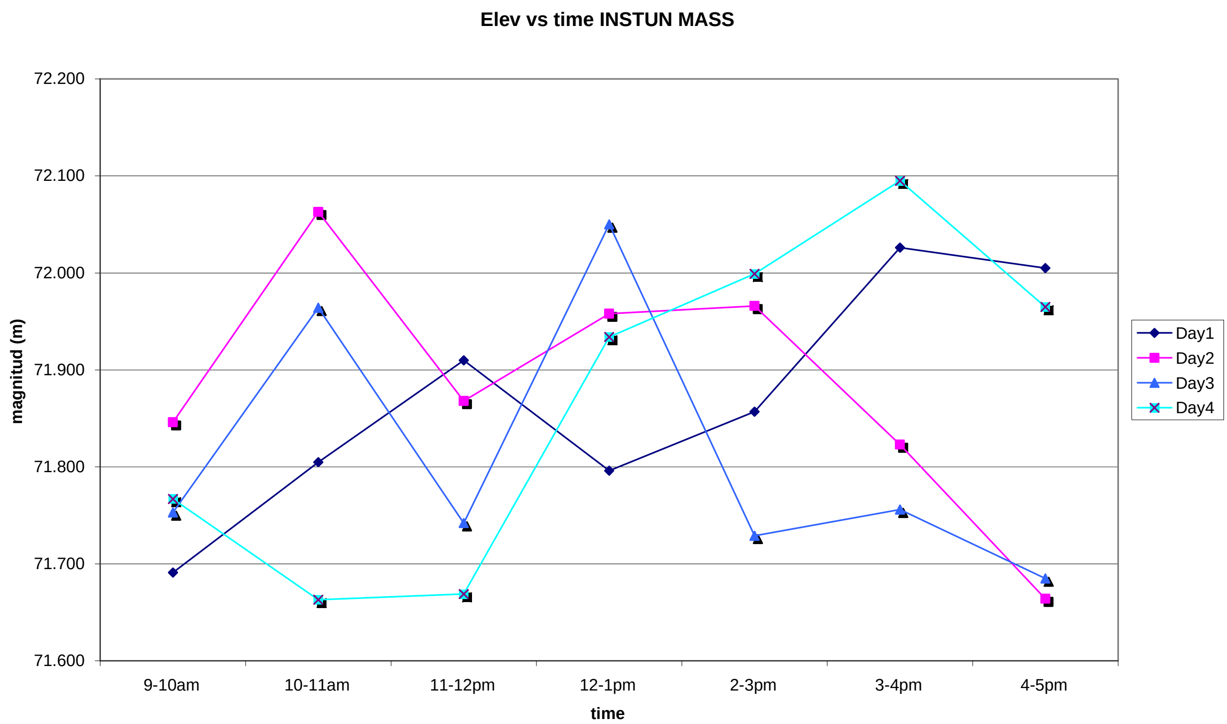


Figure 3-2: Hourly post-process GPS height component variation result of INSTUN

The result as shown in figure 3-2 shows the variations of height component value up to 0.5m after baseline processing and adjustment using a precise orbit and ionospheric free solutions. This variation is expected due to the tropospheric delay since the entire major error source has been eliminated.

To determine each individual satellites range delay, a Saastamoinen empirical model is introduce to the data using a computer program develop specially for purpose. The results are as follows.

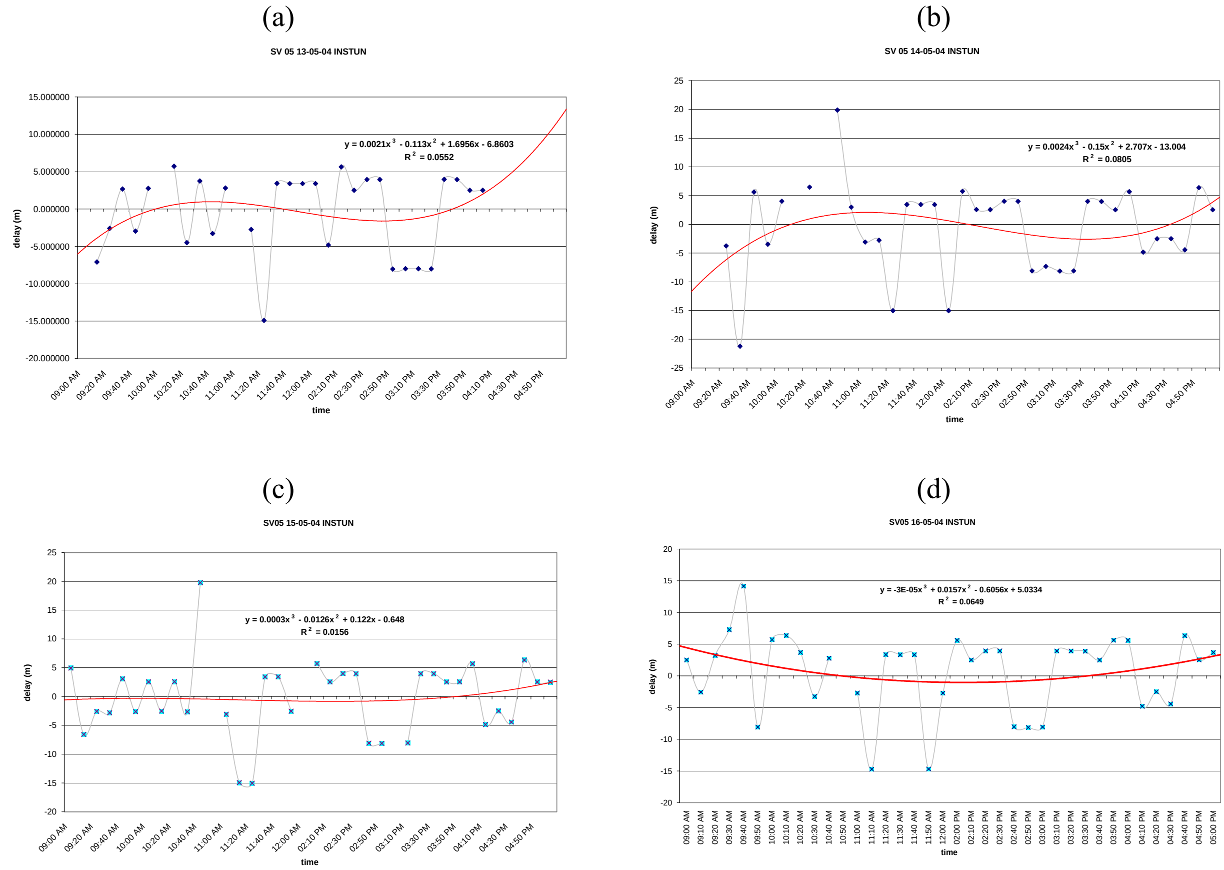
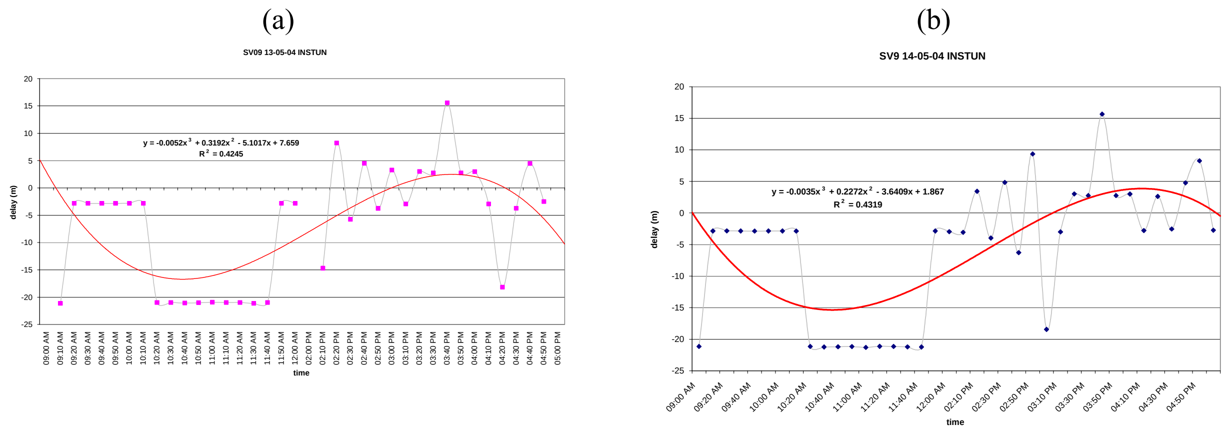
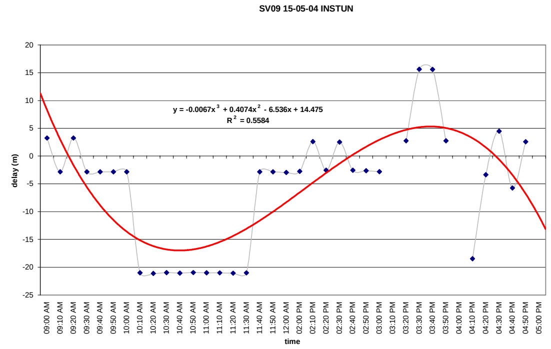


Figure 4-3: Signal refraction delay of PRN05 on day 1 day 2 day 3 and day 4



(c)



(d)

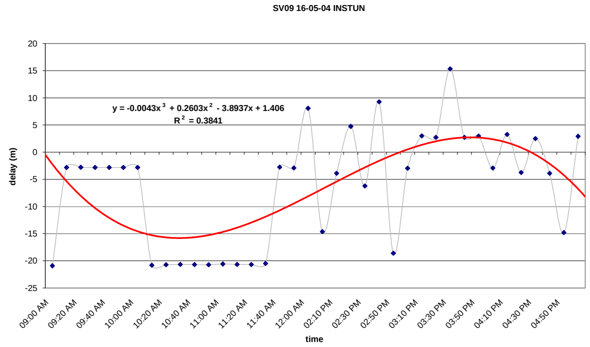
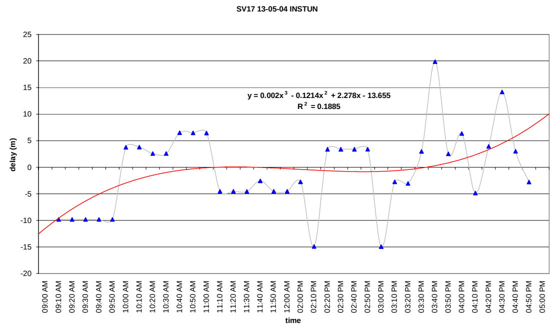
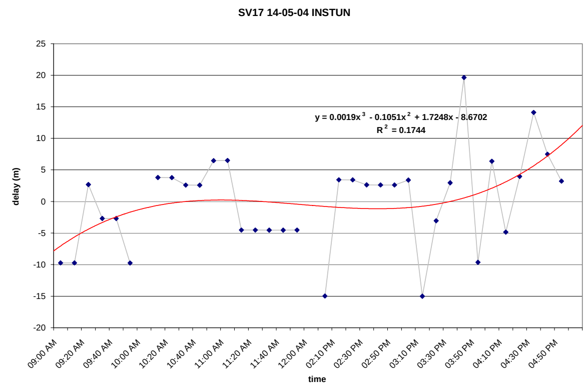


Figure 4-4: Signal refraction delay of PRN09 on day 1 day 2 day 3 and day 4

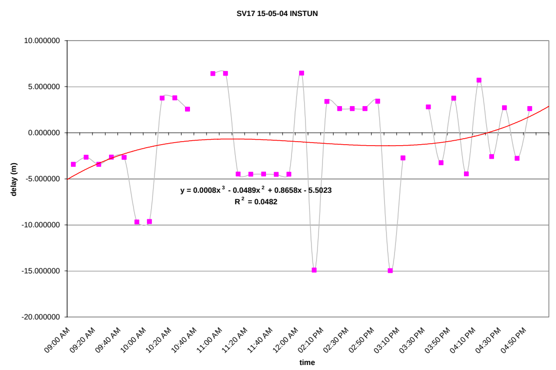
(a)



(b)



(c)



(d)

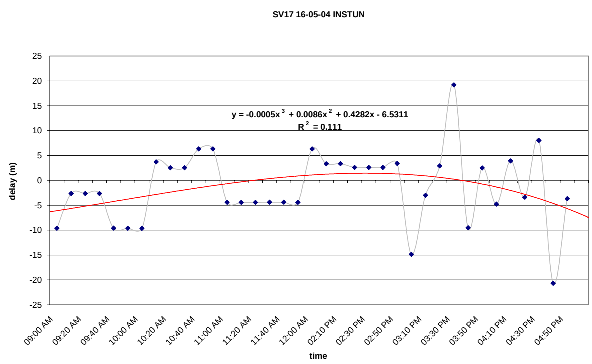


Figure 4-5: Signal refraction delay of PRN17 on day 1 day 2 day 3 and day 4

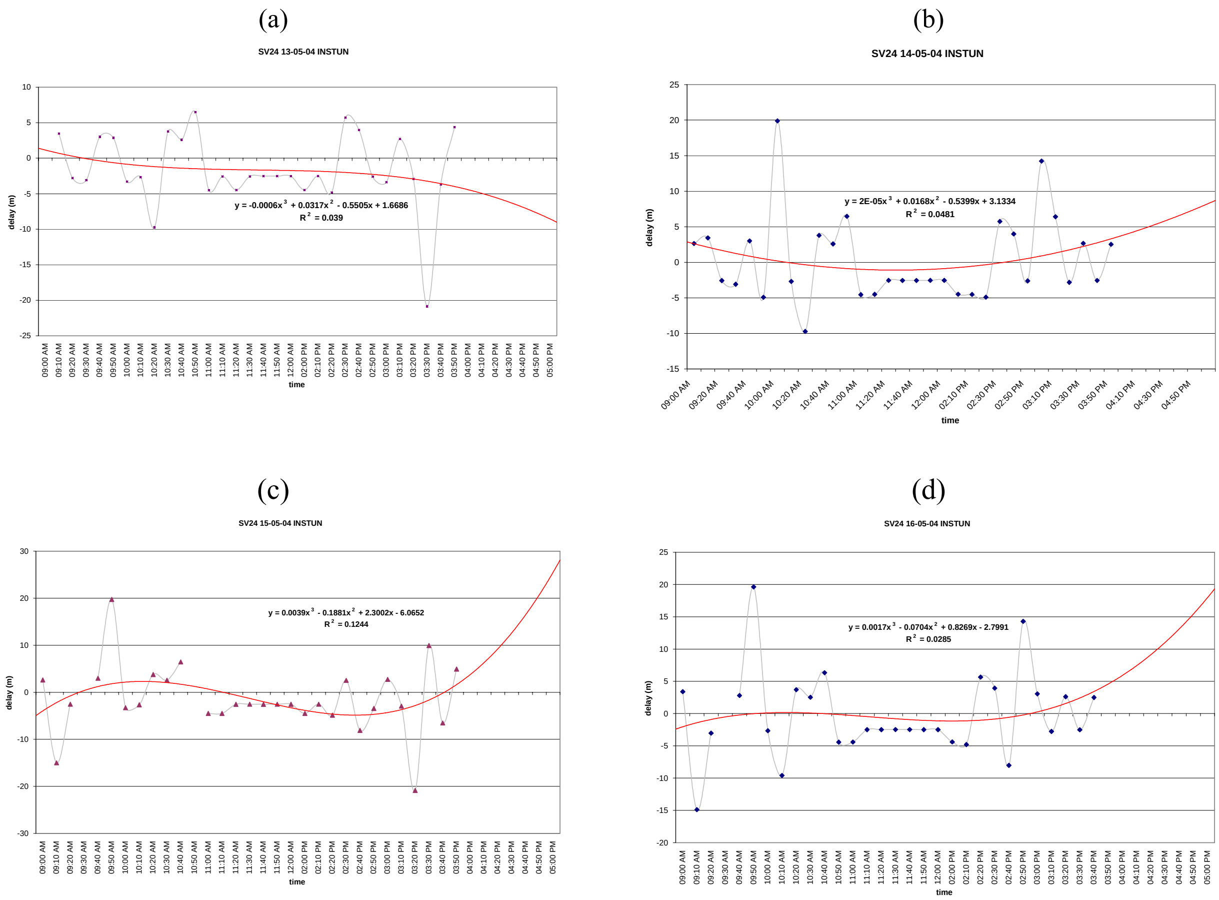


Figure 4-6: Signal refraction delay of PRN24 on day 1 day 2 day 3 and day 4

The result shows inconsistency in the delay variation but reach a maximum delay up to 20 meters in pseudorange. The sinusoidal red line in the plot shows the 3rd degree polynomial for the modeling purposes. The difference between the observe data and the control value of the point is represented in figure 4-7:-

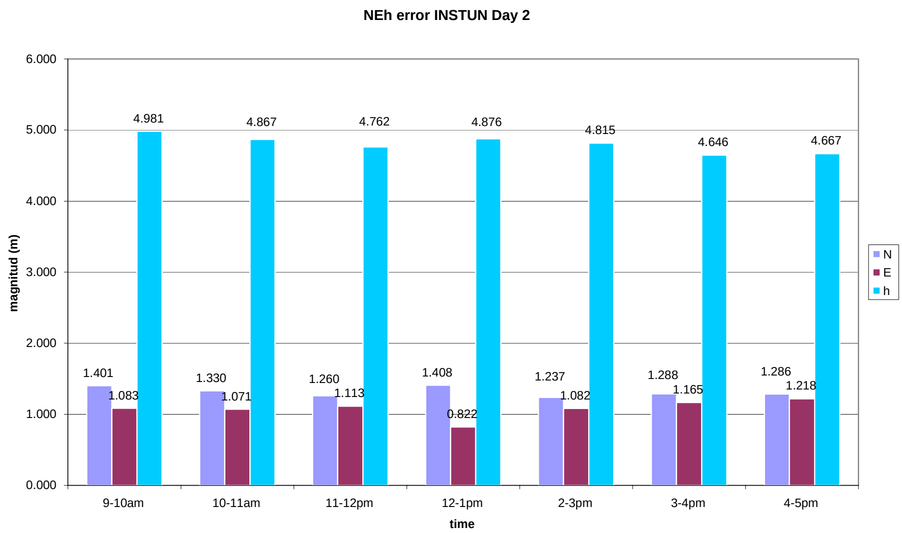


Figure 4-7: Position value differences to the control value of the point

The result as shown in figure 4-7 is base on a single long baseline processing and shows an error magnitude nearly 5 meters for the height components. This is what we believe to be the result of the 20-meter range delay experience by the signal estimated using the Saastamoinen model earlier.

4.0 CONCLUSIONS AND RECOMMENDATION

The result of introducing a Saastamoinen model into the data shows a delay variation for up to 20 meter in pseudorange, which causes an error up to 5 meter to the height component which may came from the tropospheric delay of the signal since all the major error source has been virtually eliminated during the processing. This paper verify that the integration of ground meteorological observations and GPS lead to a better understanding of the tropospheric delay to the GPS signal and improve the GPS height accuracy.

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