Dear Editor,

We welcome your comments and decision. We believe that we have exhaustively point-by-point replied to the referees' remarks in the Interactive Discussion stage. Therefore, we do not report here once again our responses. We modified the manuscript according to referees' reports. A copy of the revised manuscript with changes highlighted is attached below.

Sincerely,

F. Masci, J.N. Thomas, J. A. Secan

On a reported effect in ionospheric TEC around the time of the 6 April 2009 L'Aquila earthquake

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Abstract. In a report published in *Advances in Space Research*, Nenovski et al. (2015) analyse ionospheric TEC data from GPS measurements around the time of 6 April 2009 Mw6.1 L'Aquila (Italy) earthquake. According to the authors, TEC difference (DTEC) calculated from two GPS receivers in central Italy shows a hump-like shape (an increase followed by a decrease) during the hours just before and shortly after the main shock. They maintain that the hump-like shape is anomalous and may be explained as related to the earthquake. We show that the DTEC increase the hours before the shock, as well as its subsequent slow decrease, do not have any characteristic that might support a possible relationship with the earthquake. We have also conducted our own independent analysis using the same GPS data analysed by Nenovski et al. (2015). We have found a daily modulation in DTEC time series that shows hump-like shapes like that reported by Nenovski et al. (2015) throughout the investigated period. This demonstrates that the hump-like shape in DTEC close to the time of the 6 April earthquake is not anomalous and cannot be considered a possible earthquake-related effect.

1 Introduction

TEC (total electron content) is a metric for measuring the ionization of the ionosphere. The phase of GPS (global position system) satellite microwave signals (1575.42 and 1227.60 MHz carrier phase frequencies) ~~transmit~~received to ground is affected by the number of electrons, known as slant TEC (STEC), integrated over the path between the GPS satellite and the receiver ~~(1 TECu = 10^{16} electrons/m²)~~. By monitoring the difference of phase between the two GPS signals, we can get the temporal changes of STEC. STEC is measured in TEC units, where 1 TECu = 10^{16} electrons/m². Equivalent-vertical TEC (VTEC) is derived from STEC, and it represents the integrated electron density in the vertical column above the GPS receiver (Komjathy et al., 2005).

Co-seismic ionospheric disturbances (CIDs) are usually observed in TEC data shortly after large (Mw>6.5) earthquakes (see Perevalova et al., 2014; Cahyadi and Heki, 2015) as the response of the ionosphere to propagating atmospheric waves excited by the vertical motion of the ground or sea level (Astafyeva et al., 2014; Jin et al., 2015; Occhipinti et al., 2013). The

amplitude and duration of a CID mainly depend from the earthquake magnitude (Astafyeva et al., 2013; Cahyadi and Heki, 2015). In contrast, although there are several published papers that report ionospheric changes preceding large earthquakes (see, e. g., Heki and Enomoto 2013, 2015; Liu et al., 2015), the presence of precursors in ionospheric data is still controversial within the scientific community (see, Afraimovich et al., 2004; Dautermann et al., 2007; Kamogawa and Kakinami, 2013;

5   Masci et al., 2015; Rishbeth, 2006; Thomas et al., 2017), and many reported pre-earthquake ionospheric effects are recently shown not to be precursors (Masci, 2012a, 2013; Masci and Thomas, 2014, 2015; Thomas et al., 2012). The ionospheric conditions are subject to various influences such as solar activity, geomagnetic activity, anthropogenic effects, and meteorological events. It also shows normal seasonal, day-to-day, and diurnal variations. All this makes it difficult to identify possible earthquake-related ~~ionospheric~~ effects in the ionosphere (see, e.g., Afraimovich and Astafyeva, 2008; Astafyeva and

10   Heki, 2011), and may lead researchers to a misinterpretation of the obtained results (see, e.g., Masci, 2012a, 2013; Masci and Thomas, 2015).

This paper is organized as follows. In Section 2, we discuss the results from the GPS-TEC analysis by Nenovski et al. (2015). Afterward, in Section 3 we report our own analysis of the same GPS data they used.

2   TEC changes at time of the L'Aquila earthquake by Nenovski et al. (2015)

15   Nenovski et al. (2015) investigate the occurrence of anomalous changes in VTEC (hereinafter cited as TEC) data from GPS measurement at the time of the Mw6.1 earthquake that struck L'Aquila area on 6 April 2009 at 01:32:40 UT. TEC data they analysed are from 5 GPS receivers in central Italy: ~~Unpg~~UNPG (Perugia: 43.1N, 12.4E), ~~Untr~~UNTR (Terni: 42.6, 12.7E), A~~QUI~~qui (L'Aquila: 42.4N, 13.4E), ~~M0se~~M0SE (Roma: 41.9N, 12.5E), and P~~ACA~~aca (Napoli: 40.9N, 14.6E). Refer to Fig. 1 for the location of the GPS receivers. Note that we are following the GPS community standard station naming scheme of all

20   capitals rather than the scheme used in Nenovski et al. (2015). For example, we use UNTR rather than Untr.~~GPS measurements at Aqui, the closest station to the earthquake epicentre, stopped 1 hour after the main shock, which means that TEC data from this receiver are unreliable due to calibration problems.~~

~~The main result shown by~~ Nenovski et al. (2015) ~~are obtained by calculating~~ report the difference of TEC data (DTEC) derived from ~~Untr~~UNTR and ~~M0se~~M0SE, the two nearest GPS receivers to the epicentral area. The two receivers are

25   approximately 55 km and 90 km away from L'Aquila, respectively. As stated in Nenovski et al. (2015, pg. 245), collection of data at AQUI, the closest station to the earthquake epicentre, stopped for some hours starting at the time of the earthquake. They also state that, due to this gap in AQUI data, they were unable to use these data for calculating DTEC because of calibration problems. According to Nenovski et al. (2015), TEC derived from ~~Untr~~UNTR, the closest receiver to the epicentral area, may be indicative of ionospheric disturbances on regional scale possibly related to the 6 April earthquake. For all the

30   satellites crossing central Italy with an elevation angle EL exceeding a fixed value, they calculate the difference DTEC = $TEC_{Untr UNTR}$ − $TEC_{M0se M0SE}$ between TEC values that are simultaneously obtained from the GPS receivers of ~~Untr~~UNTR and

~~M0se~~M0SE. In Fig. 2 we show DTEC time series as reported by Nenovski et al. (2015) for EL > 67°. During 5-6 April, DTEC time series shows an increase followed by a decrease (with a maximum at about the earthquake time) that the authors define having the hump-like shape. Conversely, the TEC difference between ~~Untr~~UNTR and ~~Unpg~~UNPG (that they do not report) does not show a similar shape. Nenovski et al. (2015) conclude that the hump-like shape is anomalous and it is due to a positive

5   TEC anomaly over the ~~Untr~~UNTR receiver having maximum amplitude of ~0.5 TECu. Still, the positive TEC anomaly is extended up to ~~Unpg~~UNPG but not to ~~M0se~~M0SE. Thus, due to the shortest distance of ~~Untr~~UNTR and ~~Unpg~~UNPG from the epicentral area, they hypothesize that the hump-like shape in DTEC may be explained as related to the earthquake. We would like to point out that the hump-like shape may have an interpretation different from the positive TEC anomaly over ~~Untr~~UNTR and ~~Unpg~~UNPG: a negative TEC anomaly is in ~~M0se~~M0SE (the farthest GPS receiver from the epicentral area) and not in

10 ~~Untr~~UNTR and ~~Unpg~~UNPG data. In this case, could the negative anomaly in ~~M0se~~M0SE data be related to the 6 April earthquake?

In Fig. 3 we show an enlarged view of the hump-like shape in DTEC. We can see that DTEC starts to increase ~6-hour before the 6 April main shock reaching ~0.5TECu close to the time of the shock. A DTEC maximum having an amplitude of ~0.8-0.9 TECu can be seen to occur ~10-20 min after the main shock, lasting about 1-hour. Nenovski et al. (2015) suggest that

15 it may be due to a CID signature observed at ~~Untr~~UNTR. After, DTEC recovers to the pre-increase level in ~8-hour.

Our first remark concerns the possible CID which amplitude is about 0.3-0.4 TECu (see Fig. 2). This value is too high for a CID generated by a moderate Mw6.1 earthquake like that of L'Aquila. Cahyadi and Heki (2015) have shown that for moderate earthquakes the amplitude of the CID should be less than 1 percent of the background TEC. Thus, considering that at the time of L'Aquila earthquake the background ~~V~~TEC over central Italy is ~5 TECu (see Nenovski et al., 2015 Fig. 4), the

20 amplitude of a possible CID should be less than 0.05 TECu, much less than what we can see in Fig. 2. Moreover, the 1-hour duration of the alleged CID seems too long as well. Note that a CID effect lasting from 1 to a few hours is observed only after very large earthquakes, and it usually appears as a resonant atmospheric oscillation of about 4mHz (see Cahyadi and Heki, 2015) and not as a long-lasting positive anomaly as shown in Nenovski et al. (2015).

Leaving aside the alleged CID effect, we do not see evidence that the hump-like behaviour in DTEC during 5-6 April has

25 any characteristic that may support a possible relationship with the earthquake. Nenovski et al. (2015) report 11 days of DTEC data, from 28 March to 7 April 2009. In Fig. 2 we can see that during this period DTEC shows a daily modulation with similar maxima to what is observed on the earthquake day. The shadowed areas (that we have superimposed onto the original view) highlight DTEC maxima that, similarly to 5-6 April, occur during the same night period. Only two days (31 March and 2 April) do not show a similar maximum. The amplitude of DTEC maxima usually is ~0.3 TECu; on April 3, similar to before the

30 earthquake, the maximum amplitude of DTEC reaches ~0.5 TECu. The only difference that we note during 5-6 April is a lower dispersion in DTEC data. However, this does not mean that the better-defined increase-decrease shape in DTEC may have a relationship with the earthquake. Regarding the ~8-hour slow decrease in DTEC during 6 April (the descending branch of the

hump), while it is comparable to what we can see in the previous days, we do not see any evidence of a possible relation with the earthquake. The ~8-hour decrease cannot be interpreted as the recovery phase of an alleged CID effect as well. This because, e.g., long lasting CIDs, the duration of which, however, does not exceed 3-4 hours, are observed to be induced just by very powerful earthquakes, e.g., the M_w9 Tohoku-Oki earthquake of 11 March 2011 (Rolland et al., 2011).

5   In summary, Nenovski et al. (2015) fails to note that during the period they investigated, their analysis ~~DTEC~~ shows a daily modulation in DTEC with the occurrence of maxima in the same night period during which on 6 April the earthquake struck L'Aquila area. Furthermore, both the DTEC increase during the hours prior to the earthquake and the following slow decrease showed by Nenovski et al. (2015) during 5-6 April 2009 do not have any convincing characteristic of earthquake-related effects.

10   **2.1   On the hypothesized generation mechanisms**

Several generation mechanisms for electric, magnetic, and ionospheric disturbances possible related to the earthquake occurrence have been proposed in scientific literature (see the review paper of Cicerone et al., 2009). However, in spite of the several published studies, many researchers are sceptical of the reliability of these mechanisms (see, e.g., Dahlgren et al., 2014; Denisenko et al., 2013).

15   Among the mechanisms listed by Nenovski et al. (2015) (but not thoroughly investigated as possible generation mechanisms for the hump-like shape in DTEC) there is the air ionization caused by radon emission from the Earth's crust that may disturb the global electric circuit changing the electrical resistivity of the lower atmosphere. The possible relation between changes in air radon concentration at the Earth's surface and L'Aquila seismic sequence suggested in the monograph by Giuliani and Fiorani (2009) and presented in some meetings (see, e.g., Pulinets et al., 2009) is not convincing. This because

20   radon emissions as earthquake precursors of L'Aquila earthquake have not been confirmed by further experiments (see Cigolini et al., 2015; Pitari et al., 2014). Nenovski et al. (2015), however, conclude that the spatial and temporal characteristics of the reported changes in radon concentration appear not to be in accordance with the DTEC shape observed during 5-6 April.

     According to Nenovski et al. (2015), a promising generation mechanism for the hump-like shape in DTEC may be electric currents having seismogenic origin. The possible generation of electric currents prior to, or during the earthquake is a very

25   timely topic. Laboratory experiments have shown that electric currents are generated in dry rocks by stress loading (see, e.g., Freund et al., 2006). In a recent report, Dahlgren et al. (2014) investigate the onset of electric currents in gabbro as function of stress both for dry samples and samples saturated with fluid similar to those observed in active earthquake fault zones. Similarly to previous experiments, stress-related electric currents were observed in dry samples. On the contrary, neither transients nor stress-stimulated currents were observed during several cycles of stress loading. Because the Earth's crust is fluid saturated,

30   Dahlgren et al. (2014) conclude that significant electric currents are not expected to be generated the days before earthquakes during the slow stress accumulation in the region of earthquake nucleation; as a consequence no electric and magnetic signals

are expected to be observed on the Earth's surface. However, note that studies of data records from L'Aquila area (see Biagi et al., 2010; Masci, 2012b; Masci and Di Persio, 2012; Masci and De Luca, 2013; Villante et al., 2010) have identified no anomalous magnetic or electric effects during days to hours before and after the 6 April earthquake that might be hypothesized to have seismogenic origin. Still, in a recent report, Masci and Thomas (2016), by investigating magnetic field measurements from multiple magnetometers and seismic and strong motion records close to the earthquake epicentre, have shown that there is no evidence that might support the generation of an underground electric current in correspondence of the 6 April main shock, when the rupture occurred and the vast majority of mechanical energy was released.

3 Our own TEC analysis

In order to assess the significance of the signals identified by Nenovski et al. (2015), we have conducted our own independent analysis of GPS TEC measurements in an attempt to replicate their Fig. 10a. We acquired 30-second cadence GPS measurements (RINEX-format files) for the ~~Untr~~UNTR and ~~M0se~~M0SE from the Geodetic Data Archiving Facility of Agenzia Spaziale Italiana (ftp://geodaf.mt.asi.it/GEOD/GPSD/RINEX/2009/) for March and April 2009. The group delay and carrier phase measurements in these files were used to generate time series estimates of TEC using a method developed in the ionospheric research community (Bishop et al., 1994; Mazzella et al., 2007). This method uses the SCORE (Self Calibration Of pseudo-Range Errors) technique to account for time-delay biases in both satellites and receivers and for signal multipath contamination (Bishop et al., 1996; 1997; Lunt et al., 1999). The SCORE process produces a set of corrections that account for the sum effect of time-delay biases and multipath effects for each receiver-satellite pair for each day. It should be noted that although we will be working with TEC differences in this paper, the SCORE calibrations do not cancel out in the differencing process. The biases estimated by the SCORE process include the effects of time-delay biases in the satellite transmitters and in the receiving hardware (from the antenna to the front-end processing within the receiver), as well as multipath contamination. While the time-delay biases in the satellite transmitters will be the same for all stations, the other components of the biases are not only station-dependent, but the receiving hardware biases can also vary diurnally due to factors such as the local ambient temperature. Accepted values for the uncertainty in the absolute TEC due to uncertainties in the bias values are on the order of 1 to 2 TECu. For instance, Ciraolo et al. (2007) quote a minimum uncertainty of 1.4 TECu in a study of observed data, whereas a second study based on analysis of simulated data (Ciraolo, 2009) shows uncertainties from 0.5 to 4.0 TECu depending on latitude. These studies also show that the uncertainties in the absolute TEC measurements are uncorrelated between two receivers, even if closely spaced. Note that these uncertainties are larger than the signals identified as earthquake-related by Nenovski et al. (2015).

Our first attempt to replicate Fig. 10a by Nenovski et al. (2015) is shown in Fig. 4, which is a plot of the difference DTEC = $TEC_{~~Untr~~UNTR}$ – $TEC_{~~M0se~~M0SE}$ between VTEC at stations ~~Untr~~UNTR and ~~M0se~~M0SE for measurements with elevation angles

greater than 67°. The VTEC estimates made use of SCORE-derived biases and multipath for each station-day (ten correction sets per station). A strong diurnal variation in DTEC is very clear in this plot with values ranging from -0.7~~1~~ to +1.~~86~~9 TECu. No anomalous changes in this variation are seen prior to or after the time of the earthquake, as well as a CID effect. Hump-like shapes like that reported during 5-6 April by Nenovski et al. (2015) can be seen throughout the investigated period as daily modulation in DTEC time series with maxima in the same night period.

Since our Fig. 4 is quite different from Fig. 10a by Nenovski et al. (2015), we also take a different approach as shown in Fig. 5. Using the same data set as used to generate Fig. 4, we find the difference in the differential carrier phase (DCP) between ~~Untr~~UNTR and ~~M0se~~M0SE (ΔDCP = DCP$_{\text{\sout{Untr}UNTR}}$ − DCP$_{\text{\sout{M0se}M0SE}}$), also for elevation angles great than 67°. In order to remove the effects of the unknown number of phase cycles between the satellite transmitters and the ground receivers, the DCP at each station is offset to zero at the first point in the time series where the elevation angle exceeded 67° prior to calculating the difference between the stations. Note that these data do not include the SCORE correction factors, nor have then been modified to make them into an equivalent-vertical estimate. The diurnal signal evident in Fig. 4 has disappeared in Fig. 5. ~~As this variation is not germane to this discussion, we will not speculate on the source.~~ However, as in Fig. 4, there is no evident anomalous change in the ΔDCP time series ~~prior to or after the earthquake~~, and no hump-like shape can be seen during the hours around the earthquake time. We believe that the diurnal variation evidence in our Figure 4, as well as that we can see in Nenovski et al. (2015, Figure 10a), is not an ionospheric signal but rather an artefact due to an assumption made in the calibration processes, that the biases being solved for are constant over the time of the calibration analysis (24 hours). While this assumption is good for the time-delay biases at the satellite, it is not as good for the bias imposed at the receive end (from the antenna to the correlator processing within the GPS receiver). As described in Ciraolo et al. (2007), the time-delay on the ground segment can be effected by the ambient diurnal temperature variation, which will be different at different locations and for different equipment set-ups. Thus, the diurnal variation in Figure 4, which can be seen does not change much across the time of the earthquake, is due to a different diurnal variation in the receiver-end time-delay at the two stations being differenced (UNTR and M0SE in our case).

In summary, we believe that we have replicated, as closely as we can give uncertainties in how Nenovski et al. (2015) processed and analysed their GPS data, the results they showed in their Fig. 10a. In our analysis of both the (absolute) VTEC and the (relative) slant-path DCP measurements derived from GPS measurements taken at ~~Untr~~UNTR and ~~M0se~~M0SE around the time of the L'Aquila earthquake, we find no evidence for anomalous signals during the investigated period~~prior to, during, or after the earthquake occurrence~~.

4 Conclusion

We do not see evidence that the hump-like shape in DTEC shown by Nenovski et al. (2015) during 5-6 April 2009 may be considered an actual earthquake-related phenomenon. The hypothesis that the DTEC increase during the hours prior to the

earthquake, as well as the following slow decrease, may have seismogenic origin is not supported by evidence. The DTEC time series reported by Nenovski et al. (2015) shows a daily modulation with maxima that occur in the same night period suggesting that the hump-like shape during 5-6 April 2009 is not anomalous and its correspondence with the earthquake is just a coincidence. This is supported by our own independent analysis of the same GPS data analysed by Nenovski et al. (2015).

5   Our DTEC calculation shows that hump-like shapes like that reported by Nenovski et al. (2015) during 5-6 April can be seen as daily modulation of DTEC time series throughout the investigated period. Further analysis of the difference in the differential carrier phase between ~~Untr~~UNTR and ~~M0se~~M0SE have identified no anomalous change during the investigated period~~prior to or after the earthquake~~, and no hump-like shape has been found around the time of the earthquake.

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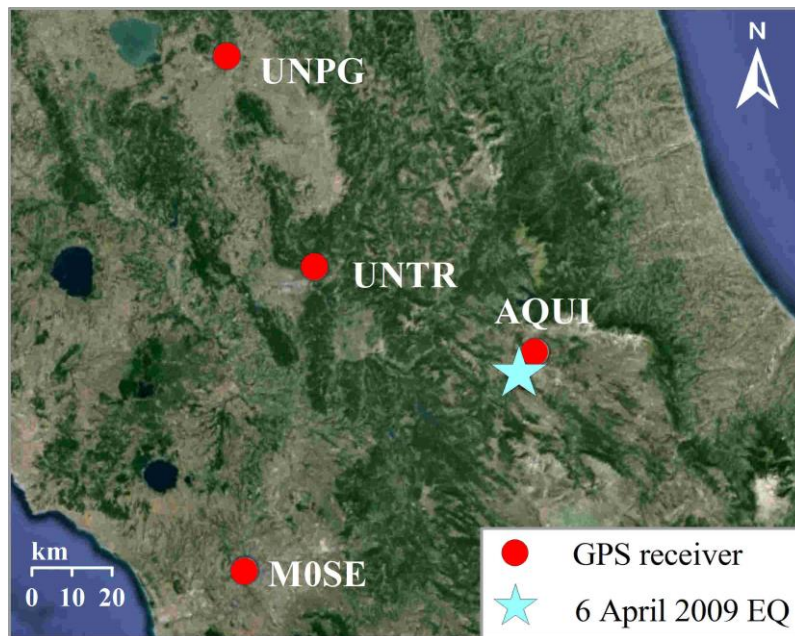

5   **Figure 1.** Four GPS receivers in central Italy whose data were analysed by Nenovski et al. (2015).

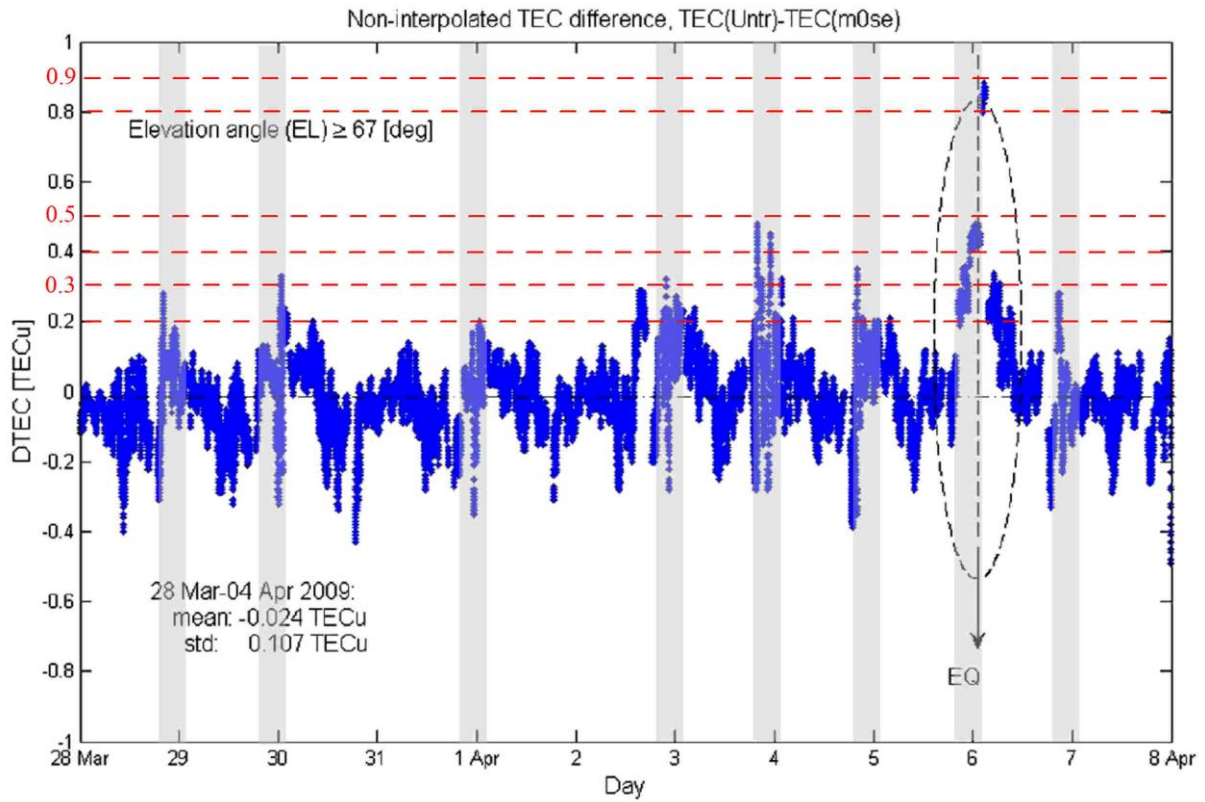



Figure 2. VTEC difference DTEC = TEC~~Untr~~UNTR − TEC~~M0se~~M0SE from all satellites crossing central Italy with an elevation angle greater than 67° as reported by Nenovski et al. (2015, Figure 10a). EQ refers to the 6 April 2009 main shock. The dashed ellipse highlights the hump-like variation in DTEC during 5-6 April 2009 that according to Nenovski et al. (2015) may have a relationship with the earthquake. Note that DTEC clearly shows a daily modulation throughout the investigated period. The shadowed areas (that we have superimposed onto the original view) highlight DTEC maxima that, as for 5-6 April, occur in the same night period.

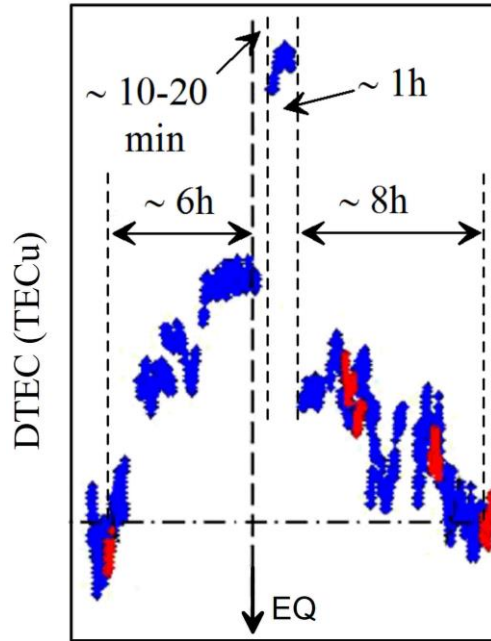
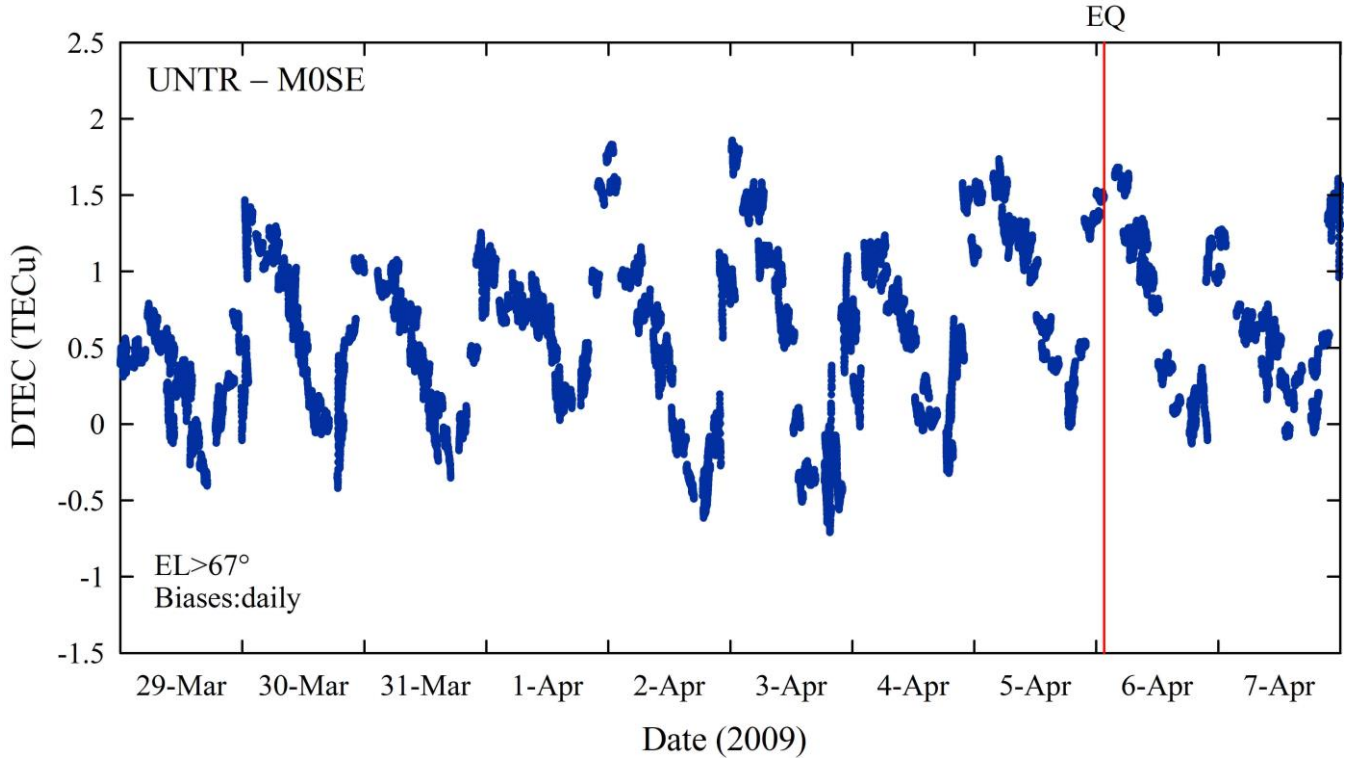
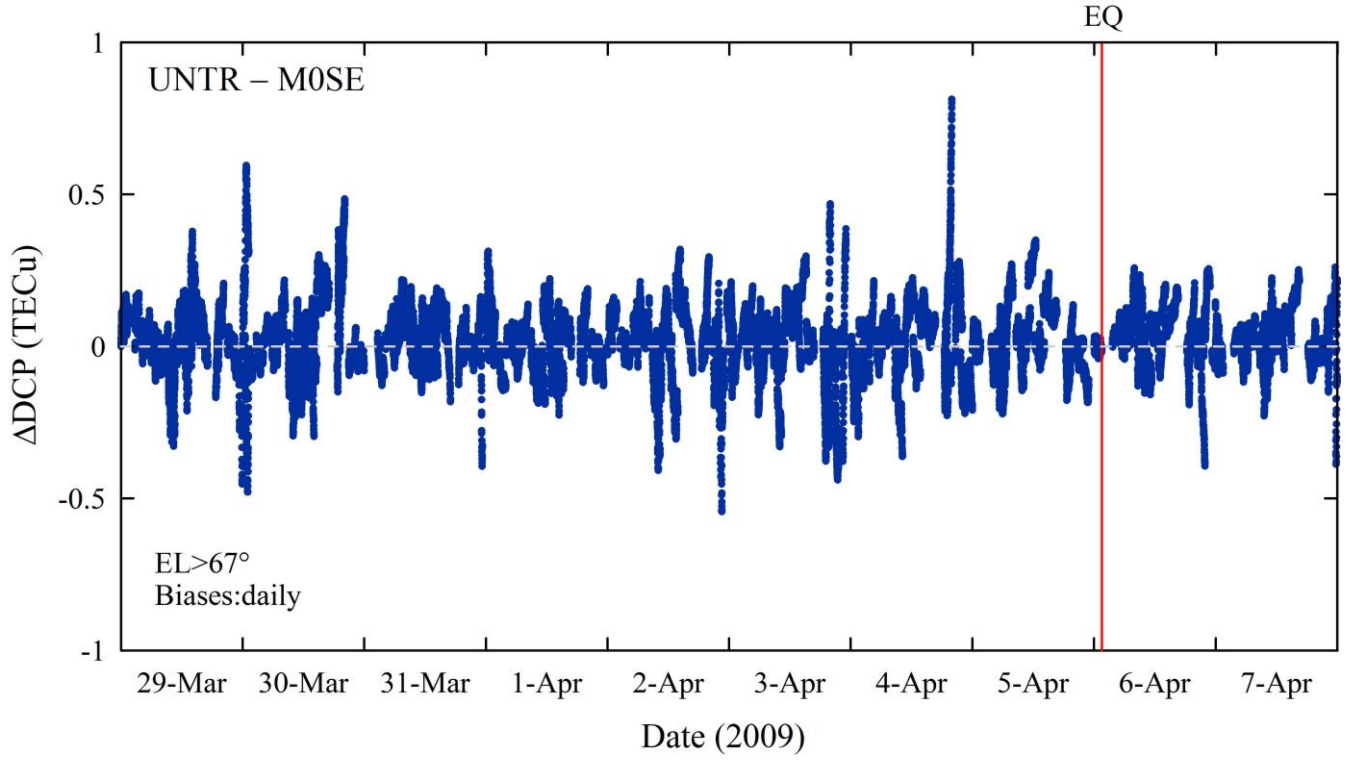



Figure 3. Enlarged view of the hump-like DTEC shape during 5-6 April 2009 (adapted from Nenovski et al., 2015, Fig. 10b). Red DTEC values are from GPS satellites with elevation angles EL > 86° (see Nenovski et al., 2015 for details). EQ refers to the 6 April 2009 main shock.

5   **Figure 4.** VTEC difference DTEC = TEC~~Untr~~UNTR – TEC~~M0se~~M0SE between ~~Untr~~UNTR and ~~M0se~~M0SE GPS receivers calculated using the same GPS data of Nenovski et al. (2015) from all satellites crossing central Italy with an elevation angle greater than 67°. The vertical red line identifies the 6 April 2009 main shock. Hump-like shapes like that reported during 5-6 April by Nenovski et al. (2015) can be seen as daily modulation in DTEC time series.

5 **Figure 5.** Differential carrier phase (DCP) difference $\Delta DCP = DCP_{\text{UntrUNTR}} - DCP_{\text{M0seM0SE}}$ between ~~Untr~~UNTR and ~~M0se~~M0SE GPS receivers calculated using the same GPS data of Nenovski et al. (2015) from all satellites crossing central Italy with an elevation angle greater than 67°. The vertical red line identifies the 6 April 2009 main shock.