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ERRORS DUE TO THE TROPOSPHERIC AND IONOSPHERIC EFFECTS ON THE GEOGRAPHIC LOCATION OF DATA COLLECTION PLATFORMS

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ABSTRACT. The use of the Doppler shift measurements to locate a transmitter has been studied and tested within the Brazilian Environmental Data Collection System. To improve the location of Data Collection Platforms (DCPs) with their transmitters, some effects such as corrections due to the ionosphere and the troposphere have been considered in a previous work (Celestino et al., 2007) using simulated data and some initial error evaluation for one existing DCP. This work presents an evaluation of the impacts on the geographical location due to the ionospheric and the tropospheric effects, however using two meteorological DCPs and covering a longer test period (one year). The seasonal and day-night effects are also analyzed during this test period. The results of the analysis indicated that correction of the ionospheric and tropospheric effects can, on the average, reduce the location errors to the scale between ten and hundred meters for the test conditions independent of the DCP location that was used. Due to the complexity of modeling sources of errors in the location of a platform, still a considerable work need to be done to reduce location errors in the system. Initial analysis indicates that the knowledge of the satellite position can be another significant source of platform position error.

Keywords: geographical location, Data Collection Platforms, Doppler shift, tropospheric and ionospheric effects.

RESUMO. O uso de medidas do desvio Doppler para localizar um transmissor foi estudado e testado considerando o Sistema Brasileiro de Coleta de Dados Ambientais. Para melhorar a localização de plataformas de coleta de dados (PCDs), com os seus transmissores, alguns efeitos como a correção devido à ionosfera e à troposfera, foram considerados no trabalho de Celestino et al. (2007) usando dados simulados e algumas avaliações dos erros iniciais de uma única PCD. Este trabalho apresenta uma avaliação dos impactos sobre a localização geográfica, devido aos efeitos da ionosfera e da troposfera, entretanto usando duas PCDs meteorológicas e cobrindo um período mais longo de testes (um ano). Os efeitos, sazonal e dia-noite, também são analisados durante este período experimental. Os resultados das análises indicam que a correção dos efeitos da ionosfera e da troposfera pode, em média, reduzir os erros de localização à escala entre dez e cem metros para as condições de testes independente da localização da PCD que foi utilizada. Devido à complexidade da modelagem das fontes dos erros na localização de uma plataforma, um trabalho considerável ainda precisa ser feito para reduzir o erro de localização no sistema. A análise inicial indica que o conhecimento da posição do satélite pode ser outra fonte significativa do erro na posição da plataforma.

Palavras-chave: localização geográfica, plataformas de coletas de dados, desvio Doppler, correção dos efeitos da ionosfera e da troposfera.

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INTRODUCTION

The Brazilian Data Collecting System consists of a set of satellites that receive and relay to a ground mission center the environmental data gathered by the Data Collection Platforms (DCPs) spread over the Brazilian territory. Currently the system is composed by the satellites SCD-1, SCD-2, CBERS-2 and CBERS-2B. The data collected through the satellites are used in several applications. Here one exploits one of the applications, that is, the geographical location using satellites. In this work the SCD-2 satellite is exercised.

The use of the Doppler shift measurements to locate a transmitter has been studied and tested within the Brazilian Environmental Data Collection System. To improve the location of Data Collection Platforms (DCPs) with their transmitters, some effects such as corrections due to the ionosphere and the troposphere has been considered in a previous work (Celestino et al., 2007) using simulated data and some initial error evaluation for one existing DCP.

With the aim of showing statistically the impacts on the geographical location due to these effects, two meteorological DCPs were analyzed for one year test period (from October 2005 to October 2006) using the SCD-2 satellite (circular low Earth orbit, 25° inclination and 750 km altitude) and the existing ground reception facilities at INPE. One DCP is located in Cuiabá, middle of South America, and other is located in Alcântara, near to the Equator (De Paula et al., 2004). The data set gathered during this test period is composed by 35 geographic locations for each platform, distributed along the year. The seasonal and day-night effects are also analyzed during this test period.

The methodology used to evaluate the location errors considering tropospheric and ionospheric effects presented here is similar to the work of Celestino et al. (2007).

This paper is divided in the following sections: section 2 covers the atmospheric effects on the geographic location as well as the models regarding the ionosphere and troposphere; section 3 presents the geographic location method adopted using Doppler shift measurements; section 4 describes the development of the work; section 5 describes the results related to seasonal and day-night effects on the two platforms of the test, as well as DCP location errors. Section 6 presents the conclusion and future steps necessary to reduce the location errors in the system.

IONOSPHERIC AND TROPOSPHERIC MODEL EFFECTS

This section describes the equations used to model the properties of the ionosphere and the troposphere and the evaluation of their effects on the geographical location errors.

Model of the ionosphere

The refraction in the ionosphere depends on frequency and is proportional to the electron density along the path traveled by the signal between platform and satellite, called *TEC* (Total Electron Content) (Bilitza, 2005, 2006). The value of *TEC* depends on the hour of the day, season, and chemical composition of the high atmosphere. To model the effects on signal delay rate due to the refraction in the ionosphere, located between 50 km and 1000 km above the Earth surface, the following equation given by Aksnes et al. (1988) was used:

$$\dot{R}_I = -\frac{36.2}{f^2}\, VTEC\, \frac{\cos\gamma \sin\gamma}{\left(1 - 0.9\cos^2\gamma\right)^{3/2}}\, \dot{\gamma} \qquad (1)$$

In the equation, $VTEC$ represents the electron content in the vertical direction (el/m^2), f is the platform transmitter frequency (Hz), that could be around 401.62 MHz or 401.65 MHz, and, γ and $\dot{\gamma}$ are elevation and elevation rate angles measured from the DCP to the satellite position.

Figure 1 shows signal delay rate samples considering two passes of the satellite over a platform on October 21st, 2005 and November 3rd, 2005.

Figure 2 shows the behavior of the elevation angle, including minimum and maximum elevation, as function of time, for a satellite pass over the platform #32003 in Alcântara on January 2nd, 2006 considering the simulation conditions.

Model of the troposphere

To model the effect of the troposphere, from ground up to 50 km altitude, on the signal delay, the density of the atmosphere and the satellite elevation regarding the DCP shall be considered. Several models can be found in the literature.

For this test period evaluation, the signal delay rate due to the troposphere was calculated by:

$$\dot{R}_t = -\left(T_{ZH} + T_{ZW}\right)\frac{\cos\gamma}{\sin^2\gamma}\, \dot{\gamma} \qquad (2)$$

where T_{ZH}, T_{ZW} are dry and wet components, respectively, downloaded from (CPTEC-INPE, 2005, 2006) and computed according to Sapucci et al. (2006).

The delay due to the dry component can correspond to approximately 2 to 3m in the zenith and varies with the temperature and the local atmospheric pressure (Monico, 2000), whereas the delay for the humid (wet) component is of approximately 1 to 30 cm in the zenith direction (Seeber, 1993).

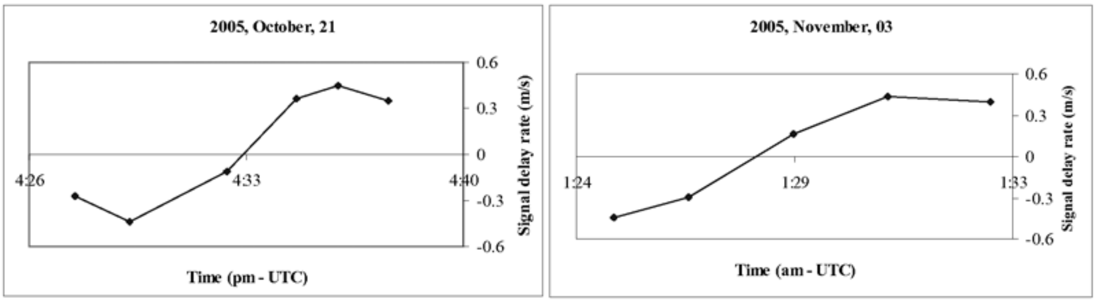

Figure 1 – The signal delay rate samples considering two passes of the satellite over a platform on 2005, October 21st (left) and 2005, November 3rd (right).

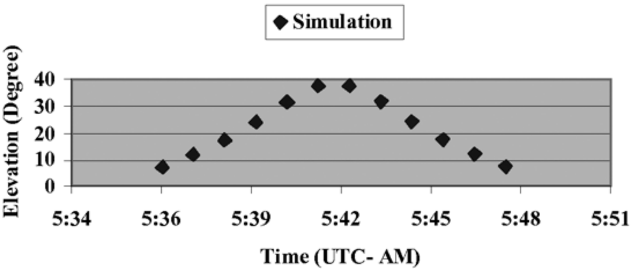

Figure 2 – Behavior of elevation angle during SCD-2 pass on January 2nd, 2006 from 5:36 to 5:49 am UTC.

DOPPLER GEOGRAPHIC LOCATION METHOD ADOPTED

This section summarizes the geographic location method using the Doppler shift measurements, based on Sousa (2000) and Sousa et al. (2003).

When a transmitted message from a platform reaches a receiving station via a satellite, a timestamp and up link frequency measurements are executed and appended in the DCP received message. A Doppler shift measurement corresponds to the difference between a received signal frequency at the satellite and the nominal platform transmitter frequency. This shift is caused by the relative velocity between the satellite and platform.

Knowing the satellite orbit positions and at least 3 Doppler shift measurements, a location of the transmitter can be estimated.

For each Doppler shift measurement a location cone is obtained as shown in the Figure 3. The satellite is in the cone vertex and its velocity vector v lies in the symmetry axis. For a second measurement, another different location cone intercepts the Earth surface and the intersection of both cones contains two possible transmitter positions. To find the correct one, additional information is required, as for example, the knowledge of an initial position. A second overpass could remove any uncertainties.

The satellite velocity relative to the transmitter $(V\cos\alpha)$ in vacuum conditions, denoted by$\dot{\rho}$, is given by the Doppler effect (Resnick, 1968) equation as follows:

$$\dot{\rho} = \left[\frac{(f_r - f_t)}{f_t}\right] c\,,$$

or

$$\delta \equiv (f_r - f_t) = \dot{\rho} f_t / c \tag{3}$$

where f_r is the transmitter frequency value received by the satellite; f_t is the reference frequency of the transmitter; δ is the Doppler shift due to the relative velocity satellite-transmitter; c is the speed of light; α is the angle between the satellite velocity vector V and the transmitter position relative to the satellite. The Doppler shift δ is measured at several points of the satellite pass and constitutes the measurement vector.

To solve equation (3) statistically, we use the least squares procedure. Let $\mathbf{X}$ and $\mathbf{y}$ be two real vectors representing a physical state and the observable states, related non-linearly. Taking into account that any observation process involve imperfections not modelled deterministically, we assume that such imperfections are modelled by a random vector $\mathbf{v}$. Therefore the Doppler shift observations are modeled by:

$$\mathbf{y} = \mathbf{h}(\mathbf{X}) + \mathbf{v}, \tag{4}$$

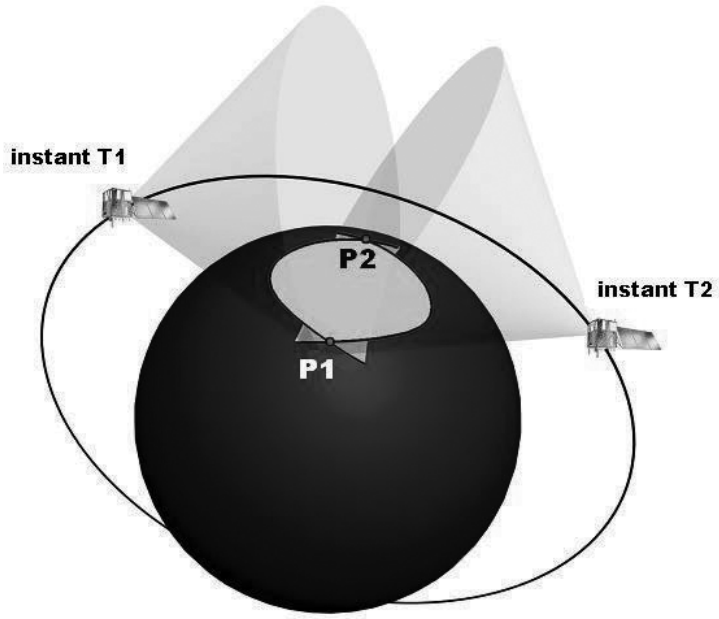

Figure 3 – Location cones.

where $\mathbf{y}$ is the set of Doppler shift measurements; $\mathbf{h}(\mathbf{X})$ is the non-linear vector function relating the measurements to the solve-for parameters $\mathbf{X}$, which includes transmitter position, and bias parameters, i.e. $\mathbf{X} = (X, Y, Z, b_0, b_1)$.

Therefore, each Doppler shift measurement is related to the location parameters by (Sousa, 2000; Sousa et al., 2003):

$$h(\mathbf{X}) = \frac{\left[(x-X)(\dot{x}-\dot{X}) + (y-Y)(\dot{y}-\dot{Y}) + (z-Z)(\dot{z}-\dot{Z})\right]}{\sqrt{(x-X)^2 + (y-Y)^2 + (z-Z)^2}} + b_0 + b_1 \Delta t \tag{5}$$

where (x, y, z) and (X, Y, Z) are the (known) satellite and (unknown) transmitter position coordinates, $(\dot{x}, \dot{y}, \dot{z})$ and $(\dot{X}, \dot{Y}, \dot{Z}) \equiv (0, 0, 0)$ represents the (known) satellite and (known) transmitter velocity vectors in the geocentric coordinates, b_0 and b_1 are (unknown) parameters associated with each Doppler curve to account for unknown bias in the Doppler measurements and a possible drift in the transmitter oscillator (see Fig. 4).

A non-linear least-squares procedure using Householder orthogonal rotations processes the Doppler shift measurements to estimate the location parameters $\mathbf{X}$, and is used for estimating the location of the two test platforms. Details can be found in Sousa (2000) and Sousa et al. (2003). The models related to ionosphere and to troposphere in section 2 were also implemented in the location software.

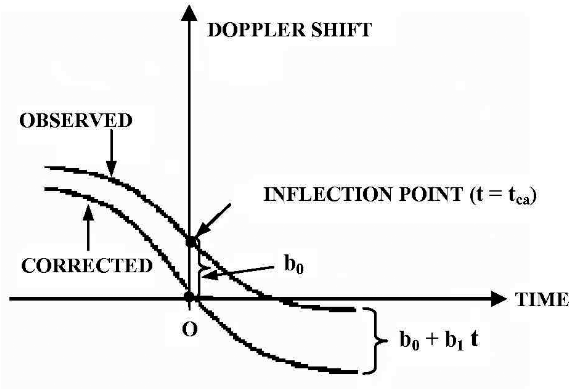

Figure 4 – Doppler curve.

DEVELOPMENT OF THE WORK

The analysis of the errors due to the tropospheric and ionospheric effects on the geographic location of DCPs was organized into the following steps, considering a test period of one year (from October 2005 to October 2006):

1. Two DCPs were selected considering that: i) DCP #32590, latitude of 15.55297°S and longitude of 56.06875°W, is at the Cuiabá Station and its nominal frequency is 401.650 MHz, and ii) DCP #32003, latitude of 2.58965°S and longitude of 44.20673°W, is at Alcântara Station and its nominal frequency is 401.650 MHz. The Cuiabá DCP observes more satellite passes, but the system load is very

heavy due to high platform density, specially related to vessel monitoring platforms operating in the Peru. On the other hand, Alcântara DCP is geographically closer to the Equator.

2. The first step was to perform numerical simulations covering the test period to quantify the errors caused by the tropospheric and ionospheric effects on the location of the two selected platforms. A simulator was implemented to generate the Doppler frequency shift values for the two DCPs taking into account the ionospheric and tropospheric models intentionally added and using the same satellite passes and DCP reception time as obtained in actual satellites passes;

3. For each satellite pass, the impacts on the location errors were estimated using the simulated Doppler shift values into the DCP Localization System as well as several graphics were produced to show effects such as seasonal or day-night conditions;

4. The tropospheric and ionospheric models were implemented in a special version of the DCP Location System (actual condition) for comparison purposes. For each platform, using the tropospheric and ionospheric zenith delays obtained from CPTEC-INPE (2005, 2006), VTEC values from IRI (Bilitza, 2005, 2006), and SCD-2 two-line orbit ephemeris elements from the INPE's Satellite Control Center, the location errors were determined either taking or not into account these atmospheric corrections. Several graphics were produced and analyzed to verify the impacts of these corrections.

ANALYSIS OF THE RESULTS

Seasonal and day-night effects of ionosphere

We investigated the ionospheric correction on the zenith direction during one year test period and no remarkable pattern was distinguished between seasons using the data acquired from the two test DCPs. Actually, each season presented local minimum and maximum zenithal delays, but without any defined behavior. It seems that, considering DCP #32590, in some months, such as February, June, July, August and September, the ionospheric effect is less pronounced. To DCP #32003 this occurs in the whole north hemisphere summer but still no conclusion can be drawn in definite terms, see Figure 5. Besides, it may be that the effects were not relevant due to the years 2005-2006 being of weak solar activity.

The day-night ionospheric effect within the twelve months comprised between October 2005 and October 2006 was investigated as well. The zenithal correction covered periods of maximum and minimum activity. This maximum occurs about 6 pm UTC with zenith delay around 100 meters, and minimum about 6 am UTC with zenith delay around 10 meters independent of the tested DCPs as shown in Figure 6. The maximum activity occurred more frequently from October to December 2005. This period coincides with the autumn-winter of the north hemisphere.

Seasonal and day-night effects of troposphere

The tropospheric effects on the zenith direction due to the epoch season and due to the hour of day (day-night effect) along one year (October 2005 to October 2006) are presented in the Figures 7 and 8. The delays correspond to approximately 2.30 and 2.60 meters on the zenith to DCP #32590 and approximately 2.50 and 2.75 meters on the zenith to DCP #32003 but without any defined behavior. The difference range seems too small to deserve a deeper investigation.

We should point out that, for the scope of this paper, the investigation considered only DCPs located in the Brazilian territory. For other world regions the troposphere delay behavior might eventually be very different.

DCP location errors

By means of simulation, considering data covering one whole year, we notice that the location errors due to the tropospheric and ionospheric effects are between 39 and 470 meters for DCP #32590 and 28 and 510 meters for DCP #32003, as shown in Figure 9.

These errors correspond to latitude errors of 0.0016° RMS and longitude errors of 0.00059° RMS for DCP #32590 and latitude errors of 0.0016° RMS and longitude errors of 0.00077° RMS for DCP #32003.

A preliminary study was shown in Celestino et al. (2007), considering only two satellite passes over a single DCP, where the location errors were between 100 and 200 meters due to ionospheric and tropospheric effects. In a follow-on work, they presented results (Celestino et al., 2008), where various conditions were tested using simulated data for two existing DCPs. They showed that location errors can present up to 600 meters difference due to ionospheric and tropospheric effects, approximately.

Considering actual acquired data, we can observe in Figures 10a-b that in most of cases the location error decreases when the ionospheric and tropospheric effects are considered.

In such actual conditions, excluding passes with low elevati-

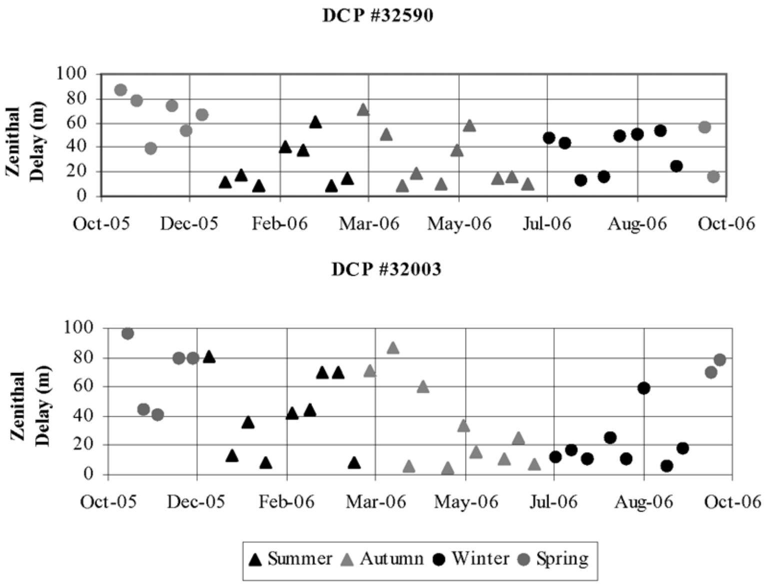

Figure 5 – The ionospheric seasonal effect during one year (October 2005 to October 2006).

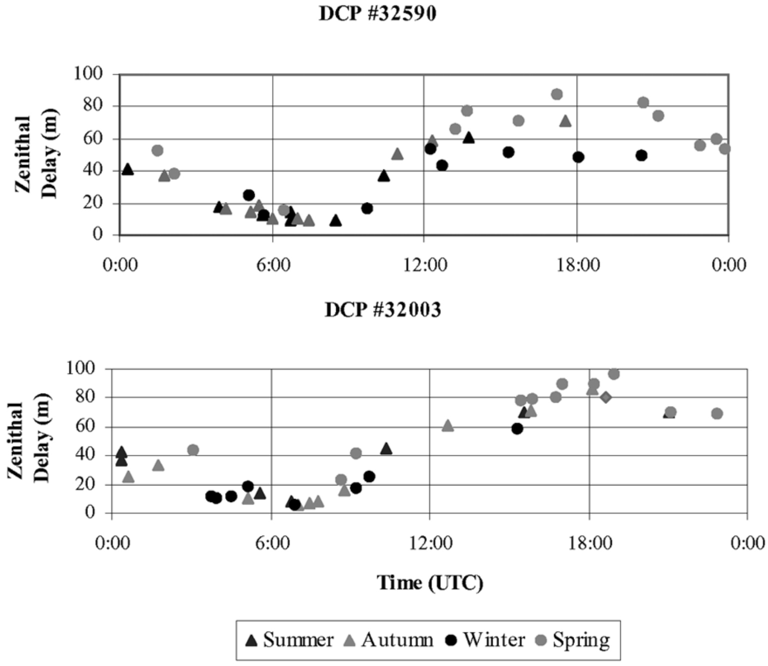

Figure 6 – The day-night ionospheric effect during one year (October 2005 to October 2006).

ons (<10°) and Doppler curves not well distributed, location of DCP #32590 improved between 10 to 420 m (average of 177 m), and between 170 to 520 m (average of 274 m) for DCP #32003.

It remains to be investigated that other effects may be superimposed and affect the location accuracy. For instance, a quick simulation introducing satellite ephemeris (position) error shows that the resulting error can be meaningful. If an along track position error in the orbit is introduced, the impact on the location is on average almost the same order, i.e., 100 m along track orbit error yields almost 100 m error on location. In the same way, frequency measurement noise, even being of random nature, can also introduce errors in the location estimates.

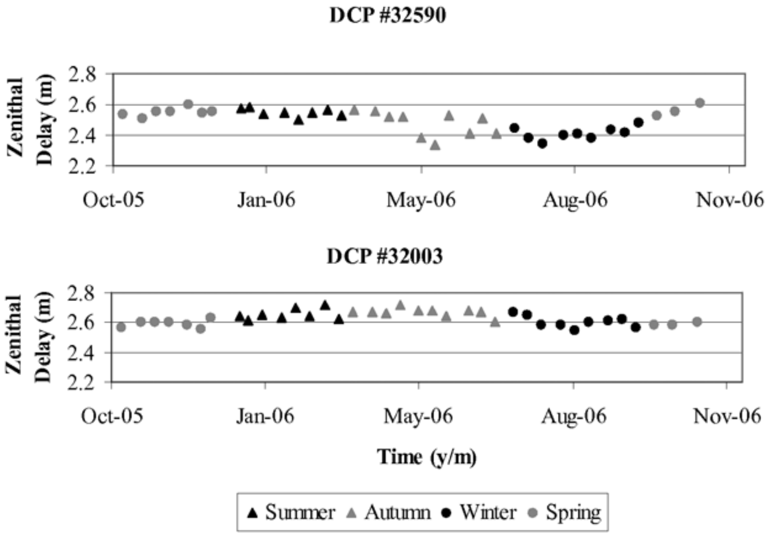

Figure 7 – The tropospheric seasonal effect during one year (October 2005 to October 2006).

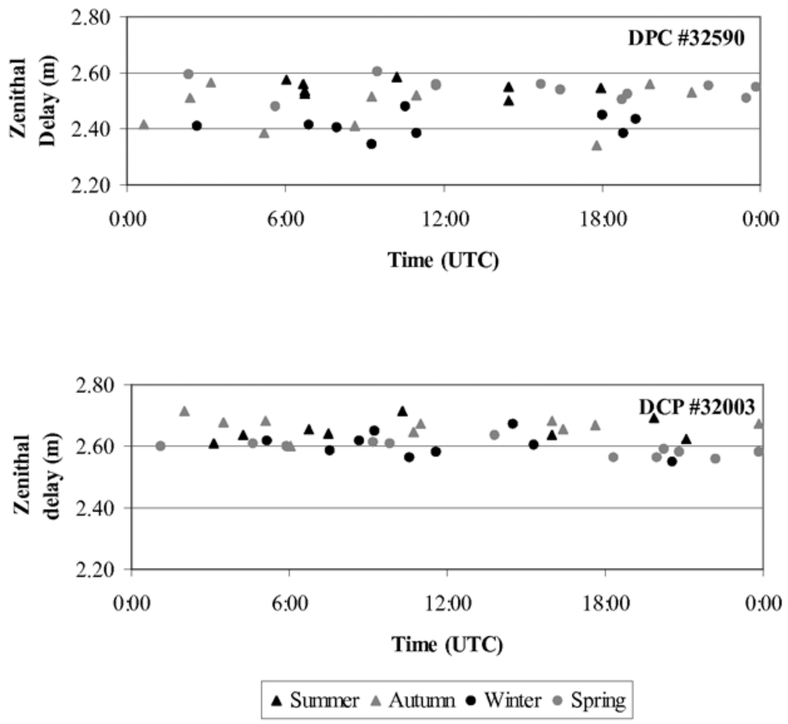

Figure 8 – The day-night tropospheric effect during one year (October 2005 to October 2006).

CONCLUSIONS

The results of the geographic location of data collection platforms and analysis of the ionospheric and tropospheric effects were shown, depicting the location accuracy achieved. We investigated the ionospheric correction due to the seasonal effect and no remarkable pattern was distinguished between seasons. On the other hand, the day-night ionospheric effect presented variable delays with maximum around 100 meters about 6 pm UTC and minimum around 10 meters about 6 am UTC, respectively. In short, the simulated results indicated that accounting for the ionospheric and tropospheric effects can reduce up to 600 meters

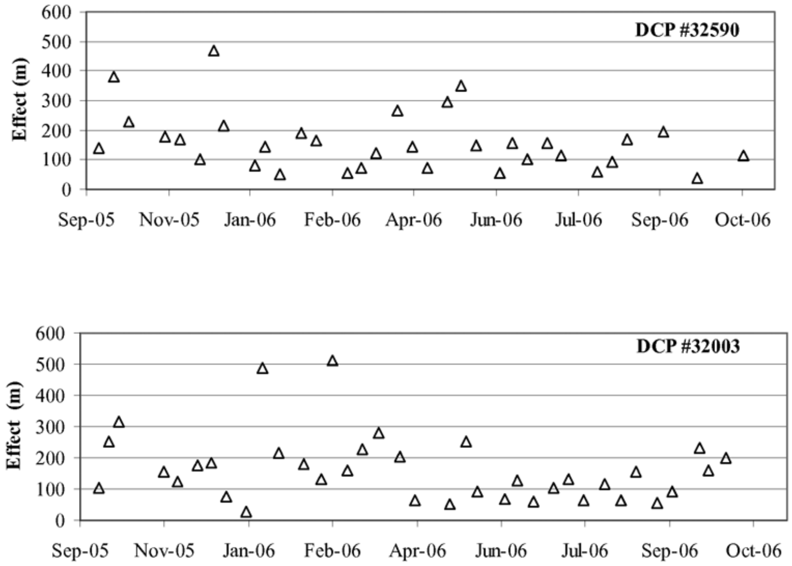

Figure 9 – Evaluation of the improvements due to ionospheric and tropospheric corrections using DCP #32590 and DCP #32003 for one year.

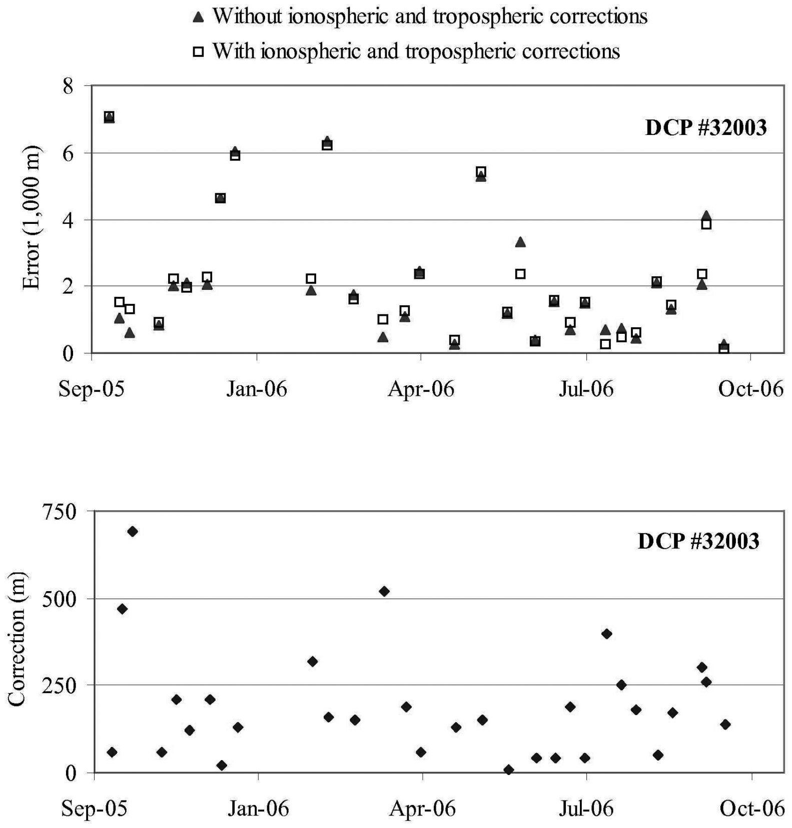

Figure 10a – Location error improvements due to ionospheric and tropospheric effects using DCP #32003 for one year and actual conditions.

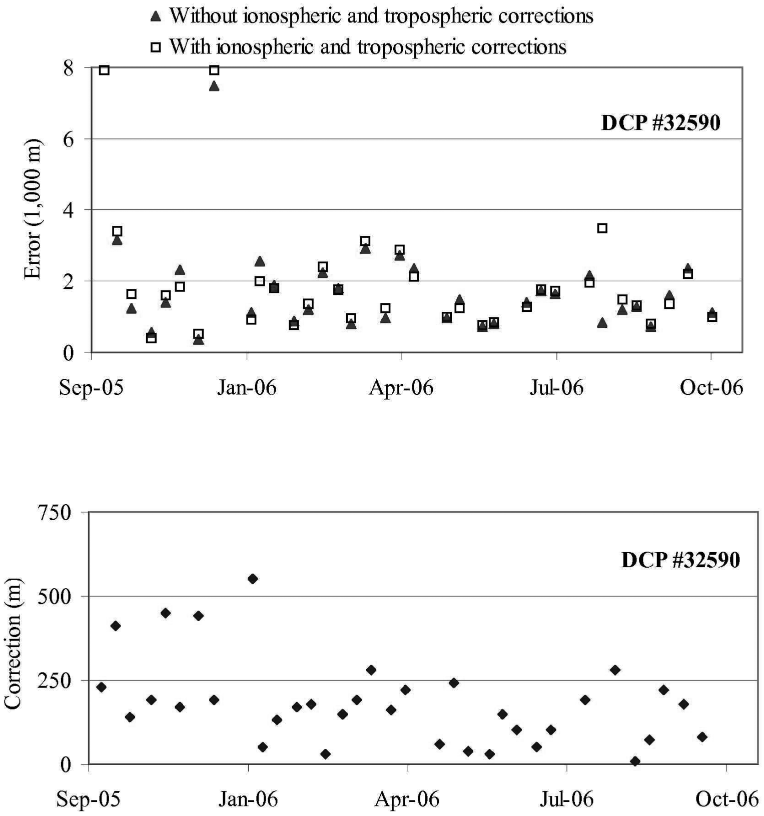

Figure 10b – Location error improvements due to ionospheric and tropospheric effects using DCP #32590 for one year and actual conditions.

the geographical location errors. Using actual data the location errors of DCP #32590 improved between 10 to 420 meters, and, between 170 to 520 meters for DCP #32003, for one year data analysis. It was also clear that some issues must be addressed in future steps such as improvement of the mapping function for low elevation angles, the use of test platforms with shorter transmission intervals (high sampling rates), better oscillator characteristics and adjustable transmission power to reduce location errors due to other factors than ionospheric and tropospheric effects. A quick investigation showed that satellite ephemeris and the frequencies noise also must be analyzed. A study over some location error sources is presented in Sousa (2000). In this work, she shows that 1 Hz random errors in Doppler measurements could cause location errors of hundreds of meters, and for 100Hz random errors, location errors of tens of kilometers. Satellite orbit ephemeris errors also result in location errors in the same order.

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