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IONOSPHERIC SCINTILLATIONS COMPUTATION USING REAL-TIME GPS OBSERVATIONS

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ABSTRACT. The following paper presents the results of quasi-real-time determination of the values of phase scintillations indices at the period of ionospheric disturbances that occurred as a consequence of the Sun flares observed on March 7 and 9, 2012. Double-frequency observations with 1-second measurement interval from the EPN (*EUREF Permanent Network)* network sites located at high latitudes were used for the analysis. To determine the phase scintillations it is necessary to apply data filtering in order to separate the trend of low frequencies (e.g. satellite motion) from high frequency oscillations (e.g. scintillations). Elimination of low frequency components of the signal using moving average was proposed in the research. This approach was conditioned by the necessity to apply an optimum method of filtering for quasi-real-time calculations. The scintillation parameters were calculated by means of three different algorithms and the results were compared. Additionally, relations between changes of the parameters and the ROTI index, describing the temporal changes of TEC, and the decrease of positioning accuracy at the analyzed sites were searched.

Keywords: GPS Scintillations, Quasi-real-time computations, Phase scintillation index, Magnetic storm

1. INTRODUCTION

Ionosphere is a dispersive environment starting at 60-100 km above the Earth's surface, depending on the location. The value of the delay of an electromagnetic wave transmission through it depends on the concentration of free electrons occurring as a result of atmospheric gasses ionizing due to space radiation and on the wave's frequency (*Ondoh and Marubashi*, 2000). The GPS system uses three basic frequencies: L1, L2 and L5. Due to the fact that comparing the ionospheric delay measured at different frequencies enables to obtain information concerning the ionized layer of the atmosphere, the GPS observations constitute commonly available and reliable source of data about parameters of the medium and its changes (*Mitch and Psiaki*, 2010). During high activity of the Sun, the increased flux of radiation reaching the Earth affects the anomalous increase of the free electrons density in the ionosphere. This phenomenon is called ionospheric disturbance. The accuracy of autonomous GPS positioning may decrease by even a few dozen meters at the time of the disturbance (*Ondoh and Marubashi*, 2000).

Irregularities of electrons density distribution, along with the change of the GPS signal propagation velocity in the ionosphere, may cause its refraction and diffraction. Refraction causes changes of the direction and velocity of the electromagnetic wave leaving its front unchanged. Diffraction results in irregular changes of the wave front without changes of its velocity. Moreover, due to signal scattering on intensive small-scale ionospheric irregularities, strong scintillations of amplitude and phase of radio signals may occur. Both phenomena are significantly correlated in time and amplitude, especially when their values are low (*Basu* et al., 1999). This phenomenon is observed as short time decrease of the signal strength which may influence the accuracy of GPS receivers positioning. In case of large irregularities, the attenuation of the electromagnetic wave in the ionosphere may be so intensive that the communication with the satellite may be broken and the measurement re-initialization may be necessary (*Datta-Barua et al.*, 2003).

The most frequently applied method of data pre-processing for scintillation parameters determination is removing low-frequency components of the signal by means of the Butterworth high-pass filter (*Forte*, 2005) with the cut-off frequencies at 0.1 or 0.3 Hz. Mushini et al. (2012) proposed to detrend data by means of wavelet filtration. In this process, in comparison with the case of applying filters unalterable in time, the signal non-stationarity is not ignored because using the wavelet transform provides the signal's temporal and frequency representation without loss of information about local features. In the above mentioned paper, the Morlet wavelet was proposed to be used as the mother wavelet because it yields the highest temporal and frequency resolution in comparison with other wavelets.

2. RESEARCH DATA

In order to ensure selection of reliable research data it was necessary to select a period of an ionospheric storm and a measurement site within an area influenced by disturbances caused by the ionized layer of the Earth's atmosphere. The periods of the ionospheric disturbances were determined using data made available by NOAA (http://www.swpc.noaa.gov): Kp index and changes of the recorded X-ray radiation. The Kp planetary magnetic index (German: planetarische Kennziffer) is determined in the NOAA Space Weather Forecasting Center in a 9-degrees scale using a weighted mean of local K index values determined from measurements conducted by means of magnetometers in 13 research centers located all over the world. The K index is a measure of irregular variations of the Cartesian components of the geomagnetic field (X,Y,Z), defined by the range R between the largest and the smallest of the three components measured in gammas (nanoTeslas) (*Komjathy*, 1997). The Kp index values greater than 4 (Kp >4) indicate geomagnetic storms.

A representative period of March 8 through 10, 2012, in which ionospheric disturbances were observed, was selected using the Kp index and X-ray radiation changes analysis results (Fig. 1).

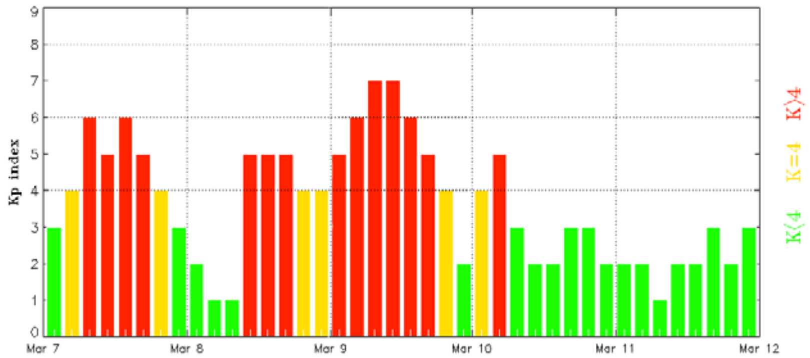

Fig. 1. Kp index values for the selected period in March 2012 (http://www.swpc.noaa.gov)

The equatorial (along the magnetic equator) and high-latitude regions are the most seriously exposed to ionospheric scintillations (*Carrano and Groves*, 2007). Measurements from the permanent EPN network sites were used because of their availability. In the selected period of ionospheric disturbances five measurement sites from the polar area were selected (Höfn, Kiruna, Reykjavik, Trondheim, Vardoe). The double frequency data (L1 and L2) from the sites were received by means of the EUREF-IP real-time service with the highest available sampling frequency of 1 Hz. Then the data completeness and the quality of the EPN sites observations were analyzed. Fig. 2 shows the analysis of the multipath error for the selected sites (*Bruyninx C. et al.,* 2012). Observations from GPS measurements conducted at the L1 frequency are used for computations for research of scintillations. In the presented analyses, the lowest value of the multipath error for the L1 signal was observed for the Trondheim (TRDS) site. Additionally, only few data were missing for the TRDS site which indicated that the observation data from this site were the best for the research.

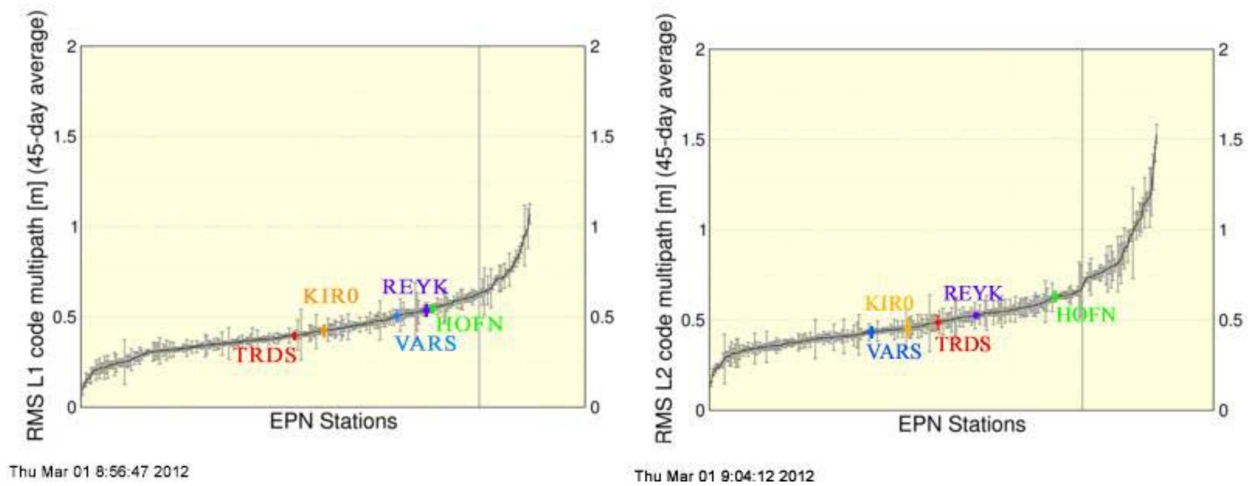

Fig. 2. Multipath error analysis for the L1 and L2 frequencies for the observations from the selected EPN sites on March 01, 2012. (http://www.epncb.oma.be)

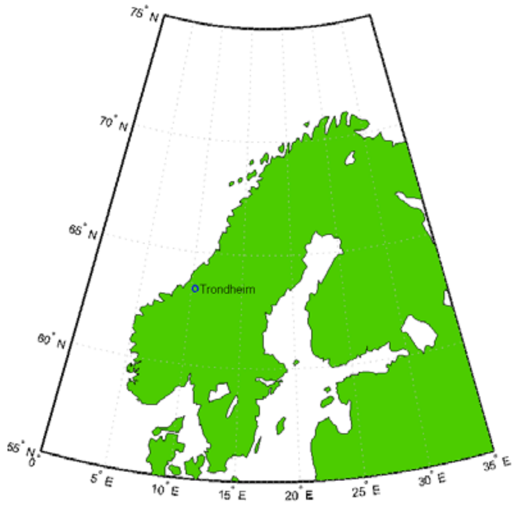

Fig. 3. The Trondheim (TRDS) site location

3. THE PHASE SCINTILLATION INDICES COMPUTATION

In the GPS system, the most frequently discussed effects of the signal transmission through the ionosphere are acceleration of the carrier phase and code delay. Other observed phenomena include sudden irregular changes of the signal phase and amplitude, called phase and amplitude scintillations, respectively (*Carrano and Groves*, 2007). They are caused by little areas of irregular density of the plasma in the upper ionosphere. The receivers receive the signal with large random fluctuations as an effect of the scintillations (*Datta-Barua et al*., 2003).

3.1. ELIMINATION OF LOW-FREQUENCY COMPONENTS OF THE SIGNAL

Data detrending is the first step of the procedure of computing the high-frequency signal scintillations. At this phase, the filtering method selection is of crucial importance for the final result of the analysis. Forte (2007) proves that application of a high-pass filter for a fixed value, e.g. 0.1 Hz, may lead to overestimating the phase scintillations value for high latitudes. Mushini et. al (2012) propose an alternative method of data detrending. Wavelet filtration with the Morlet wavelet is applied in his method. This solution enables to minimize the error related with the signal cut-off at a fixed frequency value and to reduce noise in the high-frequency signal. The disadvantage of this method is that it is designed to decompose data in the post-processing mode of operation. Therefore, it could not be used in our research. High-pass Butterworth (8^{th} order; cut-off frequency 0.193Hz (Mushini et.al, 2012)) and moving average filters (5 epochs window) were used for the analyses. The computations were made using Matlab® environment.

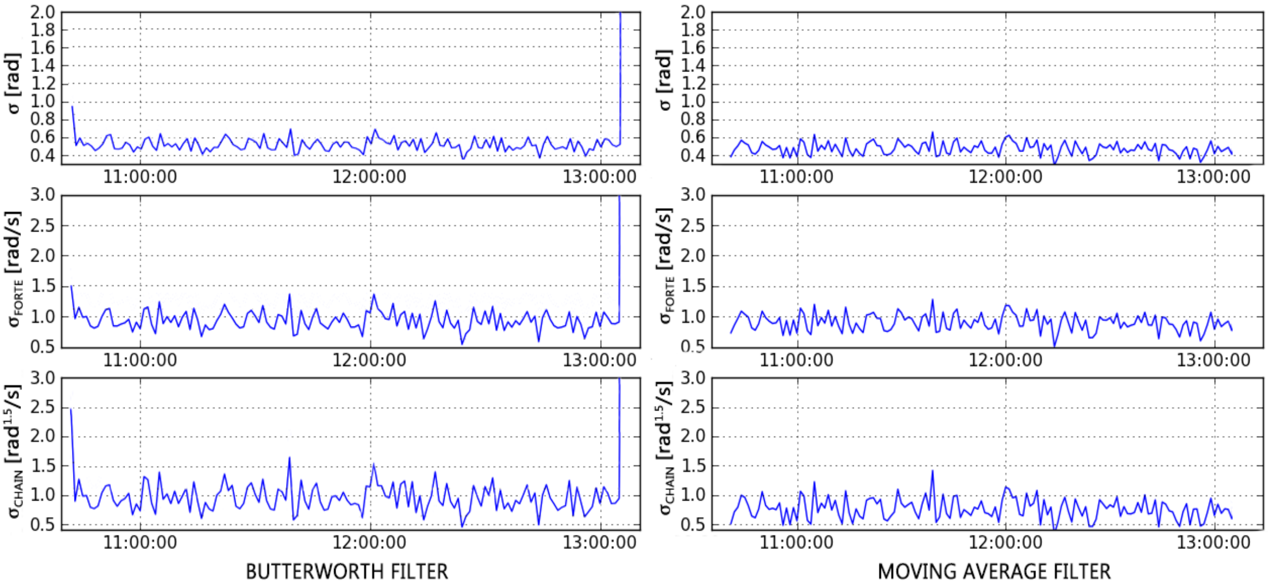

Fig. 4. Phase scintillations computed after the high-pass Butterworth and moving average filtration for the SV=12 satellite on March 07, 2012

The numeric analyses for the high-pass Butterworth and the moving average filters were done for all the observed satellites. It was proved that for quasi-real-time studies the moving average is a better method of data detrending because the edge effect is minimized, otherwise than in the case of the high-pass Butterworth filter application (Fig. 4.). The diagrams were prepared for computations conducted in post-processing, therefore the edge effect for the high-pass Butterworth filter was observed only in the beginning and in the end of the observation time interval for a specific satellite. In case of applying this filter for real-time studies the effect observed for each computational epoch will result in a loss of a great number of data.

3.2. PHASE SCINTILLATIONS INDICES

In the research the computations of the S_4 parameter defining the amplitude scintillations were neglected because the signal power values provided in the observation files were determined with too low accuracy. A correct determination of the parameter requires signal power values to be provided with accuracy of at least 0.01 dBW while in the observation files they were given as integers. Therefore, we limited our computations to determining the phase scintillations index.

Parameters properly representing the phase scintillations of the GPS signal may be different for different latitudes (*Forte*, 2005; *Mushini et al.,* 2012). For this reason, in this research the phase scintillations were determined with 60-second interval according to three different indices:

- σ_ϕ classical index (*Forte*, 2005):

$$\sigma_\phi = \sqrt{\langle \phi^2 \rangle - \langle \phi \rangle^2} \qquad \text{[rad]} \qquad (1)$$

- σ_{FORTE} FORTE index proposed by Forte (2005). In comparison with the classical index it is more proper for assessing the values of scintillations at high latitudes:

$$\sigma_{FORTE} = \sqrt{\left\langle \left(\frac{\Delta \phi}{\Delta_t} \right)^2 \right\rangle} \qquad \text{[rad/s]} \qquad (2)$$

- σ_{CHAIN} CHAIN index (*Mushini* et al., 2012), a modification of the σ_{FORTE} index also adopted for measurements at high latitudes. It describes scintillations with respect to temporal phase changes and with respect to the values of the oscillations:

$$\sigma_{CHAIN} = \sqrt{\left\langle \left(\frac{\Delta \phi}{\Delta_t} \right)^2 |\phi| \right\rangle} \qquad \text{[rad}^{1.5}\text{/s]} \qquad (3)$$

where:

- average value for the selected interval of scintillations determining
- L1 signal phase after removing the low-frequency components
- phase average value after removing the low-frequency components

In this article 1Hz observational data were used with averaging for 1 minute intervals.

The classical index of phase scintillations (1) is overstated for measurements at high latitudes due to combining the real values of phase scintillations with oscillations of the TEC values. Furthermore, it shows great dependence on the selected method of the signal's low-frequency components elimination (*Forte*, 2005; *Mushini et al*., 2012).

4. RESULTS AND DISCUSSION

The computed specific indices of scintillations are presented in a graphical form in Fig. 5. Occurrence of phase scintillations was assumed for values extending triple standard deviation σ. It was noticed that with that assumption the σ_{CHAIN} parameter course highlights significant phase fluctuations of the received signal in a better way than the remaining indices. Red ellipses in Fig. 5 indicate phase scintillations observed at about 21:30 and 22:50 UTC.

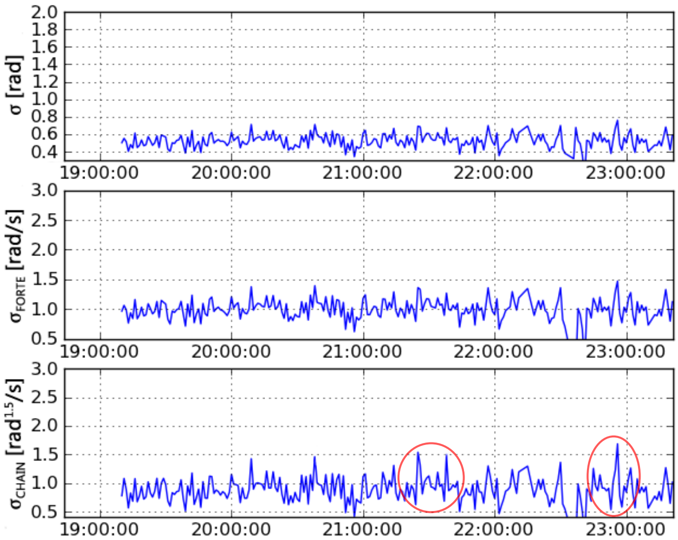

Fig. 5. Phase scintillations indices for the SV14 on March 08, 2012

Phase scintillations occurrence is also related with significant changes of the signal to noise ratio *S/N* (*Forte*, 2005). It may be noticed that the observed oscillations of the signal to noise ratio at L1 frequency (Fig. 6.) occur at the same time as the phase scintillations determined according to the σ_{CHAIN} index (Fig. 5.). Hence, it proves correctness of the applied research method.

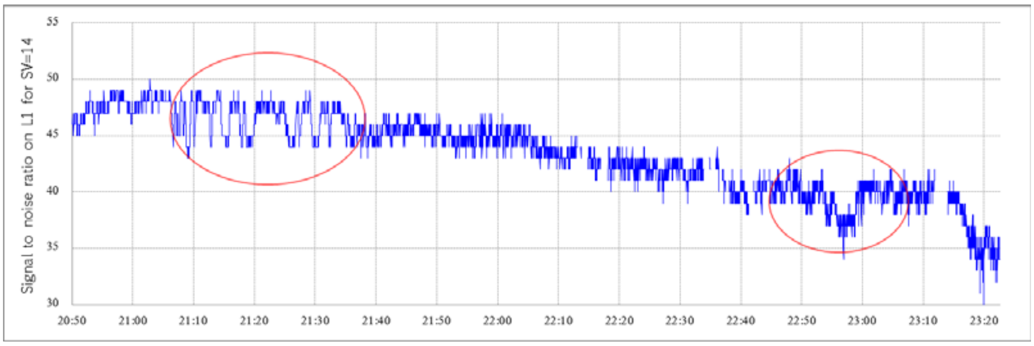

Fig. 6. The signal to noise for the SV14 on March 08, 2012

The obtained results of scintillations indices were compared with the changes of free electrons density in the ionosphere. For this purpose, the TEC values were determined by means of the L_4 linear combination for each of the observed satellites (*Mayer et al.,* 2008). The ROTI parameter, being the standard deviation of the TEC changes within the = 60s interval (*Carrano and Groves*, 2007), was then determined:

$$ROTI = \left(\left\langle \left(\Delta TEC / \Delta t \right)^{2} \right\rangle - \left\langle \Delta TEC / \Delta t \right\rangle^{2} \right)^{0.5} \quad \text{(TECU/s)} \qquad (4)$$

The ROTI values determined for all the satellites on March 08, 2012 are presented in Fig. 7. The increased values of the index, marked in blue, are related with ionospheric disturbances. However, they are observed mainly for satellites at low elevation angles, which may also indicate errors related with reflections and and more influenced delays due to extended transmission through ionosphere and troposphere. In addition, in Figure 7, large gaps in the observational data may be seen. It was noticed that this phenomenon corresponds with the increased value of ROTI. Similar effect was also highlighted by Datta-Barua in 2003 (*Datta-Barua et al.*, 2003).

For the investigated data any relationship between the increase of the scintillations parameters values and the increase of the ROTI values was observed.

Fig. 7. ROTI values for the specific satellites on March 08, 2012

Additionally, the site position was computed by means of the Single Point Positioning (SPP) method in order to check the relationship between the change of the determined parameters (temporal change of the density of free electrons and the value of signal phase fluctuations) and the decrease of accuracy of autonomous positioning. The differences between the determined coordinates and the precisely defined location of the TRDS reference station obtained from the EPN data were transformed into the NEU topocentric system (*North East Up*). Precise ephemerides with the assumed minimum elevation angle of h=15°, the Saastamoinen tropospheric model and the Klobuchar ionospheric model were used for computations. The applied algorithm of the solution (Fig. 8) enabled to minimize the errors other than the ionospheric delay. Due to this, during disturbed ionospheric conditions it was possible to highlight invalidity of daily parameters of the Klobuchar model transmitted in the navigational message (*Klobuchar*, 1987).

However, for the analyzed data no unambiguous relationship between the changes of the phase scintillations parameters and ROTI, and the decrease of accuracy for the SPP navigational solution was observed. The observed jumps of coordinates are not a result of ionospheric influence but just of changes of the observed satellites constellation (Fig. 9). It was observed that the RMS error value of the computed position and standard deviation of the measurement results with respect to the arithmetic mean (defining the accuracy of positioning) determined for the period of high activity were not increased in comparison with the ones determined for the period of calm ionosphere (Table 1; Fig.10).

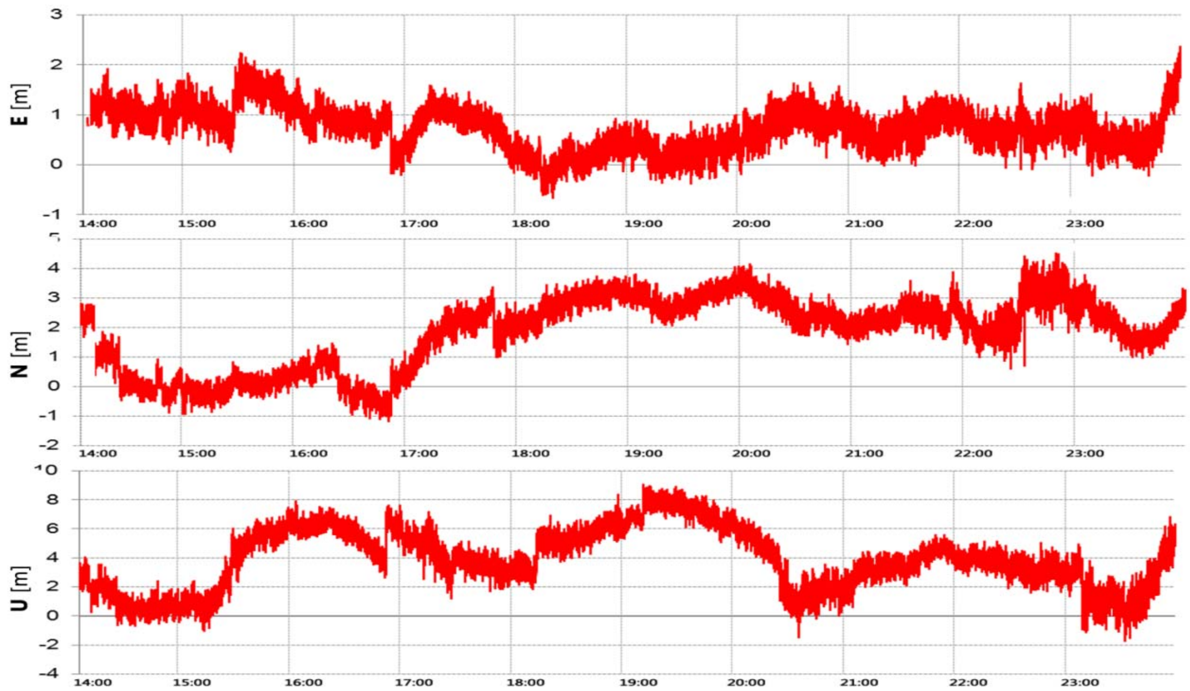

Fig. 8. The computed temporal changes of the ENU coordinates on March 08, 2012

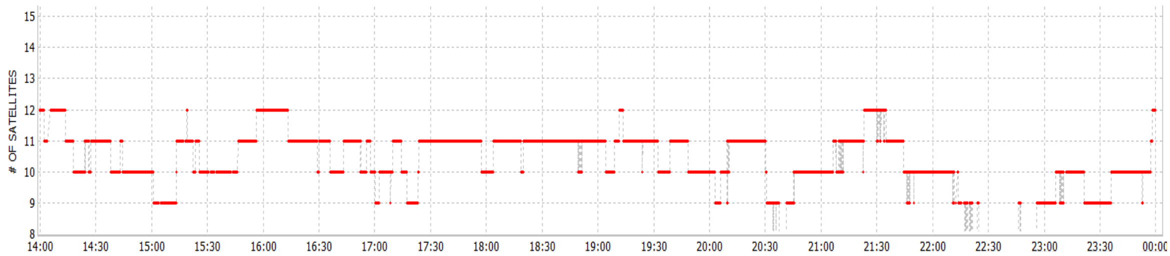

Fig. 9. Temporal changes of the number of satellites on January 29, 2012

Table 1. Standard deviation values*

	Standard deviation [m]			
	29.01.12	*08.03.12*	*09.03.12*	*10.03.12*
N	1.24	1.10	0.87	0.60
E	0.87	1.17	1.19	0.73
U	1.95	1.93	2.31	1.85

Table 2. Mean error values*

	Mean error [m]			
	29.01.12	*08.03.12*	*09.03.12*	*10.03.12*
N	1.74	2.45	1.93	1.13
E	1.08	1.25	1.11	0.71
U	2.93	3.71	2.81	2.35

*Blue and yellow backgrounds indicate low and high ionospheric activity days, respectively

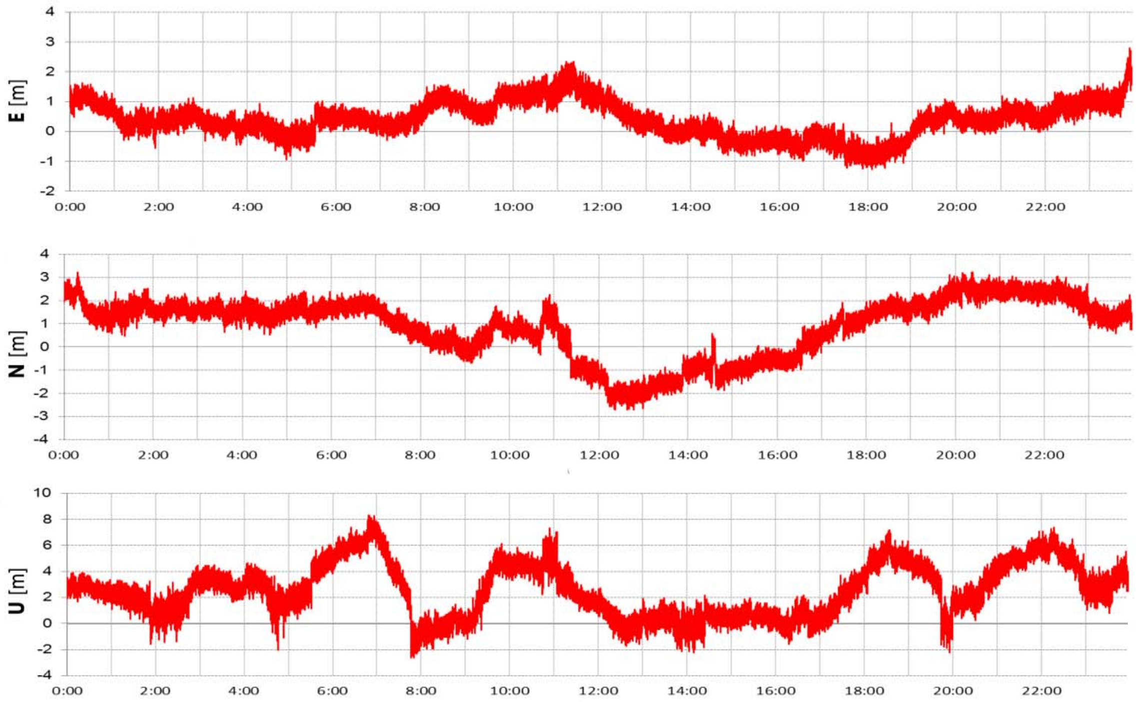

Fig. 10. The computed temporal changes of the ENU coordinates on January 29, 2012

5. CONCLUSIONS

In conclusion, the moving average filter used as the detrending method provides correct results of phase scintillations indices computed in the real-time. Additionally, its application enables to minimize the edge effect in comparison with the high-pass Butterworth filter.

The analysis of observations for the Trondheim site shows that the σ_{CHAIN} parameter values course highlights significant phase fluctuations of the received signal in a better way in comparison with the σ_{ϕ} classical index and the σ_{FORTE} index. For the analyzed data no relationship between the changes of the scintillations indices values and the ROTI index values, and the decrease of positioning accuracy in the Single Point Positioning solution was observed. However, in the period of scintillations and increased values of ROTI, more frequent cases of signal loss were observed

Observations conducted with 1 Hz frequency were used for the research because of the data availability. Phase scintillations' feature is fast changing; therefore using such measurements may be related with partial loss of information. Hence, higher frequency of measurements sampling is recommended for investigating the scintillations and for analyzing their correlation with the ROTI index and with changes of positioning accuracy by means of the SPP method.

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