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

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ABSTRACT

Triple frequency Global Navigation Positioning Systems (GNSS) will be totally operational in the next few years. The second frequency already allows to study the ionosphere trough the estimation of Total Electron Content (TEC). Nevetheless, precision is limited by the ambiguity resolution process based on phase-to-code levelling. This paper studies a triple frequency TEC monitoring technique in which the use of new linear combinations improves the ambiguity resolution and therefore the precision of TEC.

Key words: Ionosphere, TEC, GNSS, Triple frequency.

1. INTRODUCTION

Triple frequency Global Navigation Satellite Systems (GNSS) will be totally operational in the next few years. Nowadays, the Global Positioning System (GPS) transmits two carrier signals, but an initial look at the third frequency (tab. 1) has already been given. Galileo transmits three frequency bands (L1-E5-E6) but in reality five distinct frequencies exist (tab. 1). The open services are realized by using the L1 and E5 signals, while E6 signals are encrypted. Up to now, the first two Galileo test satellites, Giove-A and Giove-B, have been launched and tested successfully.

GNSS	Carrier signal	Frequency (MHz)	λ (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 second frequency allows to obtain estimates of 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), either by using code P_p^i or phase Φ_p^i measurements, respectively in meters and cycles :

$$P^i_{p,\mathrm{GF}} = P^i_{p,k} - P^i_{p,m} \quad (1)$$

$$\Phi^i_{p,\mathrm{GF}} = \Phi^i_{p,k} - (f_k/f_m), \Phi^i_{p,m} \quad (2)$$

with f the frequency and $k,\ m$ two distinct signals.
In such a combination, all frequency-independent effects are eliminated, so that it only remains ionospheric delay and other frequency-dependent effects : satellite and receiver hardware delays, multipath delays, measurement noise and - for phase measurements - the integer ambiguity N_p^i. 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):

$$\mathrm{TEC}_{km} = \frac{\Phi^i_{p,\mathrm{GF}} + N^i_{p,\mathrm{GF}}}{a_{km}} \quad (3)$$

with $a_{km} = 40.3 \times 10^{16}\,(f_\mathrm{k}/c)\,(1/f_\mathrm{m}^2 - 1/f_\mathrm{k}^2)$

The main issue in Eq. (3) is the resolution of the so-called real GF ambiguity $N^i_{p,\mathrm{GF}}$ (in cycles):

$$N^i_{p,\mathrm{GF}} = N^i_{p,k} - (f_k/f_m)\,N^i_{p,m} \quad (4)$$

With dual-frequency GNSS (L1/L2 GPS), this is done by the phase-to-code levelling process, which consists in shifting the GF phase combination $\Phi^i_{p,\mathrm{GF}}$ by a constant value ($N^i_{p,\mathrm{GF}}$) to match the GF code combination $P^i_{p,\mathrm{GF}}$. According to [3], there remains a levelling error from 1 to 5 TECU in the GF ambiguity, due to code multipath delays but also to variations in differential satellite and receiver code hardware delays. As a consequence, the precision of the TEC is limited ([2],[3],[17]).

With triple frequency GNSS - modernized GPS and Galileo - new linear combinations of undifferenced measurements will be available and more particularly geometric and ionospheric free (GF+IF) combinations. This

will open opportunities for new applications, in particular multipath analysis and multi-frequency ambiguity resolution algorithms ([10]).
The objective of this research is to develop and validate a new triple frequency TEC monitoring technique. In this context, new linear combinations help improving the ambiguity resolution process.

We will first explain the procedure applied to monitor the TEC with triple frequency GNSS code and phase measurements (see section 2), and then the results obtained with a set of Giove-A data (L1-E5b-E5a) will be presented (see section 3). For more readability in the equations, the E5b channel will be named L2 and the E5a channel L5.

2. METHODOLOGY

2.1. Widelane ambiguity resolution

By definition, a widelane combination has a wavelength greater than that of GPS L5 frequency or Galileo E5a frequency. As it is well known that increasing the wavelength of a combination makes the resolution of integer ambiguities easier, we can take the benefit of triple frequency undifferenced code and phase measurements to form the so-called **extra-widelane-narrowlane** (EWLNL) combination C_{25} (in cycles):

$$\begin{aligned} C_{25} &= \Phi^i_{p,\mathrm{L2}} - \Phi^i_{p,\mathrm{L5}} - \frac{f_{\mathrm{L2}} - f_{\mathrm{L5}}}{f_{\mathrm{L2}} + f_{\mathrm{L5}}} \\ &\quad \times \left(\frac{f_{\mathrm{L2}}}{c}\, P^i_{p,\mathrm{L2}} + \frac{f_{\mathrm{L5}}}{c}\, P^i_{p,\mathrm{L5}} \right) \\ &= N^i_{p,\mathrm{L5}} - N^i_{p,\mathrm{L2}} + \Delta C_{25} \\ &= N_{25} + \Delta C_{25} \end{aligned} \tag{5}$$

In this combination, all the terms cancel out, except the extra-widelane (EWL) ambiguity N_{25} and a residual term ΔC_{25} which contains - for both code and phase measurements - satellite and receiver hardware delays, multipath delays and measurement noise. So Eq. (5) is a dual frequency GF+IF combination of code and phase measurements.

The benefit of C_{25} is its significantly increased wavelength, $\lambda_{25} = c/(f_{\mathrm{L2}} - f_{\mathrm{L5}})$, which equals 9.768 m for Galileo. We can see from Eq. (5) that it is critical that ΔC_{25} be less than half a extra-widelane wavelength (0.5 cycle or 4.884 m) to resolve the EWL ambiguities. This is a rather large margin error.
However, as drawback, the noise and multipath of the combination is increased. By considering measurement noise and multipath delays together as quasi random errors ([2]), and using the values of standard deviation (SD) given in tab. 2 ([9],[11],[12]), the law of error propagation gives us a SD on C_{25} equals to 0.017 cycles. To make a complete analysis, we also have to consider the influence of satellite and receiver **hardware delays** on C_{25}. First, we can make the assumption that satellite and receiver code and phase hardware delays are constant in time ([2]). Secondly, because of the lack of information about those delays, we have to make some other assumptions. If we consider that they follow a normal distribution, with μ=0 and 99 % of values below 2 m ad 1 mm respectively for code and phase delays- both satellite and receiver -, we find a SD on C_{25} equal to 0.084 cycle. By addition of all errors, we obtain a SD of 0.120 cycle. As a consequence, by taking all the assumptions into account, the error on C_{25} (i.e. ΔC_{25}) will not be greater than approximatively 0.31 cycle with a 99 % level of confidence. In conclusion, C_{25} combination allow to resolve EWL ambiguities.

	Signal	noise SD (m)	multipath SD (m)
Code	L1	0.18	0.4
	E5b	0.11	0.2
	E5a	0.11	0.2
Phase	L1	0.0019	0.003
	E5b	0.0024	0.003
	E5a	0.0025	0.003

Table 2. Standard deviation of code/phase measurement noise and multipath delays for Galileo observables ([9],[11],[12]).

In a second step, we can form the **differenced widelane** (DWL) combination (see [13]), which can be written as follows (in cycles):

$$\begin{aligned} C_{125} &= \left(\Phi^i_{p,\mathrm{L1}} - \Phi^i_{p,\mathrm{L2}}\right) \\ &\quad - \left(\Phi^i_{p,\mathrm{L2}} - \Phi^i_{p,\mathrm{L5}} - N_{25}\right) \frac{\lambda_{25}}{\lambda_{12}} \\ &= N^i_{p,\mathrm{L2}} - N^i_{p,\mathrm{L1}} + \Delta C_{125} \\ &= N_{12} + \Delta C_{125} \end{aligned} \tag{6}$$

In this combination, all the terms cancel out, except the widelane (WL) ambiguities N_{12} and a residual term ΔC_{125} which can be divided in two parts. The first one depends on all phase delays, the second one is an ionospheric term which approximately equals 0.5 $I^i_{p,\mathrm{L1}}$ - ionospheric delay on L1 - or 0.08 TEC. As a consequence, as already seen in [13], ΔC_{125} can clearly exceed 0.5 cycle. In conclusion, C_{125} combination does not allow to resolve WL ambiguities, but it gives us the opportunity to reduce the ambiguity search space (see section 2.2).

2.2. Ambiguity search space and fixing

The availability of triple frequency measurements allows to reduce the ambiguity search space by limiting the number of **ambiguity candidates**, and therefore to limit the complexity of the search process. Let us explain how. Firstly, we have resolved the EWL ambiguities N_{25} by using Eq. (5). Secondly, by using Eq. (6), we can significantly limit the number of N_{12} candidates. We can reasonably take 10 candidates around the value given by

Eq. (6). Thirdly, let us use a GF system (two $\Phi^i_{p,GF}$) as described in [13]. In this study based on simulated data, the influence of phase delays was underestimated ; here we found out that it finally does not lead to a precise monitoring of TEC values. However, it helps limiting the number of N_2 candidates. If we introduce the values of N_{25} and N_{12} candidates in the GF system, we obtain a rough estimation of N_2 values ; we will consider 100 candidates.
Finally, by computing all those information together, we can constitute all (N_1, N_2, N_5) sets of ambiguity candidates.

The next step is to apply a procedure to **resolve the ambiguities**. For that purpose, we will use triple frequency combinations of phase measurements.
First we can form the following combination ([10]) :

$$\begin{aligned} S_{125} &= \lambda_5^2\left(\lambda_1\Phi^i_{p,\mathrm{L1}} - \lambda_2\Phi^i_{p,\mathrm{L2}}\right) \\ &\quad +\lambda_2^2\left(\lambda_5\Phi^i_{p,\mathrm{L5}} - \lambda_1\Phi^i_{p,\mathrm{L1}}\right) \\ &\quad +\lambda_1^2\left(\lambda_2\Phi^i_{p,\mathrm{L2}} - \lambda_5\Phi^i_{p,\mathrm{L5}}\right) \end{aligned} \tag{7}$$

Eq. (7) is expressed in cube meters, but by dividing it by ($\lambda_2^2 - \lambda_1^2$) we can expressed in meters ([12]) :

$$s_{125} = a_1\lambda_1\Phi^i_{p,\mathrm{L1}} + a_2\lambda_2\Phi^i_{p,\mathrm{L2}} + a_5\lambda_5\Phi^i_{p,\mathrm{L5}} \tag{8}$$

Each a_i coefficient is unitless and depends on a combination of λ_i, with $a_1 \approxeq 0.128$, $a_2 \approxeq$ -1.128 and $a_5 = 1$. Eq. (7) and Eq. (8) actually combine all three dual frequency GF phase combinations. As we can show that ionospheric terms (first-order ones) cancel out, the result is a geometric-free and ionospheric free combination (GF+IF), in which remain the ambiguities and all phase delays - hardware, multipath, noise -, so that we can write (in meters):

$$\begin{aligned} s_{125} &= a_1\lambda_1\left(-N_1 + \Delta d_{\mathrm{L1}}\right) + a_2\lambda_2\left(-N_2 + \Delta d_{\mathrm{L2}}\right) \\ &\quad + a_5\lambda_5\left(-N_5 + \Delta d_{\mathrm{L5}}\right) \\ &= -a_1\lambda_1 N_1 - a_2\lambda_2 N_2 - a_5\lambda_5 N_5 + \Delta s_{125} \end{aligned} \tag{9}$$

with $\Delta d_{\mathrm{L}i}$ the sum of all phase delays on each frequency (in cycles) and Δs_{125} the combined term. As we have resolved N_{25} we can substitute N_5 by $N_2 + N_{25}$, so that Eq. (9) becomes :

$$s_{125} = -a_1\lambda_1 N_1 - (a_2\lambda_2 + a_5\lambda_5)N_2 - a_5\lambda_5 N_{25} + \Delta s_{125} \tag{10}$$

Moreover, we can form another GF+IF triple frequency phase combination :

$$\begin{aligned} t_{125} &= c_1\Phi^i_{p,\mathrm{L1}} + c_2\Phi^i_{p,\mathrm{L2}} + c_5\Phi^i_{p,\mathrm{L5}} \\ &= -\left(c_1 N_1 + c_2 N_2 + c_5 N_5\right) \\ &= -c_1 N_1 - (c_2 + c_5)N_2 - c_5 N_{25} \end{aligned} \tag{11}$$

We can show that it does not contain any residual term and that $-c_1 = c_2 + c_5$, so that Eq. (11) allows us to fix N_{12}, but not N_1 and N_2 separately. This helps to reduce once more the ambiguity search space : the number of (N_1, N_2, N_5) sets of candidates is divided by the number of N_{12} candidates.

The next step is to introduce the ambiguity candidates in Eq. (10) in order to resolve the ambiguities. For that purpose we search for the minimum of the averaged difference (on one continuous arc)between Eq. (8) and Eq. (10), which is only valid if $\left|\overline{\Delta s_{125})}\right|$ is smaller than $\frac{1}{2}\left|a_1\lambda_1 + a_2\lambda_2 + a_5\lambda_5\right|$. To study this condition, we can reasonably consider that measurement noise and multipath average on one period (μ=0), so that there remain only phase hardware delays in $\overline{\Delta s_{125}}$. By using SD of hardware delays, we can show that $\left|\overline{\Delta s_{125})}\right|$ could be greater that the limit mentioned here above. However, this leads to an error of maximum 2 cycles on each ambiguity (N_1, N_2, N_5) in the same way. In Eq. (3) this corresponds to an error of approximately 1 TECU on TEC values.

2.3. TEC computation

Once the ambiguities N_1, N_2, N_5 are resolved, we can introduce them in Eq. (4) to resolve $N^i_{p,GF}$ and then to compute TEC by using Eq. (3). 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.
We still have to consider the influence of all phase delays on TEC computed from Eq. (3). First, by having a look to a_{km} coefficients ($a_{12} = 0.600$, $a_{15} = 0.676$ and $a_{25} = 0.058$), we can see that a_{25} is one order of magnitude smaller than the two other ones. As phase delays have approximately the same amplitude on all frequencies (tab. 2), it means that TEC_{25} will be less precise ; by applying the same procedure than in section 2.1, SD of multipath and noise equals 0.01 TECU for TEC_{12}/TEC_{15} but 0.095 TECU for TEC_{25}. By adding the influence of hardware delays, we obtain a SD of respectively 0.017 and 0.165 TECU. Even with taking into account the error caused by the ambiguity resolution (see section 2.2), the precision of TEC is better than 1.5 TECU.

3. RESULTS

Tab. 3 gives the main characteristics of the Giove-A data set used in this research : four-character station name, location of the receivers and observation period. Those three stations are part of the Galileo Experimental Sensor Stations Network ([5]). Note that as Giove-A satellite can only transmit two frequency bands at a time (i.e. L1+E5 or L1+E6), we had to choose a L1+E5 period. The observables used in this work are the code measurements on E5b and E5a frequencies and the phase measurements on L1, E5b and E5a frequencies. More details can be found in [5].

Fig. 1 shows the EWLNL combination C_{25} in four cases of study. The observed variability is relatively low. We have computed SD of C_{25} - representing the variable part of it - of the whole data set, and they are actually in agreement with the value given in section 2.1 regarding noise

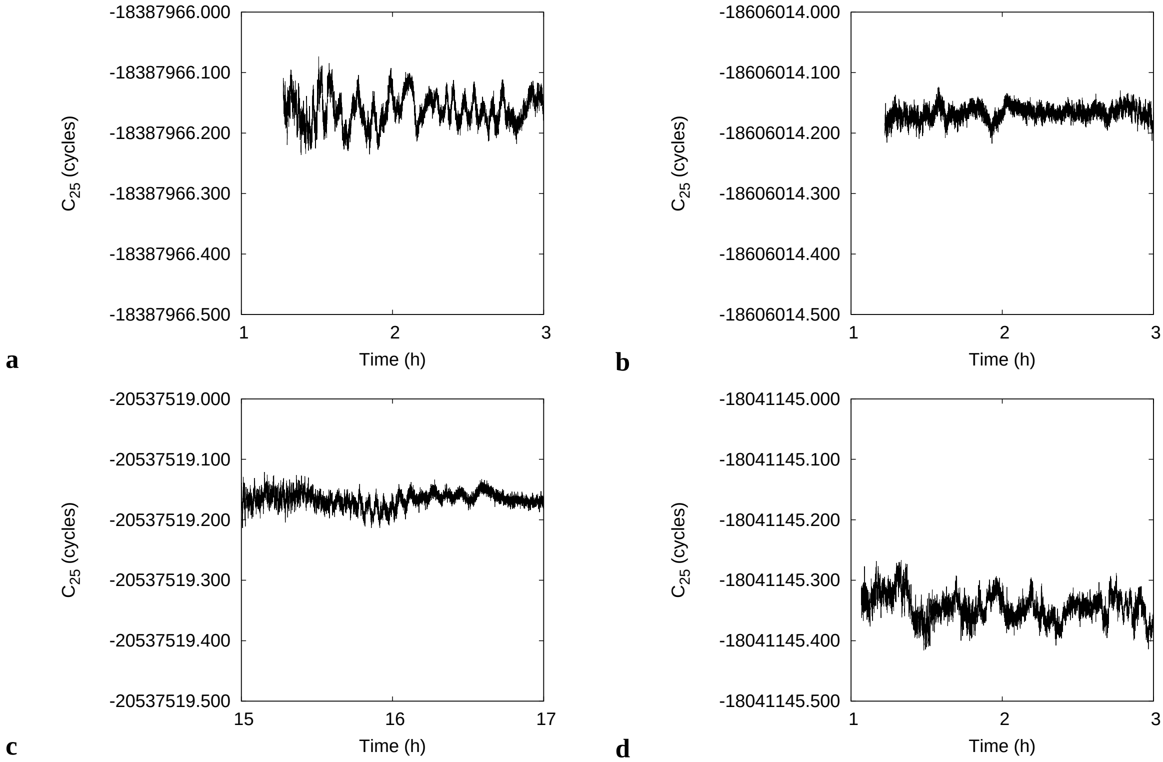

Figure 1. EWLNL combination (C_{25}) for GNOR 013/08 (a), GIEN 013/08 (b), GIEN 016/08 (c), GKOU 015/08 (d).

Station	Location	DoY 2008
GNOR	Noordwijk, Netherlands	013,016,017,019,020
GIEN	Torino, Italy	013,016,017,020
GKOU	Kourou, French Guyana	014,015,018

Table 3. Giove-A data set.

and multipath (i.e. 0.017 cycle). As far as hardware delays is concerned, we have made some assumptions about their amplitude (see section 2.1), but this can only be verified by the final validation of the method. Up to now, we can reasonably state that ΔC_{25} is smaller than 0.5 cycle and that the EWL ambiguities N_{25} are resolved.

Fig. 2 shows the DWL combination C_{125} on 13th January 2008 in Noordwijk. Even without taking a constant bias (hardware delays) into account, the variability is too large to resolve N_{12} and can be explained by time-varying residual terms (noise, multipath and ionosphere).

Fig. 3 represents s_{125} combination on 13th January 2008 in Noordwijk. We can clearly see the influence of phase multipath and measurement noise, with the same pattern than in Fig. 2. This combination could be used as phase multipath indicator ([12]). Here it is used on its mean basis (see section 2.2), which is supposed to be very closed to zero once the ambiguities are resolved.

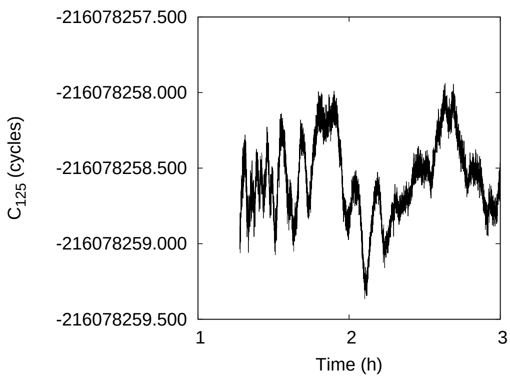

Figure 2. DWL combination (C_{125}) for GNOR 013/08.

We have computed TEC for the whole data set following the methodology described in section 2. All TEC values are in agreement (within maximum 3 TECU) with dual frequency TEC estimation based Global Ionospheric Map levelling ([1]).

Fig. 4 makes the comparison between TEC_{12} and TEC_{25} for the same period and receiver (GNOR 013/08). As predicted in section 2.3, TEC_{25} is much less precise than TEC_{12}. TEC_{15} has the same precision level as TEC_{12}, so

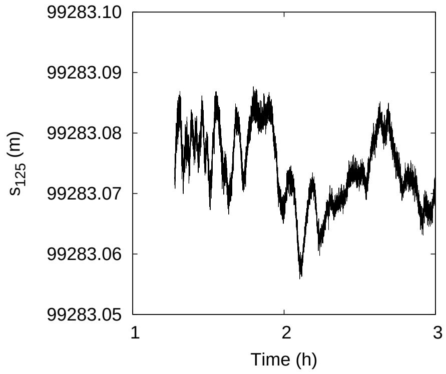

Figure 3. Triple frequency GF and IF phase combination (s_{125}) for GNOR 013/08.

that we could not have seen both on the same graph.

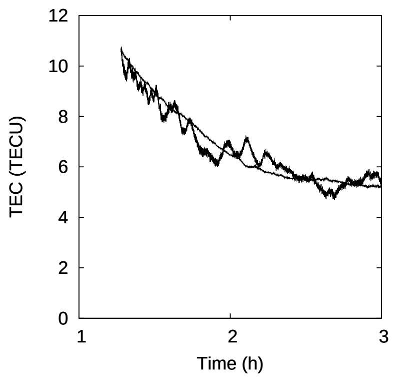

Figure 4. TEC values for GNOR 013/08 - TEC_{25} *is less precise than* TEC_{12}.

4. CONCLUSIONS

This paper has introduced a triple frequency TEC monitoring technique which uses new linear Geometric Free and Ionospheric Free combinations improving the ambiguity resolution process. First, thanks to its increased wavelength, the dual frequency EWLNL combination of code and phase measurements allows us to resolve the EWL ambiguities N_{25}. Then by using two triple frequency GF+IF phase combinations together in an ambiguity search process, we solve the ambiguities N_1, N_2, N_5. Finally, we can monitor the TEC with dual frequency GF phase combination.

This technique has been validated on a set of Giove-A triple frequency code and phase measurements. The results show that the EWL ambiguities are correctly resolved. Nevertheless, due to the influence of phase hardware delays, an error in the resolution N_1, N_2, N_5 could happen. Together with the influence of all phase delays on the GF phase combination, precision of TEC is still better than 1.5 TECU, which is an improvement in regards with the dual frequency technique ([2],[3],[17]). Further validation of the method is ongoing.

ACKNOWLEDGMENTS

The section containing acknowledgments should use the `\section*` form, as shown, to prevent it from being numbered.

REFERENCES

[1] Bidaine, B., Warnant, R., 2009. Measuring Total Electron Content with GNSS: Investigation of Two Different Techniques. Paper presented at IRST 2009, edimbourd, United Kingdom.

[2] Brunini, C., Azpilicueta, F., 2009. Accuracy assessment of the GPS-based slant total electron content. Journal of Geodesy 83(8), 773-785.

[3] Ciraolo, L., Azpilicueta, F., Brunini, C., Meza, A., Radicella, S.M., 2007. Calibration errors on experimental slant total electron content (TEC) determined with GPS. Journal of Geodesy 81(2), 111-120.

[4] Giove-A Signal-in Space Interface Control Document SIS-ICD, First issue. Mars 2, 2007. Galileo Project office.

[5] Galileo Open Service Signal In Space Interface Control Document OS SIS ICD, Draft 1. February, 2008. European Space Agency / European GNSS Supervisory Authority.

[6] Hofmann-Wellenhof, B., Lichtenegger, H., Collins, J., 1997. GPS: Theory and Practice. Springer-Verlag. 370 p.

[7] Interface Control Document ICD-GPS-200, Revision C, IRN-200C-004. April 12, 2000. ARINC, Incorporated, El Segundo, CA.

[8] Leick, A., 2004. GPS Satellite Surveying. John Wiley & Sons. 435 p.

[9] Simsky, A., Sleewaegen, J.-M., De Wilde, W., Wilms, F., 2005. Galileo Receiver Development at Septentrio. Paper presented at the European Navigation Conference (ENC-GNSS), Munich, Germany.

[10] Simsky, A., 2006. Three's the Charm - Triple Frequency Combinations in Future GNSS. Inside GNSS 1(5), 38-41.

[11] Simsky, A., Sleewagen, J.-M., 2006. Performance Assessment of Galileo Ranging Signals Transmitted by GSTB-V2 Satellites. Paper presented at ION GNSS, Forth Worth, United States.

[12] Simsky, A., Mertens, D., Sleewagen, J.-M., Hollreiser, M., Crisci, M., 2008. Experimental Results for

the Multipath Performance of Galileo Signals Transmitted by GIOVE-A Satellite. International Journal of Navigation and Observation, vol. 2008, Article ID 416380, 13 pages, 2008. doi:10.1155/2008/416380

[13] Spits, J., Warnant, R., 2008. Total electron content monitoring using triple frequency GNSS data: A three-step approach. Journal of Atmospheric and Solar-Terrestrial Physics 70, 1885-1893.

[14] Teunissen, P., Joosten, P., Tiberius, C., 2002. A comparison of TCAR, CIR and LAMBDA GNSS Ambiguity resolution. Paper presented at ION GPS, Portland, United States.

[15] Tiberius, C., van der Marel, H., Sleewagen, J.-M., Boon, F., 2008. Galileo Down to the Millimeter - Analyzing a GIOVE-A/B Double Difference. Inside GNSS 3(6), 40-44.

[16] Urquhart, L., 2008. An analysis of multi-frequency carrier phase linear combinations for GNSS. Paper presented at 37th COSPAR Scientific Assembly, Montreal, Canada.

[17] Warnant, R., Pottiaux, E., 2000. The increase of the ionospheric activity as measured by GPS. Earth Planets Space 52, 1055-1060.

[18] Wilson, B.D., Mannucci, A.J., 1993. Instrumental Biases in Ionospheric Measurements Derived from GPS Data. Paper presented at ION GPS, Salt Lake City, UT, United States.