

*Full Length Research Paper*

# **Test of velocity-displacement estimation using variometric method under the condition of ionospheric scintillation during equinoctial months of solar maximum period 2012**

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The Global Navigation Satellite System (GNSS) technologies have made significant contribution to seismology studies. Some processing strategies are well known, like real time PPP and DGPS techniques. These two methods have been widely used for GNSS based seismic activities monitoring. The first method requires accurate models of GNSS measurement errors to achieve accuracy in centimeter (cm) and need convergence time in order of minutes to hours. The second method need relative short distance of reference stations to reduce significantly measurement errors. To overcome disadvantages of such two methods, the variometric method was used to attain accuracy, but the method needs to be tested in the high ionospheric disturbance of equatorial region. During occurrences of plasma bubble, the radio signals from satellite passing through the ionosphere sometimes show rapid amplitude and phase variations called ionospheric scintillation. The occurrences of ionospheric scintillation could degrade the performance of systems and generate errors in received messages. In this study, variometric measurements are performed during the equinoctial month (March 2012) when the occurrence of scintillation was more intense. Results showed degradation of measurement accuracy during strong scintillation occurrences. The errors reached more than 1 m/s, especially for up-down measurement.

**Key words:** Equinox, GISTM, ionospheric scintillation, variometric.

## **INTRODUCTION**

The ionosphere is a part of upper atmosphere which consists of plasma ions and electrons. The solar and geomagnetic activities can change particles composition in the upper atmosphere, producing corresponding changes in the ions and electrons of ionosphere region

which then often develop density irregularities. Some irregularities are known as plasma depletion or plasma bubbles. These plasma bubble irregularities affect radio waves propagation signal from satellites in the frequency range of 100 MHz - 4 GHz (Aarons, 1993). During

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occurrences of plasma bubble, the radio signals from satellite passing through the ionosphere sometimes show rapid amplitude and phase variations which are called ionospheric scintillation. The Global Navigation Satellite System (GNSS) is one of the systems affected by the occurrences of ionospheric scintillation because it can degrade the performance of systems and generate errors in received messages. Ionospheric scintillations may cause degradation of position determination by GNSS receivers (Carrano and Groves, 2010; Seo et al., 2011; Akala et al., 2012), data loss and cycle slips (Jiao et al., 2014, 2016). Severe phase fluctuation may stress phase-locked loops in GPS receivers and give rise to loss of phase lock (Liu et al., 2017). The most significant manifestation of ionospheric scintillation often takes place in equatorial region approximately 15°N and S of magnetic equator (Ray et al., 2006). It is well known that equatorial ionospheric scintillation is primarily controlled by the generation and growth of irregularities over the magnetic equator. It is found that the seasonal variation of scintillations in the Indonesian sector shows two peak occurrences during the equinox months, March-April and September-October (Abadi et al., 2014) and more intense during maximum solar activities.

GNSS technologies have contributed to seismology studies to demonstrate effectively in estimating co-seismic displacement waveform induced by an earthquake with accuracies ranging from millimeter to centimeter. Some processing strategies have been well known, for example, Precise Point Positioning (PPP) and differential positioning. The PPP method processing requires ancillary products (e.g. information regarding satellites orbits, clocks, etc) in real-time. Previously, PPP has problem on ambiguity resolution but many studies have been conducted for ambiguity-fixing (Ge et al., 2012; Li, 2012) and to achieve comparable accuracy with relative/network positioning (Li et al., 2013). On the other hand, differential kinematic positioning (RTK) is based on a complex infrastructure (GPS permanent network) and has been managed by research centers to obtain high accuracies in real-time. A new method has been proposed known as variometric processing (Colosimo et al., 2011) to recover the seismic waveforms from observations recorded by a single GNSS receiver. Some successful case studies using variometric approach include the Tohoku-oki earthquake (M9.0) in Japan

$$\Delta I_{r,j}^s(t_n, t_{n+1}) = -\mathbf{u}_r^s(t_{n+1}) \cdot x(t_{n+1}) + \mathbf{u}_r^s(t_n) \cdot x(t_n) + \Delta t_r(t_n, t_{n+1}) - \Delta o^s(t_n, t_{n+1}) - \Delta t^s(t_n, t_{n+1}) - \Delta I_{r,j}^s(t_n, t_{n+1}) + \Delta T_r^s(t_n, t_{n+1}) + \Delta \varepsilon_r^s(t_n, t_{n+1}) \quad (2)$$

where  $\Delta I_{r,j}^s(t_n, t_{n+1})$  is time single-difference phase observation  $I_{r,j}^s(t_{n+1}) - I_{r,j}^s(t_n)$ ,  $\mathbf{u}_r^s(t_n)$  and  $\mathbf{u}_r^s(t_{n+1})$  are the unit direction vectors from receiver to satellite at epoch  $t_n$  and  $t_{n+1}$ ;  $x(t_n)$  and  $x(t_{n+1})$  are the receiver position increments at epoch  $t_n$  and  $t_{n+1}$ .

The location of study is shown in Figure 2 and Table 1, as can be seen in the GISTM receiver for monitoring the ionospheric scintillation relatively close to the GNSS (IGS) single station. To process GPS observation data for measurement of velocity

(Benedetti et al., 2014), the Emilia earthquake (M6.0) in Italy (Benedetti et al., 2013), Wenchuan earthquake (M 8.0) in China (Li et al., 2014) and real-time detection of tsunami (Savastano et al., 2017). However, the method needs to be tested during high ionospheric disturbance at equatorial region.

In this paper, the measurement of velocity displacement estimation variometric method under condition of ionospheric scintillation is discussed using GISTM data during solar maximum Period 2012.

## DATA AND METHODS

Ionospheric scintillation data are retrieved from GISTM (GPS Ionospheric Scintillation and TEC Monitor) based GPS dual frequency L1 (1575.42 MHz) and L2 (1227.60 MHz) receiver, installed at Space Science Center LAPAN, an equatorial station Bandung (6.89 S, 107.59E) Indonesia. This receiver measures the intensity (amplitude, S4) scintillation index, phase ( $\sigma$ ) scintillation index and total electron content (TEC). In this study, we used the amplitude scintillation (S4) index to examine the ionospheric irregularities related to the occurrence of ionospheric scintillation that affected the accuracies of velocity displacement measurement. Figure 1 shows a GISTM type of GSV4004B Novatel receiver, antenna and PC data logger.

The intensity scintillation indices (S4) is a parameter typically used to determine the level of scintillation activity. The S4 index represents the normalized standard deviation of detrended signal intensity (P), and is typically computed over 60-s intervals as follow (Van Dierendonck et al., 1993).

$$S_{4T} = \sqrt{\frac{\langle P^2 \rangle - \langle P \rangle^2}{\langle P^2 \rangle^2}} \quad (1)$$

The  $S_{4T}$  in Equation 1 which denotes the total  $S_4$  has a significant amount of ambient noise, as well as signal intensity variations due to changing range and multipath. The noise has to be removed before further analysis. Gharoori and Skone (2015) explains how to remove this noise. Regarding the value of  $S_4$ , ionospheric scintillation is cataloged as: weak scintillation, ( $0.1 < S_4 < 0.3$ ); moderate scintillation ( $0.3 < S_4 < 0.5$ ) and strong scintillation ( $S_4 > 0.5$ ) (Li et al., 2007). For this paper, we consider  $0.25 < S_4 < 0.4$  as weak and  $S_4 > 0.5$  as a strong scintillation event.

The RINEX observation data from IGS station Cibirong (BAKO) (Crustal Dynamics Data Information System, CDDIS DAAC), 2014) was used to examine the velocity displacement in the post processing mode. A variometric method based on the time single difference of the carrier phase observations between two consecutive epochs ( $t_n, t_{n+1}$ ) on the assumption that the observation data is continuous is as follows (Colosimo et al., 2011):

displacement, we used an independent software packages goGPS (<http://www.gogps-project.org/>). The package is based on least square variometric in the post processing scheme.

## RESULTS AND DISCUSSION

Ionospheric scintillation data was used in this study

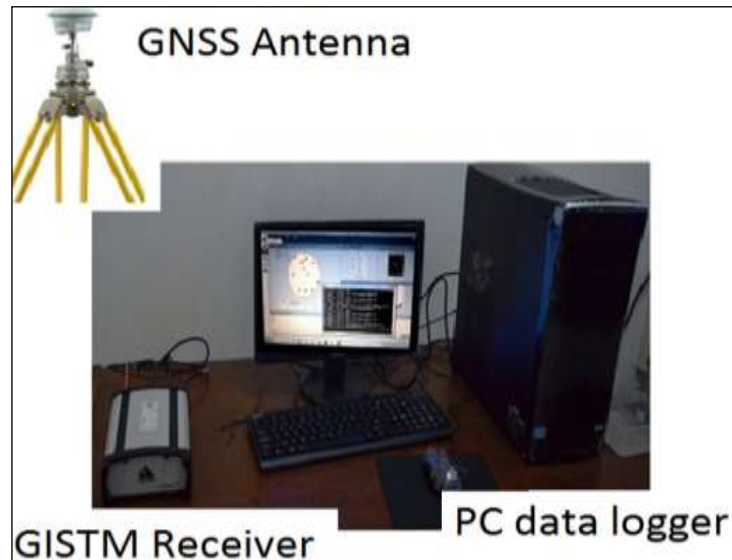


Figure 1. The GISTM system for monitoring ionospheric scintillation.

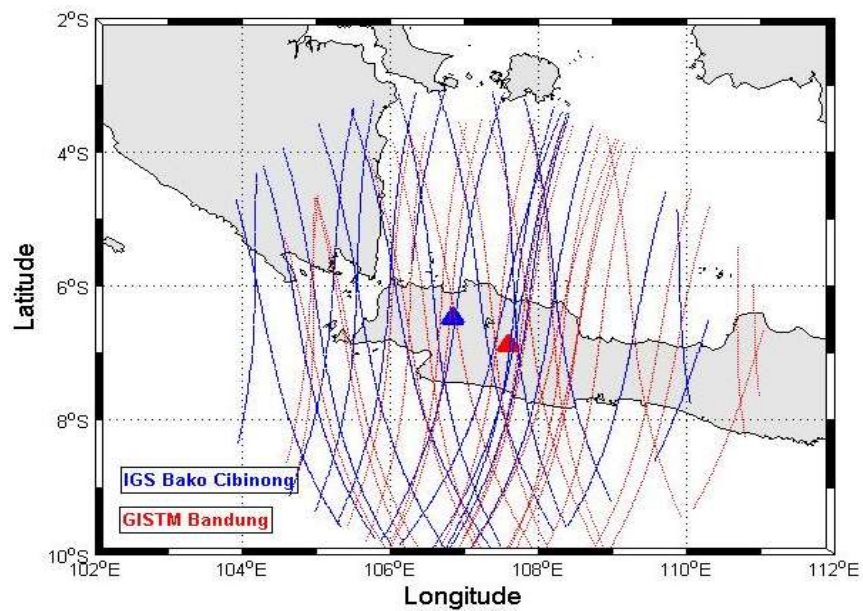


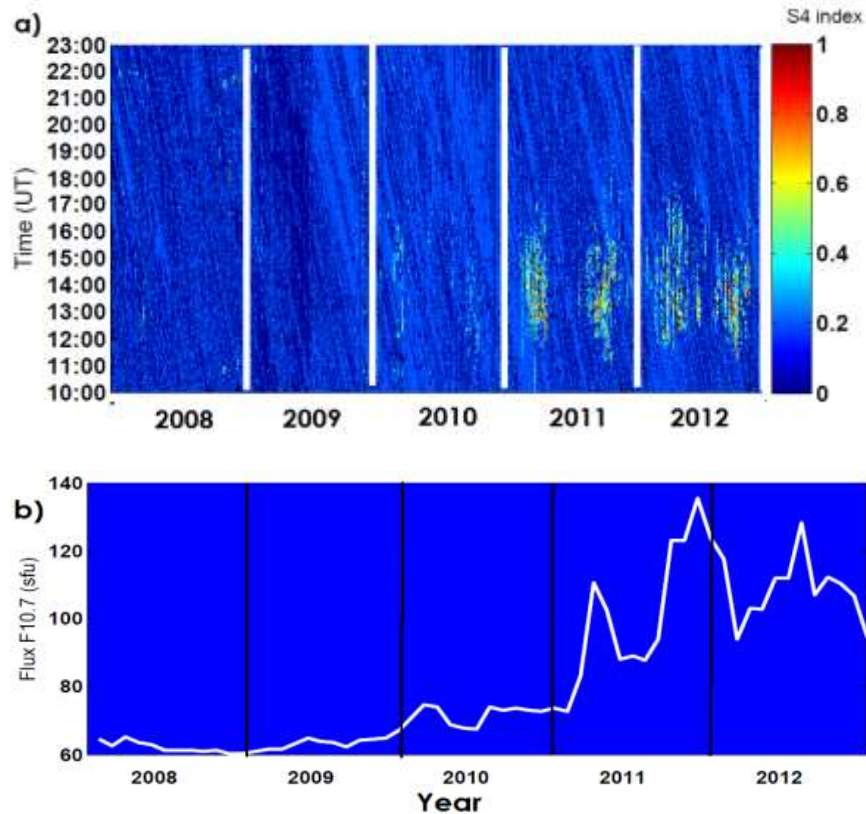
Figure 2..Location of receiver GISTM Bandung (red) and IGS stations BAKO Cibinong (blue). The line indicated the trajectory of satellites on ionospheric pierce point.

Table 1. Geographic location of GNSS receiver.

Stations name	Geographic latitude	Geographic longitude
GISTM, Bandung	-6.91	107.61
IGS, Bako Cibinong	-6.49	106.85

during the equinox March 2012. This month was chosen because of the most intense scintillation occurrences as

shown in Figure 3. Figure 3(a) represents the contour plot for the occurrence of amplitude scintillation for year 2008



**Figure 3.** The occurrences of ionospheric scintillation during minimum (2008) to maximum (2012) solar activity in Indonesia and solar activity indicated by F10.7.

to 2012. As shown in Figure 3(a), the occurrence of amplitude scintillation starts at 11:00 UT (18:00 local time) and faded at about 19:00 UT (02:00 post mid-night, local time). During the maximum solar activity, there are two maximum scintillation of most occurrences on equinoctial month (March-April and September-October). The solar activity is indicated by the solar flux F10.7 as shown in Figure 3 (b) which reaches maximum in 2012.

Figure 3(a) indicated that ionospheric scintillations are mostly observed during the equinoctial months of maximum solar activities. Intensity of scintillation is determined by the equatorial electron density irregularities and controlled by the generation and growth of F-region irregularities over the magnetic equator. (Carrano et al., 2012). Measurement testing is performed during equinox March 2012 when the occurrence of scintillation is more intense. The computed velocities displacement based on variometric method during quiet scintillation on March 27 - 28, 2012, and strong scintillation on March 26 and 31, 2012, are presented in graphical form in Figures 4 and 5 respectively. As can be observed in Figure 4, there was high accuracies of velocities displacement measurement during no scintillation occurrence. On the other hand, during strong scintillation occurrences, the velocity displacement indicated degradation of accuracies as shown in Figure 5. Maximum error reached more than 0.5

m/s for Up-Down and East-West measurement.

In order to see how many visible satellites experience scintillation on the signal, the graphs are shown in Figures 6 and 7. Figure 6 shows observation during strong scintillation on March 26 and 31, 2012. There are eight satellites that have experienced strong scintillation, beginning from 12:00 UT (19:00 Local Time) and finishing at 18:00 UT (01:00 Local Time, after midnight). As can be observed, these strong scintillations impact on accuracies measurement of velocity displacement. The errors reach more than 1 m/s, especially for Up-Down measurement and are significant for centimeter level resolution. These eight satellites experienced amplitude scintillation as shown in Figure 6 and have led to data dropouts. This is of concern to the GNSS user because his constellation for positioning measurement is affected by the gain or loss of satellites that apparently flicker in and out of visibility when scintillation or fading causes temporary loss of lock.

Figure 7 shows no scintillation situation of each satellite on 27 and 28 March, 2012. Apparently, the measurement of velocity displacement on March 28 did not show interference, but on March 26, an error and even no scintillation was shown. As we can see, the error is quite different from that caused by the scintillation which will continue in the next several hour.

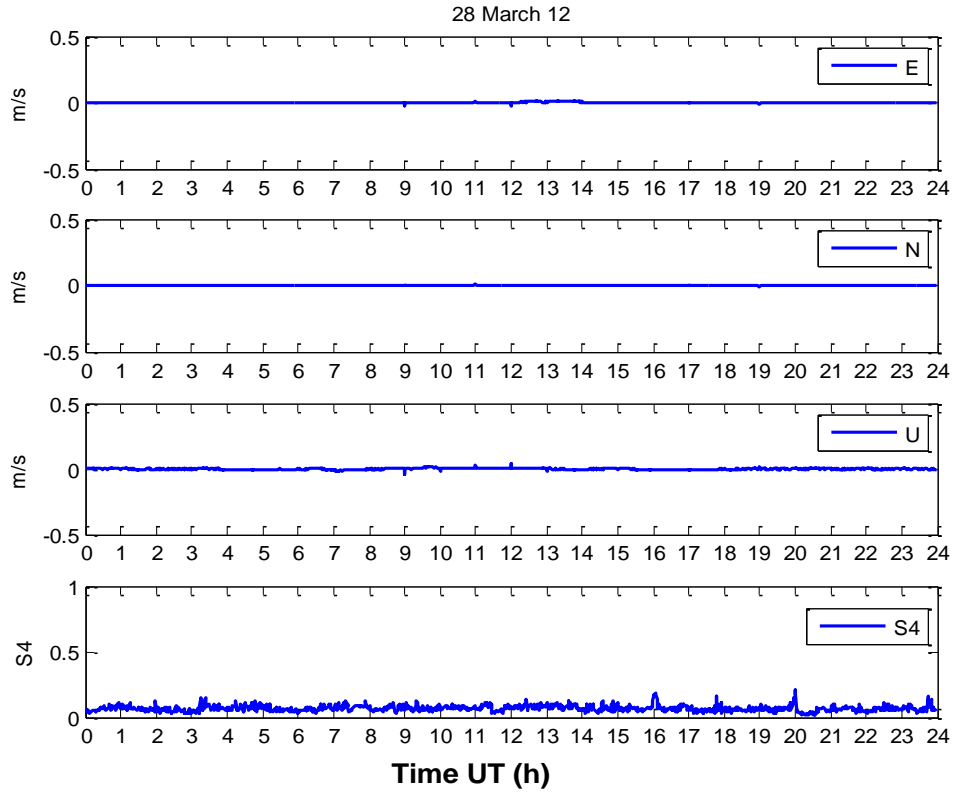


Figure 4. Temporal changes of the ENU velocities under quiet scintillation March 28, 2012.

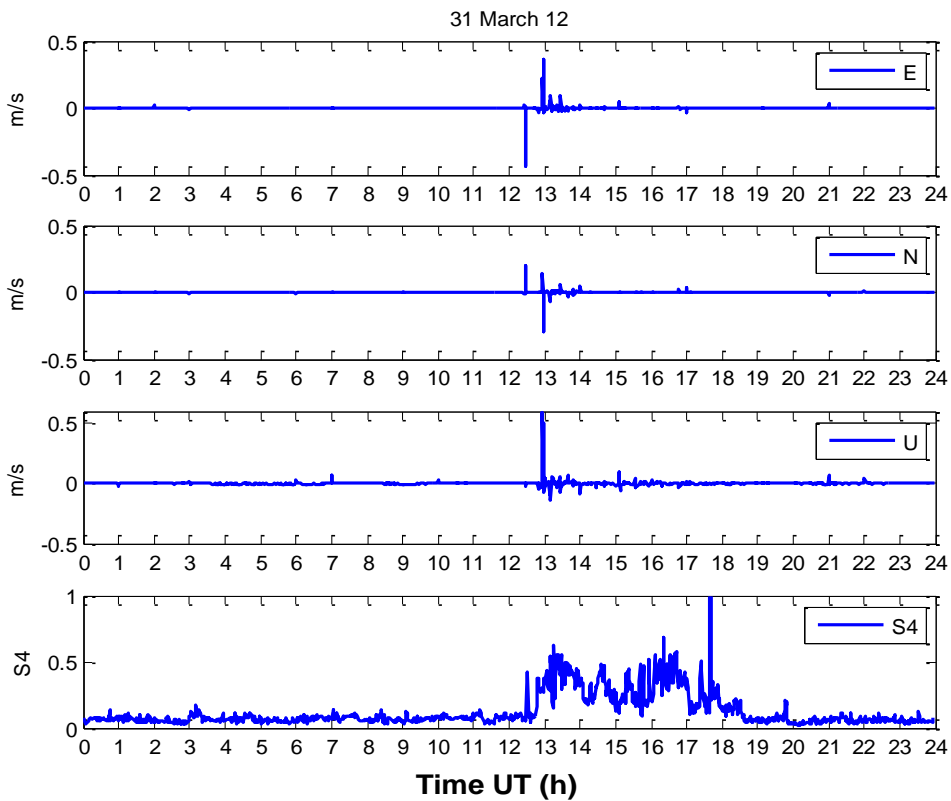


Figure 5. Temporal changes of the ENU velocities under strong scintillation March 31, 2012.

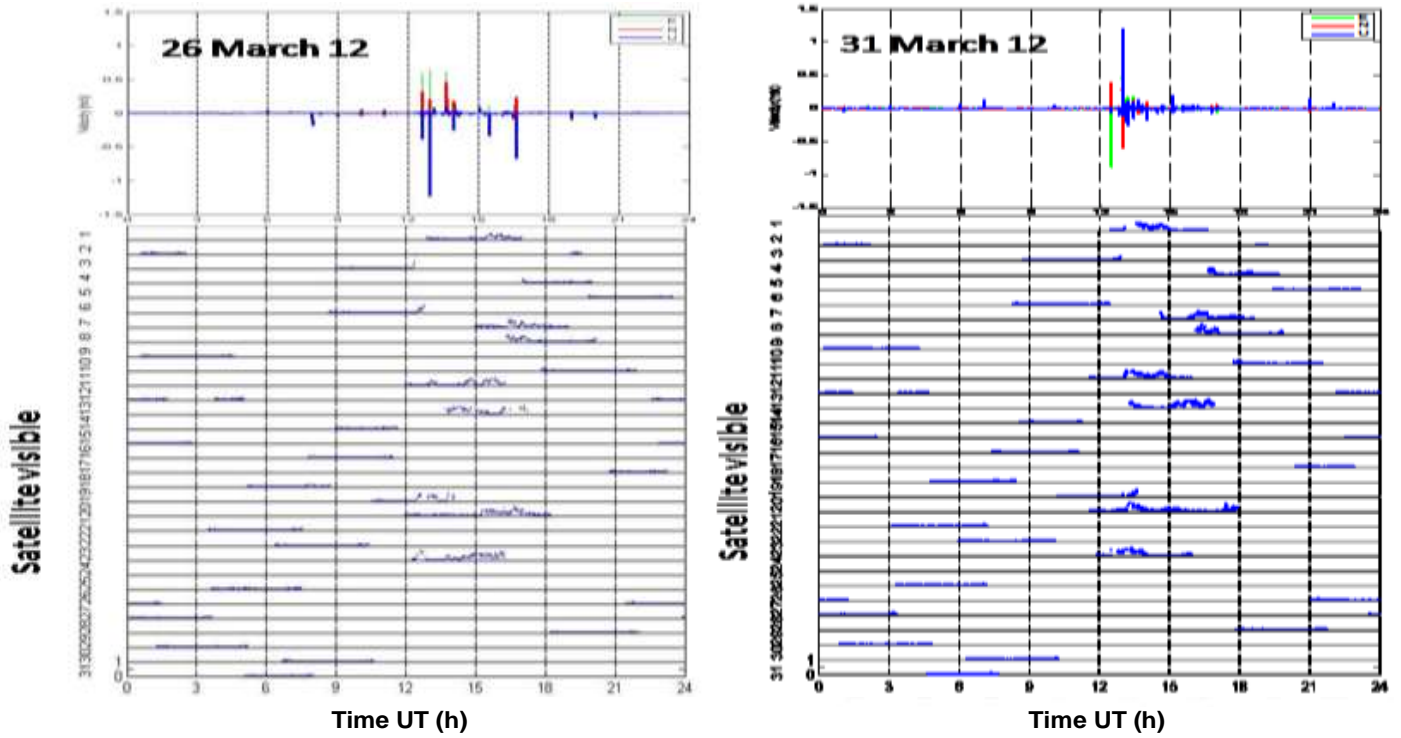


Figure 6. Temporal changes of the ENU velocities under strong scintillation March 26 and March 31, 2012 with all visible satellite signal of 24 hour observation

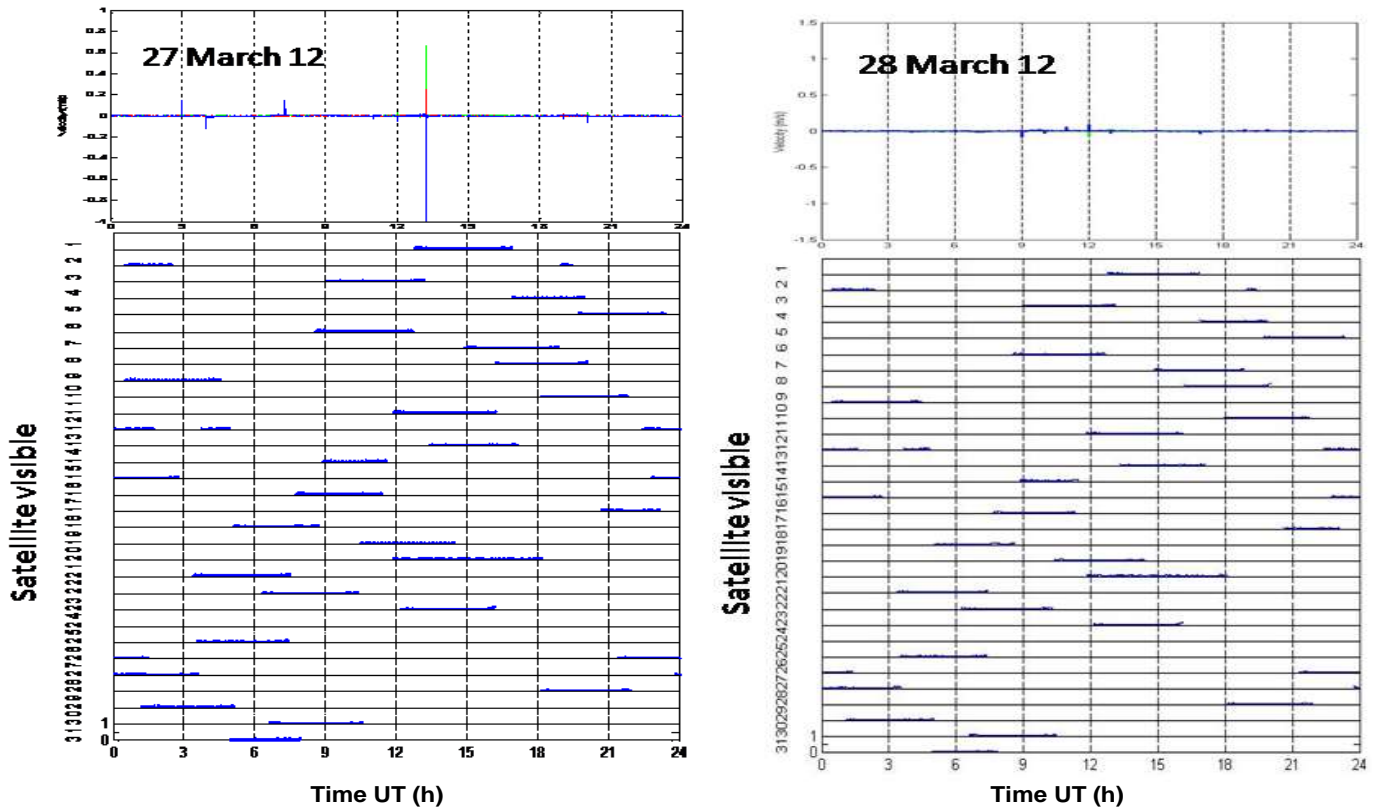


Figure 7. Temporal changes of the ENU velocities under quiet scintillation March 26 and March 31, 2012 with all visible satellite signal of 24 h observation.

## Conclusions

The presence of the ionospheric irregularities can impact on different communication and navigation systems. The occurrences of ionospheric scintillation may become problem for velocity displacement estimation using GNSS variometric method. Results show that during strong scintillation, the accuracies measurement of velocity displacement has degraded. The errors reached more than 1 m/s, especially for Up-Down measurement. The knowledge about morphology and dynamics of the ionospheric irregularities, dependences on geophysical factors is very important for mitigation of the space weather effects on GNSS, especially information scintillation. Technique to mitigate scintillation effects on positioning is needed. Scintillation leads to degradation in the GNSS receiver signal tracking performance, so that measurement is avoided during high scintillation occurrences, especially during maximum solar activity, and equinox month. A stochastic model is needed to improve the positioning performance.

## CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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