Mitigation of ionospheric effects on GNSS positioning over Antarctica: a case study during low solar activity

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Introduction

The aim of this study is to investigate the performance of a method based on improving the stochastic model to mitigate ionospheric scintillation effects on GNSS positioning by processing experimental data from GISTM (GPS Ionospheric Scintillation and TEC Monitor) receivers, which are capable of computing amplitude and phase scintillation parameters from GPS signals.

We investigated the case study of 21 November 2009 using data from GISTM stations located in Antarctica to apply the approach to mitigate ionospheric scintillation effects in the Precise Point Positioning (PPP) solution. We used an in-house software called FCT_RT_PPP which is under development at FCT/Unesp - Brazil.

Despite the solar activity being very low, observations from ACE indicated the influence of a recurrent coronal hole high speed stream. Solar wind speed ranged from 430 to 575 km/s, with Bz fluctuations from -8 to +9 nT, generally leading to the formation of ionospheric irregularities responsible for the scintillation effects on GNSS signals.

The results have shown improvements varying from 20 to 60 percent in in 3D and height accuracy in the PPP results when applying the proposed stochastic modeling based on scintillation data. (It would be better to say results at the end…Galera)

Stochastic modeling for absolute GNSS positioning

The usual GPS data processing strategy for PPP solution considers a stochastic model based on the covariance matrix ($\sum_{obs}$) that is given by a simplified form:

$$\sum_{obs} \begin{bmatrix} \sigma^2_{PR^{s1}_{IF}} & 0 & 0 & 0 & 0 & 0 & \cdots & 0 \\ 0 & \sigma^2_{PR^{s2}_{IF}} & 0 & 0 & 0 & 0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \cdots & \sigma^2_{PR^{sn}_{IF}} & 0 & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & \sigma^2_{\varphi^{s1}_{IF}} & 0 & \cdots & 0 \\ 0 & 0 & \cdots & 0 & 0 & \sigma^2_{\varphi^{s2}_{IF}} & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & \cdots & \sigma^2_{\varphi^{sn}_{IF}} \end{bmatrix}$$

where:

$\sigma^2_{PR^{si}_{IF}}$ - Pseudorange Ionosphere Free variance;

$\sigma^2_{\varphi^{si}_{IF}}$ - Phase Ionosphere Free variance;

S_i - Satellite i (i=1,...,n).

Stochastic Model incorporating ionospheric scintillation effects

The strategy used to consider the ionospheric scintillation effects in the stochastic model relies on the estimation of the tracking errors when the satellites' signals are subject to the occurrence of ionospheric scintillation (Aquino et al. 2009). The variances are calculated based on the tracking models of Conker et al. (2003), which are then used to assign weights to the different satellites in view by the GNSS receiver antenna.

As an illustration of these models, the tracking error variances at the output of the receiver PLL (Phase Lock Loop) for the GPS L1 carrier is given by:

$$\sigma^2_{PLL} = \sigma^2_{\phi_{S_{L1}}} + \sigma^2_{\phi_{T_{L1}}} + \sigma^2_{\phi_{OSC}}$$

where:

$\sigma^2_{\phi_{S_{L1}}}$ – phase scintillation variance for the L1 carrier;

$\sigma^2_{\phi_{T_{L1}}}$ – thermal noise variance for L1 carrier;

$\sigma^2_{\phi_{OSC}}$ – receiver/satellite oscillator noise variance ($\sigma_{\phi_{OSC}}$= 0.1 rad).

$$\sigma^2_{\phi_{T_{L1}}} = \frac{B_{n_{L1}}\left[1+\frac{1}{2\eta(c/n_0)_{L1-CA}(1-2S_4^2(L1))}\right]}{(c/n_0)_{L1-CA}(1-S_4^2(L1))}$$

where:

$B_{n_{L1}}$ – L1 third-order PLL one-sided bandwidth, equal to 10 Hz;

η – Pre-detection integration time, equal to 0.02 s for GPS;

$(c/n_0)_{L1-CA}$ – Fractional form of signal-to-noise density ratio, equal to $10^{0.1(C/N_0)_{L1-CA}}$;

model valid only for S4(L1) < 0.707*; loss of lock is assumed for greater values of S4;*

$$\sigma^2_{\phi_{S_{L1}}} = \frac{\pi T}{k f_n^{p-1} \sin\left(\frac{[2k+1-p]\pi}{2k}\right)}$$

where:

T – Spectral strength of the phase noise at 1 Hz;
k – Order of the PLL (3 for carrier L1);
fn – loop natural frequency, 1.91 Hz for carrier L1;
p – Spectral slope of the phase PSD (Power spectral density) for f >> f0, where f0 is the frequency corresponding to the maximum irregularity size in the ionosphere (1 < p < 2k).

Stochastic modeling on GNSS positioning

The tracking error variance at the output of the DLL (Delay Locked Loop) for the L1 CA code is given (in C/A code chips) by:

$$\sigma^2_{DLL} = \sigma^2_{\phi_{T_{CA}}}$$

where, $\sigma^2_{\phi_{T_{CA}}}$ is the thermal noise variance for carrier CA and is given by:

$$\sigma^2_{\phi_{T_{CA}}} = \frac{B_{n_{CA}} d\left[1+\frac{1}{\eta(c/n_0)_{L1-CA}(1-2S_4^2(L1))}\right]}{2(c/n_0)_{L1-CA}(1-S_4^2(L1))}$$

where:

B_n - one-sided noise bandwidth;
d - correlator spacing;
$(c/n_0)_{L1-C/A}$ - fractional form of signal-to-noise density ratio, equal to $10^{0.1C/N0}$;
η - predetection integration time, equal to 0.02s;
model valid only for $S_4(L1)$ < 0.707; loss of lock is assumed for greater values of S4.

Stations location and geomagnetic scenario

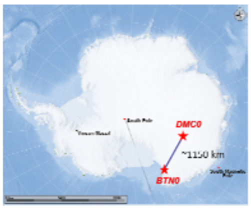

Fig. 1 – BTN0 and DCM0 stations localization

ID	Location	Latitude	Longitude
BTN0	Mario Zucchelli Station	74.7°S	164.1°E
DMC0	Concordia Station	75.1°S	123.2°E

Kp index = 3
Dst index = -3 nT
Ae index = 99 nT
Low ionosphere activity

Phi60 and S4 indices for BTN0 and DMC0 stations (satellites elevation angles > 10°):

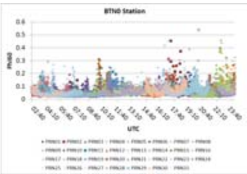

Fig. 2 – Phi60 for BTN0 station

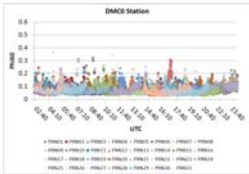

Fig. 3 – Phi60 for DCM0 station

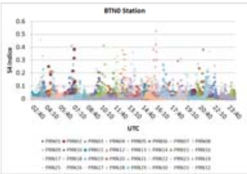

Fig. 4 – S4 for BTN0 station

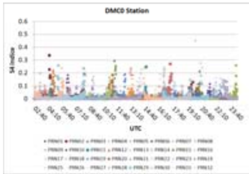

Fig. 5 – S4 for DCM0 station

Static PPP

The GNSS data from BTN0 and DMC0 stations were processed in the PPP mode using an in-house software called FCT_RT_PPP which is under development at FCT/UNESP - Brazil. The PPP method was implemented using an extended Kalman Filter and the DIA (Detection, Identification and Adaptation) quality control procedure.

The results were generated using precise orbits and clocks from IGS. The first order ionosphere effects were eliminated through the Ionosphere Free combination for Code and Phase observables. The troposphere was estimated as a random walk process (2mm/hour) together with coordinates and receiver clock errors. Concerning the stochastic model the following precision was used for the observables:

$$\sigma_{L1} = 0.01\,m\,;\ \sigma_{L2} = 0.02\,m$$
$$\sigma_{CA} = 0.30\,m\,;\ \sigma_{P2} = 0.40\,m$$

Two strategies were applied in the PPP processing:

1) Taking into account the observables variances as a function of the satellites elevation angle (Stoch_Mod_Elev)

$$\sigma_{obs^{s_i}_r} = \sigma_{obs} \cdot \frac{1}{\sin(Elev^{s_i})}$$

2) Using the variances as a function of the ionospheric scintillation effects as in Aquino et al. (2009) (Stoch_Mod_Scint).

The estimated coordinates were compared against the average of the entire period what for the sake of this study was denominated as "error". Figs. 6 and 7 show the time series of the errors for BTN0 station.

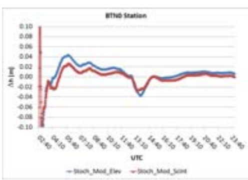

Fig. 6 – Height error – BTN0

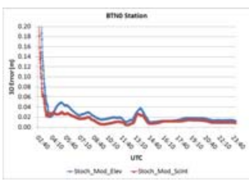

Fig. 7 – 3D error – BTN0

Figs. 8 and 9 show the time series of the errors for DMC0 station in the PPP processing.

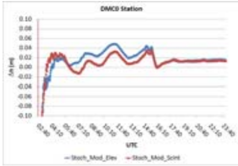

Fig. 8 – Altimetric error - DCM0

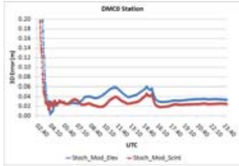

Fig. 9 – 3D error - DCM0

Table 1 shows the height and 3D error RMS (Root Mean Square) for BTN0 and DMC0 stations together with the percentage improvement when considering the two stochastic modelling proposed.

Table 1 – Statistic summary of th PPP processing

Stations	RMS (m)	Stoch_Mod_Elev	Stoch_Mod_Scint	Improvement(%)
BTN0	Δh	0.069	0.026	62.552
	3D Error	0.089	0.050	43.812
DMC0	Δh	0.107	0.075	30.325
	3D Error	0.148	0.120	19.513

From the time series in Figs. 6, 7, 8 and 9, it is possible to see that when the scintillation mitigation approach was applied the coordinates accuracy has improved. Also, it is possible to verify the correlation of these figures with the Phi60 and S4 indices (Figs. 2 to 4).

In Table 1 it can be seen that the improvements in terms of RMS reached the order of approximately 63% and 44 % in height and 3D error, respectively, for BTN0 station and 30.3% (height) and 19.5% (3D error) for DMC0 station.

Kinematic Precise Point Positioning

The data from BTN0 was also processed in the PPP kinematic mode considering the elevation angle and the proposed ionospheric scintillation mitigation in the stochastic model. The same corrections applied for the static case were applied for the kinematic PPP. The figures below show the 3D error RMS and the 3D coordinates accuracy **precision** for the BTN0 station (porque precision? Nao foi comparado com ground truth?):

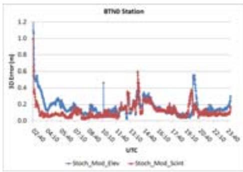

Fig. 10 – Kinematic height error – BTN0

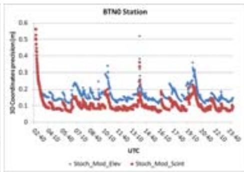

Fig. 11– Kinematic 3D error – BTN0

From the figures above it is possible to see that in most cases the mitigation approach by considering the scintillation effects on the stochastic model has improved the results. In the case of the 3D error the improvement reached **~29.224% (porque tantas casas decimais?)**. Concerning the 3D coordinates precision from the Figure 11 can be verify that in the most of cases the **precision or accuracy?** improved.

Conclusions

The

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