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TOTAL ELECTRON CONTENT MONITORING USING TRIPLE FREQUENCY GNSS:RESULTS WITH GIOVE-A/-B DATA

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Abstract. Triple frequency GNSS will be fully operational in the next few years, opening opportunies for new applications. The second frequency already allows to study the ionosphere through the estimation of Total Electron Content (TEC). However, the precision is limited by the ambiguity resolution process. This paper studies a triple frequency TEC monitoring technique in which the use of new linear combinations will improve the ambiguity resolution process and therefore the precision of TEC.

1 INTRODUCTION

Triple frequency Global Navigation Satellite Systems (GNSS) will be fully operational in the next few years. Table 1 shows all GPS and Galileo frequencies and wavelengths.

GNSS	Carrier signal	Frequency (MHz)	$\lambda(m)$
GPS	L1	1575.42	0.1903
	L2	1227.60	0.2442
	L5	1176.45	0.2548
Galileo	L1	1575.42	0.1903
	E6	1278.42	0.2345
	E5b	1207.14	0.2483
	E5a+b	1191.795	0.2515
	E5a	1176.45	0.2548

Table 1: GPS and Galileo frequencies and wavelengths.

In GNSS, the availability of dual frequency measurements allows to reconstruct the total electron content (TEC) of the ionosphere, i.e. the integral of the electron concentration on the receiver-to-satellite path. TEC is computed by using Geometric Free (GF) combinations of measurements from the same satellite/receiver (undifferenced), by using code P_p^i and/or phase Φ_p^i measurements. As phase measurements are much less affected by measurement noise and multipath delays than code measurements, TEC is computed from the GF phase combination $\Phi^i_{p,GF}$ as follows (in TECU):

$$TEC_{km} = \frac{\Phi^i_{p,GF} + N^i_{p,GF}}{a_{km}} \tag{1}$$

with

$$\Phi^i_{p,GF} = \Phi^i_{p,k} - (f_k/f_m)\Phi^i_{p,m}$$
$$a_{km} = 40.3 \times 10^{16}(f_k/c)(1/f_m^2 - 1/f_k^2)$$

The main issue in Eq. (1) is the resolution of the so-called real GF ambiguity N^i_{pGF} (in cycles):

$$N^i_{p,GF} = N^i_{p,k} - (f_k/f_m)N^i_{p,m} \tag{2}$$

With dual-frequency GNSS (L1/L2 GPS), this is usually done by the phase-to-code levelling process which limits the precision of TEC[1,2,4] . Triple frequency GNSS open opportunities for new applications. In particular, the objective of this research is to develop a triple frequency TEC monitoring technique in which the use of new linear combinations will improve the ambiguity resolution process and therefore the precision of TEC.

2 METHODOLOGY

2.1 Extra-widelane ambiguity resolution

The objective of this step is to resolve extra-widelane (EWL) ambiguities N25 by using the extra-widelane-narrowlane (EWLNL) combination C_{25} (in cycles):

$$\begin{aligned} C_{25} &= \Phi^i_{p,L2} - \Phi^i_{p,L5} - \frac{f_{L2} - f_{L5}}{f_{L2} + f_{L5}} \times \left(\frac{f_{L2}}{c} P^i_{p,L2} + \frac{f_{L5}}{c} P^i_{p,L5} \right) \\ &= N^i_{p,L5} - N^i_{p,L2} + \Delta C_{25} \\ &= N_{25} + \Delta C_{25} \end{aligned} \tag{3}$$

This combination is GF and IF and gives the integer ambiguities N_{25} plus a residual term ΔC_{25} depending on hardware delays, multipath delays and measurement noise of both code and phase measurements. It is critical that the residual term ΔC_{25} be less than half a wavelength of C_{25} (9.768 m for Galileo) to resolve EWL ambiguities. Several assumptions on amplitude and variation of delays allow us to conclude that it is actually possible to fix EWL ambiguities at their correct integer numbers. Note that we will tacitly refer to those assumptions in the next three steps.

2.2 Widelane ambiguity resolution

The objective of the second step is to resolve the integer widelane (WL) ambiguities N_{12} by forming the so-called widelane-narrowlane (WLNL) combination C_{12} (in cycles):

$$\begin{aligned} C_{12} &= \Phi^i_{p,L1} - \Phi^i_{p,L2} - \frac{f_{L1} - f_{L2}}{f_{L1} + f_{L2}} \times \left(\frac{f_{L1}}{c} P^i_{p,L1} + \frac{f_{L1}}{c} P^i_{p,L2} \right) \\ &= N^i_{p,L2} - N^i_{p,L1} + \Delta C_{12} \\ &= N_{12} + \Delta C_{12} \end{aligned} \tag{4}$$

Similarly to C_{25}, this combination is GF and IF and gives the integer ambiguities N12 plus a residual term ΔC_{12} depending on hardware delays, multipath delays and measurement noise of both code and phase measurements. As the wavelength of C_{12} equals 0.814 m for Galileo, we conclude that this combination does not allow to resolve WL ambiguities. For this reason, we try to resolve WL ambi- guities by using another combination called differenced widelane (DWL) combination C125 (in cycles):

$$\begin{aligned} C_{125} &= (\Phi^i_{p,L1} - \Phi^i_{p,L2}) - (\Phi^i_{p,L2} - \Phi^i_{p,L5} - N_{25}) \frac{\lambda_{25}}{\lambda_{12}} \\ &= N^i_{p,L2} - N^i_{p,L1} + \Delta C_{125} \\ &= N_{12} + \Delta C_{125} \end{aligned} \tag{5}$$

This combination is GF but not IF; it gives the integer ambiguities N_{12} plus a residual term ΔC_{125} depending on all phase delays but also on the ionosphere by a contribution of $0.08 \times TEC$.

Even without taking the influence of phase delays into account, ΔC_{125} can clearly exceed 0.5 cycle. In conclusion, either C_{12} or C_{125} only gives approximate integer values of the WL ambiguities.

2.3 Ambiguity fixing

The objective of this step is to resolve the integer ambiguities N_1 , N_2 , N_5 . For this purpose, we use a GF and IF triple frequency phase combination s_{125} (in meters) :

$$\begin{aligned} s_{125} &= a_1\lambda_1\Phi^i_{p,L1} + a_2\lambda_2\Phi^i_{p,L2} + a_5\lambda_5\Phi^i_{p,L5} \\ &= -a_1\lambda_1 N_1 - a_2\lambda_2 N_2 - a_5\lambda_5 N_5 + \Delta s_{125} \end{aligned} \tag{6}$$

Let us average s_{125} on one continuous arc and then introduce N_{25} and N_{12} from previous steps, so that we can obtain N_2 (and so N_1 , N_5) as follows:

$$N_2 = \frac{\overline{s_{125}} - a_1\lambda_1 N_{12} + a_5\lambda_5 N_{25} - \Delta\overline{s_{125}}}{-(a_1\lambda_1 + a_2\lambda_2 + a_5\lambda_5)} \tag{7}$$

However, we know from Section 2.2 that N_{12} are only approximated integer values, so are the N_2 resulting values. As we can derive that an error of +1 cycle on N_{12} corresponds o an error of -26 cycles on N2 and of + 11.5 on TEC, the use of approximated TEC values computed by the dual frequency method allows us to fix N_{12} at their correct integer values[3].

Moreover, the residual term $\Delta\overline{s_{125}}$ is considered to cause an error of about 2.2 cycles on N_2, N_1 and N_5 . As a consequence, Eq. (1) and Eq. (2) shows that the resulting error on TEC would reach about 1 TECU.

2.4 TEC computation

The objective of this step is to compute TEC. As in previous steps we have resolved all integer ambiguities (N_1 , N_2 , N_5), we can introduce them in Eq. (2) to resolve $N^i_{p,GF}$ and then to compute TEC by using Eq. (1). There are three different ways to obtain TEC - TEC_{12} , TEC_{15} and TEC_{25} - respectively by using L1/L2, L1/L5 and L2/L5 combinations.

The total error caused by all phase delays on TEC in Eq. (1) should not exceed 0.5 TECU for TEC_{25} and 0.05 TECU for TEC_{12} and TEC_{15} .

3 RESULTS

The methodology presented here below has been tested on a Giove-A/-B data set, i.e. on triple frequency L1-E5b-E5a code and phases measurements processed by four stations belonging to the Galileo Experimental Sensor Stations (GESS) network. The results are in agreement with all statements presented in Section 2 and confirm the improvement of the GF ambiguity resolution process and therefore of the precision of TEC.

4 CONCLUSIONS

This paper presents a triple frequency TEC monitoring technique. Its validation is performed on a set of Giove-A/-B data shows that the use of new linear combinations improve the ambiguity resolution process and therefore the precision of TEC.

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