Near-Real-Time Analysis of Traveling Ionospheric Disturbances for The Fundamental Science, Natural Hazards and Space Weather Applications

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IONOSPHERE & GNSS

The ionosphere is the ionized part of Earth's upper atmosphere. It impacts the propagation of radiowaves, therefore affects systems of location, navigation and precise timing on which our society heavily relies.

The ionosphere is a highly dynamic and variable medium. It is characterized by a number of disturbances generated in response to a wide range of phenomena (natural hazards, space weather events, etc.) Such travelling ionospheric disturbances (TID) are often present, and it is extremely difficult to identify their origin, especially in real or near-real-time (NRT). It is one of the most interesting scientific questions and a big challenge.

When people mention GNSS, they think only about its navigational application; however, they are a useful tool for ionospheric research. Its main advantage is good spatial and temporal resolution. There are ~8000 receivers providing data nowadays, each having a constellation of 20 satellites at any given time. Therefore we have a tremendous number of piercing points to observe the ionosphere

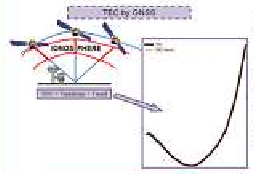


Fig. 1. Measurements from GNSS receivers allow to estimate the ionospheric total electron content, which is equal to the number of electrons along a line-of-sight between a satellite and a receiver. TEC consist of trend caused by satellite motion and variations caused by ionospheric activity

The variation provides important "scientific" information. The ionosphere is an extremely disturbed medium, you can observe plenty of disturbances related to various sources at any time. Therefore, it leads to one of the most fundamental scientific questions in ionospheric research - find and prove the relationship between a particular driver and a particular disturbance.

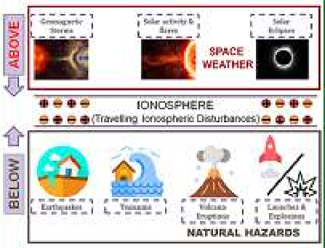
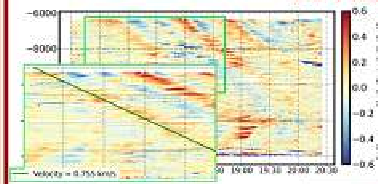


Fig. 2. Here's some of the sources of different nature and background. We can distinguish it into two groups: sources that come from above the ionosphere, sources from below.

SPACE WEATHER



Ionospheric storm is a common term that describes the entirety of ionospheric variations induced by geomagnetic disturbances. The ionospheric storms primarily occur as a consequence of a sudden input of solar wind energy into the magnetosphere - ionosphere - thermosphere system. Ionospheric effects of geomagnetic storms have been studied for decades but not yet completely understood. Therefore, it's hard to predict storm effects on the ionosphere, and NRT-analysis is important for tracking its state.

Fig. 6. The 17th Mar. 2015 St. Patrick's Day storm NRT-TTD. The source is located in the North Geomagnetic Pole. Data from all available satellites were used.

Solar flares produce large and rapid increases of solar X-ray and extreme-ultraviolet (EUV) radiation. These rapid increases directly enhance ionization in the upper atmosphere, causing "sudden ionospheric disturbances" (SID), which disrupts navigation systems and communications that rely on ionosphere electron density. Consequently, many phenomena associated with SID, including short wave fadeout, sudden phase anomalies, and others

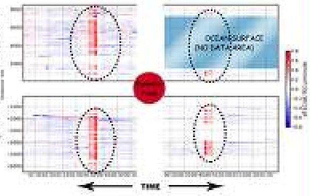
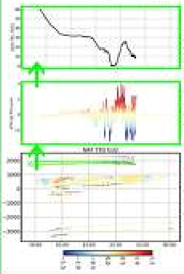


Fig. 7. The 25th Feb. 2014 Solar Flare NRT-TTD. The source is located in the centre of Subsolar Point. The left side corresponds the values to the left of the Subsolar Point, the right side - the values to the right of the Subsolar Point. Data from all available satellites were used.



Equatorial plasma bubbles (EPB) are plasma density depletions of different scale (50–1000 km) observed in the equatorial ionosphere. During geomagnetic storms, when the storm-induced electric fields occur in the dusk sector, they superimpose on the normal prereversal enhancement and can lead to the suppression of postsunset EPB occurrence.

Fig. 8. The upper panel is the example of TEC series by station «MAS1». The middle panel is dTEC/dt from the upper panel. The lower panel is the 22nd Jun. 2015 EPB NRT-TTD. The source is the solar terminator (the moving source). Data from satellite G32 were used.

KEY POINTS

We developed a novel method that enables to automatically detect TID in data series of total electron content (TEC) and to determine their spatio-temporal characteristics in NRT.

Our method, called "D1-GNSS-RT", is mostly suitable for detection of TID with high rate of TEC change.

Also, we suggest Near-Real-Time travel time diagrams as an additional way to obtain and verify spatio-temporal characteristics in NRT.

CONCLUSIONS

In NRT, TEC time derivative (dTEC/dt), we observe **diverse responses** related to different physical phenomena.

By using the novel methods and our dTEC/dt approach, we obtain the results in the NRT scenario **similar** to the ones from retrospective studies

We **can distinguish** different sources in NRT based on their **spatio-temporal properties** because of diverse responses.

FIRST AUTHOR PUBLICATIONS

1. Maletckii, B. & Astafyeva, E. Determining spatio-temporal characteristics of coseismic travelling ionospheric disturbances (CTID) in near real-time. https://www.nature.com/articles/s41598-021-99906-5

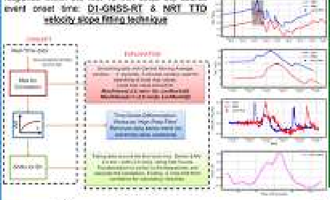
2. Maletckii, B. & Astafyeva, E. Near-Real-Time analysis of the ionospheric response to the 15 January 2022 Hunga Tonga-Hunga Ha'apai volcanic eruption. Resubmitted to JGR (under revision)

3. Maletckii, B. & Astafyeva, E. Ionospheric response to solar flares – how fast does the disturbance propagate? Submitted to GRL

NEW METHODS

We suggest to use dTEC/dt parameter to analyze ionospheric disturbances in NRT. We developed novel methods based on it allowing to characterize response within the first 15 min since the source event onset time: D1-GNSS-RT & NRT TTD velocity slope fitting technique

graphic example for each step based on The Great Tohoku-oki Earthquake data



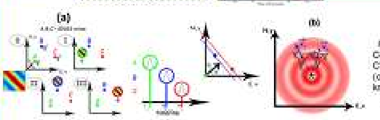
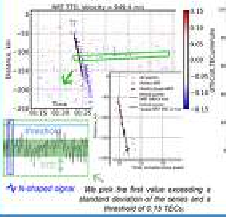


Fig. 3. (a) Explanation of D1 technique. A, B, C—GNSS stations that are used to determine the CTID parameters: horizontal velocity (v_h) and azimuth (α); (b) Ionospheric localization of TIDs based on the known location and values of two velocity vectors V_1 and V_2 as determined by using the D1-method

Similar to the D1-GNSS-RT, for NRT-TTD we also use the dTEC/dt parameter. As the source, we take the disturbance source position. From TTD, the velocity can be estimated as the slope, however, up to now, there was no NRT-compatible automatique method to do that. For the first time, we developed a novel technique to fit the slope line in NRT. The automatic NRT TTD fitting technique consists of two stages: 1) the first maximum "picker" and 2) the "filter" based on these maxima.

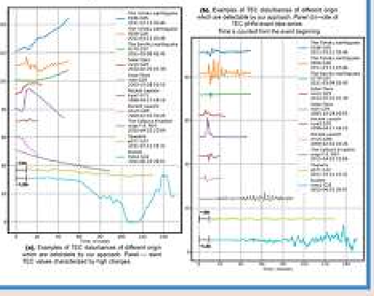
Fig. 4. NRT-TTD plotted by using dTEC/dt data for the M6.6 16 July 2007 Chuetsu earthquake in Japan, which is the smallest earthquake ever recorded in the ionosphere



We pick the first value exceeding a standard deviation of the series and a threshold of 0.15 TECu.

BY USING OUR NOVEL METHODS WE CAN ANALYZE RESPONSE GENERATED BOTH BY SPACE WEATHER AND NATURAL HAZARDS. HERE WE PRESENT SIGNATURES OF TRAVELLING IONOSPHERIC DISTURBANCES CREATED BY DIFFERENT PHYSICAL PHENOMENA (SOURCE)

Fig. 5. TID's dTEC/dt signatures by different sources



(a). Examples of TEC disturbances of different origin which are detectable by our approach. Panel — sixed TEC values characterized by high changes.

(b). Examples of TEC disturbances of different origin which are detectable by our approach. Panel (b)—rate of TEC (differenced) time series. Time is counted from the event beginning.

NATURAL HAZARDS

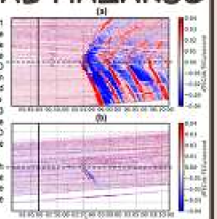
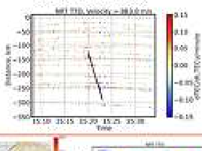
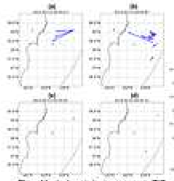


Fig. 9. (a) The great M9.1 Tohoku-oki earthquake NRT-TTD (sat. G26). The propagation speed of the observed coseismic-TID (CTID) can be estimated from the slopes on the TTD. We find the speeds to be 2.3–2.8 km/s.
(b) The 2011 M7.3 Sanriku-oki earthquake NRT-TTD (sat. G07). The CTID speed is estimated to be 1.2–1.6 km/s.
All of this is in line with previous retrospective observations for the ionospheric response to the both earthquakes

Fig. 10. The 4 August 2020 Beirut explosion NRT-TTD.
The response to it was captured by satellite GPS G22. Clear N-shaped disturbances emerged ~12 minutes after the explosion onset and their velocity is estimated to be 883 m/s.
Our estimation is in agreement with the retrospective estimations (0.8 km/s). We note that the spatial resolution of the GNSS network was very poor, which made it challenging to automatically process it, but our method succeeded.





(a-d) The Great Tohoku-oki Earthquake 1-sec data; PRN G26
(e-f) The Tonga Eruption 30-sec data. All Sats

Fig. 11. (a-b, e) Instantaneous TID velocity field calculated from the first TID detected after the event onset.
(c–d, f) Localization of the source as estimated from the first velocity vectors shown on panels (a–b, e).

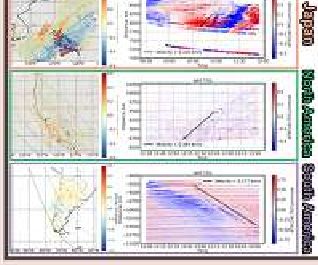


Fig. 12-13. The 2022 Tonga oceanic volcanic eruption began on the 15 January 2022. It was an incredibly impulsive and high energy event. In the near-field (fig. 12), our newly developed fitting method estimates the velocity to be 621.1 m/s.

On the left panels (fig. 13), we demonstrate how our methods can perform in the Far-Field (i.e., several thousands of km away from the source) and process traveling disturbances with lower velocities and frequencies. Perturbations with such characteristics include tsunami-induced gravity waves. Therefore, the NRT-method can be used for early warning systems.