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GPS MEASUREMENTS OF TEC VARIATION DURING IONOSPHERIC PLASMA BUBBLE EVENTS

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Abstract.

1 INTRODUCTION

Plasma bubbles are regions of low plasma density within the ionosphere, which usually form after sunset. They typically occur around the equinoxes when the sunset terminator (twilight zone) aligns itself with the magnetic meridian. The boundaries of a bubble are habitually sharp, leading to steep gradients in electron density along the path of a GPS signal.

The varying electron density along the signal path causes an apparent Doppler shift that sometimes exceeds the bandwidth of the receivers phase lock loop (PLL). When this situation occurs, the receiver loses lock on the signal, leading to cycle slips. A similar consequence can occur due to the diffraction of GPS signals, leading to destructive interference at the antenna and resulting in lower signal power. This problem is amplified by the fact that acquisition by civil receivers of the legacy signal on L2 is not done by direct cross-correlation as on L1 due to the unknown encrypted pseudorandom noise sequence.

While GPS is an interesting tool for monitoring the state of the ionosphere, it faces challenges to accomplish this task reliably during ionospheric plasma bubble events due to the abovementioned reasons. In this contribution, we focus on two aspects: reducing the impact of L2-only signal loss on total electron content (TEC) determination, and improving the continuity of TEC time series by correcting for cycle slips.

The most common method for determining the ionospheric delay variation along a signal path from a given satellite (i) to a receiver uses the geometry-free (GF) time-differenced (δ) combination of carrier-phase (Φ) measurements on two frequencies (subscripts 1 and 2):

$$\delta\Phi^i_{GF} = \delta\Phi^i_1 - \delta\Phi^i_2 = (\alpha - 1)\delta I^i + \varepsilon_{\delta\Phi_{GF}} \tag{1}$$

where I is the ionospheric delay, α is a constant dependent on the frequencies of the carriers and ε includes residual errors. Since this approach explicitly combines carrier-phase measurements on both frequencies, the ionospheric delay variation cannot be computed when one observation is missing. Cycle slips on at least one of the carriers will also introduce a jump in the geometry-free time-differenced combination.

Several approaches have been proposed over the years to account for cycle slips in GPS data: polynomial fitting1, searching for cycle-slip candidates that minimize the geometry-free combination variation2, statistical testing of time-differenced least-squares solutions3, etc. While those methods are suitable for most applications, the characteristics associated with plasma bubbles (rapid ionospheric delay fluctuations, numerous data gaps, increased noise, etc.) reduce their performance significantly.

In this extended abstract, we propose a geometric approach as an alternative to the geometry-free linear combination for determining TEC variation. Preliminary results of this model are shown using GPS data collected during a plasma bubble event that occurred in Okinawa, Japan, in 2004.

2 DETERMINATION OF TEC VARIATION USING A GEOMETRIC APPROACH

In an attempt to solve the issues mentioned in the previous section, an alternative to using the geometry-free linear combination for TEC variation determination is proposed. Instead of explicitly combining carrier-phase observations on the L1 and L2 bands and processing all satellites independently, the following functional model is used:

$$\begin{aligned} \delta\widetilde{\Phi}^i_1 &= \delta dT - \delta I^i + \lambda_1 \delta N^i_1 + \varepsilon_{\delta\Phi_1} \\ \delta\widetilde{\Phi}^i_2 &= \delta dT - \delta I^i + \lambda_2 \delta N^i_2 + \varepsilon_{\delta\Phi_2} \end{aligned} \tag{2}$$

The tilde symbol is used to indicate that all known geometric effects (i.e. variation in satellite geometry, satellite clock variation, tropospheric delay, etc.) have been removed from the measurements. It is assumed that the antenna is static and that its coordinates are known to a satisfactory level of accuracy so as not to introduce significant errors. When using this formulation, the only unknown geometric effect is the variation in receiver clock offset (δdT), common to all measurements made simultaneously. The variation in ambiguity parameter (δN) is zero for continuous carrier-phase measurements, while it is an integer number when cycle slips occur. In equation 2, δN is scaled by the signal wavelength (λ).

This model addresses the issue of missing L2 data as follows: the observations from all satellites are used simultaneously in a least-squares adjustment to estimate the values of the unknown parameters (variation in receiver clock offset, ionospheric delays and ambiguities, if required). This implies that, when at least one satellite has dual-frequency measurements free from cycle slips, it can be used to solve for the variation in receiver clock offset (δdT). In this case, if only the L2 measurement ($\delta\widetilde{\Phi}_2^i$) is missing for another satellite, the variation in ionospheric delay for this satellite can still be recovered using the continuous L1 measurement ($\delta\widetilde{\Phi}_1^i$) since $\delta N_1^i = 0$. This can easily be seen by examining equation 2.

The issue of cycle slips can also be dealt with by estimating the variation in ambiguity (δN) when a discontinuity is detected in the signal. The least-squares adjustment will provide float estimates for those parameters, along with their covariance matrix. This information can be used to fix those values to integers using, for example, the LAMBDA method [4]. More details regarding this process will be provided in future publications.

3 PRELIMINARY RESULTS

In order to show the applications of the theory introduced in the previous section, we use data collected on 23 March 2004 on Okinawa Island in southern Japan. This site is located at a geomagnetic latitude of approximately 16° 30'N, and this particular event occurred near the last maximum of the last 11-year solar cycle. Two GPS stations, located only a few meters apart, observed an ionospheric plasma bubble event that affected significantly the measurements of four satellites for a period totaling nearly three hours.

Figure 1 shows the TEC variation of PRN 21 at one of the stations, determined using the geometry-free model (equation 1). One can notice that several cycle slips contaminate the results and that almost no information of the ionospheric structure can be extracted.

Figure 2 shows the ionospheric delay variation obtained using the geometric approach (equation 2). The results from two stations (A and B), located only a few meters apart, are included as a means of validation. Not all cycle slips could be corrected, which explains the divergences observed between both solutions. Work is still under way to improve the cycle- slip fixing procedure. Still, the improvement over the geometry-free approach is obvious.

4 CONCLUSIONS

This contribution showed that plasma bubbles within the ionosphere can lead to severe tracking problems for GPS receivers. The main challenges to tackle were the numerous L2- only losses of lock, as well as cycle slips on both carriers. In order to overcome those limitations, a geometric model has been proposed as a viable alternative to the geometry-free linear combination of carrier-phase measurements to determine TEC variations. The advantages of this approach are mainly twofold: TEC variation can be obtained when solely L1 observations are available, and cycle slips can be corrected as an integral part of the approach. While the geometric approach does not resolve all issues, it is expected that enhancements in the performance of GPS receivers tracking capabilities, combined

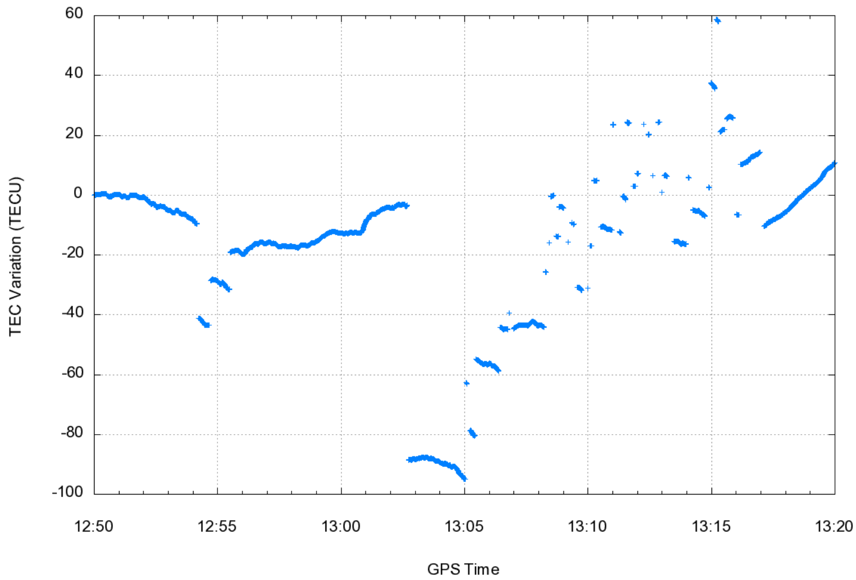

Figure 1: TEC variation computed using the geometry-free model for PRN 21 on 23 March 2004, Okinawa, Japan.

with this approach, could improve monitoring of irregular ionospheric structures.

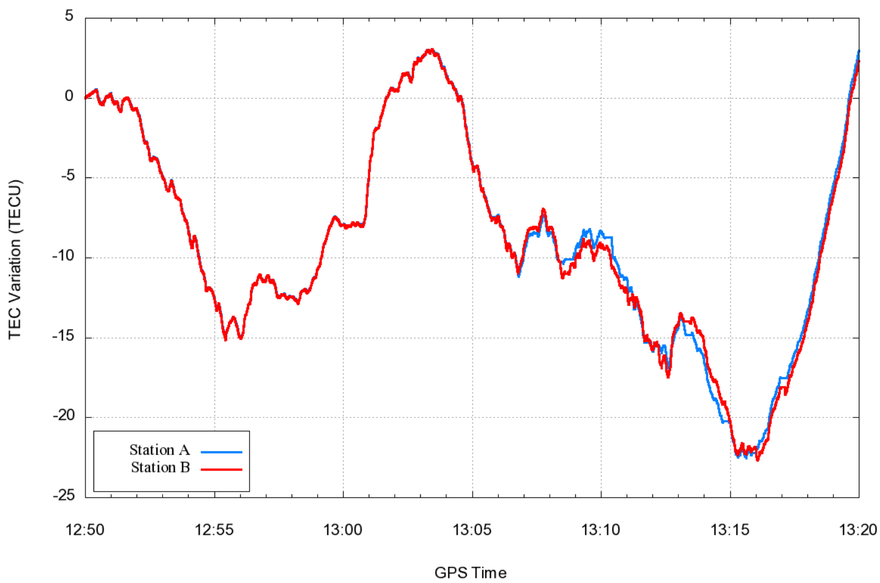

Figure 2: TEC variation computed using the geometric model for PRN 21 on 23 March 2004, Okinawa, Japan.

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6 INTRODUCTION

REFERENCES

[1] Beutler, G., D.A. Davidson, R.B. Langley, R. Santerre, P. Vanicek and D.E. Wells. *Some Theoretical and Practical Aspects of Geodetic Positioning Using Carrier Phase Difference Observations of GPS Satellites.* Technical Report No. 109, University of New Brunswick, Canada (1984).

[2] Blewitt, G. *An automatic editing algorithm for GPS data.* Geophysical Research Letters, 17(3), 199-202 (1990).

[3] Kim, D. and R.B. Langley. *Instantaneous Real-time Cycle-slip Correction of Dual-frequency GPS Data.* Proceedings of the International Symposium on Kinematic Systems in Geodesy, Geomatics and Navigation, Banff, Alberta, Canada, 5-8 June, 255-264 (2001).

[4] Teunissen, P.J.G. *Least-squares Estimation of the Integer GPS Ambiguities.* LGR Series 6, Delft Geodetic Computing Centre, Delft University of Technology, Delft, The Netherlands (1993).