Near-real-time Identification of the Source of Ionospheric Disturbances

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Abstract

The ionosphere is characterised by a large number of disturbances generated in response to a wide range of phenomena, including natural hazards, space weather and man-made events. Such disturbances are known as travelling ionospheric disturbances (TID). Identification of the origin of TID, especially in real or near-real-time (NRT), is an extremely difficult task, and it is one of the most interesting scientific questions. In this paper we present, for the first time, an approach for an automatic and NRT-compatible detection and recognition of the source of ionospheric disturbances in time series of total electron content (TEC) measured by the Global Navigation Satellite Systems (GNSS) method. The main idea is 1) to analyse main characteristics (such as spatio-temporal features and frequency content) of TID generated by known sources, and 2) in NRT, to rapidly examine TID’s, and, based on this information, recognize their source. Currently, our database contains TEC data series with response to earthquakes, volcanic eruptions, tornadoes, explosions, rocket launches and equatorial plasma bubbles. Our developments are important for the future assessment of natural hazards from the ionosphere, and also for NRT Space Weather nowcast and applications. Also, our work presents important information about the physical properties of TID of different origins.

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Key Points:

- For the first time, we present a technique enabling identification of the source of ionospheric disturbances of different origins
- Our approach can be used for Near-Real-Time application and Near Real Time discrimination of the source of ionospheric disturbance
- A database with different Space Weather and Natural Hazard events is created and analysed to study parameters of ionospheric disturbances

Keyword(s):

Ionosphere, Travelling Ionospheric Disturbances, Near-Real Time, GNSS, Natural Hazards, Space Weather
Abstract

The ionosphere is characterised by a large number of disturbances generated in response to a wide range of phenomena, including natural hazards, space weather and man-made events. Such disturbances are known as travelling ionospheric disturbances (TIDs). Identification of the origin of TIDs, especially in real or near-real-time (NRT), is an extremely difficult task, and it is one of the most interesting scientific questions. In this paper we present, for the first time, an approach for an automatic and NRT-compatible detection and recognition of the source of ionospheric disturbances in time series of total electron content (TEC) measured by the Global Navigation Satellite Systems (GNSS) method. The main idea is 1) to analyse main characteristics (such as spatio-temporal features and frequency content) of TID generated by known sources, and 2) in NRT, to rapidly examine TID’s, and, based on this information, recognize their source. Currently, our database contains TEC data series with response to earthquakes, volcanic eruptions, tornadoes, explosions, rocket launches and equatorial plasma bubbles. Our developments are important for the future assessment of natural hazards from the ionosphere, and also for NRT Space Weather nowcast and applications. Also, our work presents important information about the physical properties of TID of different origins.

1 Introduction

The ionosphere is a part of the Earth’s upper atmosphere that extends from 60-80 to 800-1000 km of altitude, where the concentration of charged particles (i.e., free electrons and ions) is increased. The ionosphere is an extremely variable medium. Its properties significantly depend on the time of a day, season, latitude, altitude, but also on the coupling with the neutral upper atmosphere (thermosphere) and the magnetic field.

The ionosphere is sensitive to a wide range of phenomena, including natural hazards, space weather and man-made events. All these impacts can generate disturbances in the ionosphere that are known as travelling ionospheric disturbances (TIDs). The identification of the origin of TIDs, especially in real or Near-Real Time (NRT), is an extremely challenging task, and it is one of the biggest scientific challenges.

TIDs constitute an important Space Weather (SW) effect. They can severely affect the propagation of radio-signals and often lead to disruption of radio-communication. Their rapid detection and characterization are crucial for the SW nowcast and forecast [Reinisch et al., 2018; Belehaki et al. 2020; Altadill et al., 2020]. A major step toward the NRT detection of TID of different scales and origins was done recently with the H2020 TechTIDE project (warning and mitigation technologies for TID effects). However, the outputs of the project mostly concern large-scale and medium-scale TID generated by geomagnetic storms [Belehaki et al., 2020; Altadill et al., 2020].
In the context of Natural Hazards (NH), recently numerous demonstrations have been made from the community regarding the possible use of ionospheric measurements for potentially rapid assessment of parameters of earthquakes, eruptions, and tsunamis from the ionosphere [Heki, 2006; Cahyadi and Heki, 2015; Savastano et al., 2017; Astafyeva, 2019; Manta et al., 2020; Ravanelli et al., 2021]. Which, in turn, makes it possible to apply ionospheric GNSS data for early tsunamis warnings. In the timeline of tsunami arrival at the coast in the near field scenario, we should detect Co-Seismic Ionospheric Disturbance (CSID) in 7-9 minutes after earthquake time, which leaves a couple minutes to analyse disturbance and provide ionospheric solution to meet the requirements of NRT. Based on this timing, in this work, we define NRT as 15 minutes after the earthquake onset, or 6-8 minutes after the TID detection (Figure 1). Previously developed methods are not directly applicable for NRT by this definition and, in addition to that, for better reliability of such a system, one needs to confirm the link between the detected disturbance and the source that generated it.

Despite the fact that potential sources of TIDs are fairly well-known, the main challenge remains in their predictability and their impacts on the ionosphere. For instance, the spatial and temporal scales that are associated with predictable features are yet to be quantified [Zawdie et al., 2020]. Hence, for both Space Weather and Natural Hazard domains, it is crucial to be able to identify the source of TIDs in NRT. However, up to now, there are no techniques that are capable of doing that.

Here, for the first time, we present NRT-compatible methods for automatic detection and characterization of TIDs that allow to distinguish their origin in NRT.

2 Data and Methods

Dual-frequency receivers of the Global Navigation Satellite Systems (GNSS) were used to estimate total electron content (TEC). TEC is an ionospheric parameter representing the number of electrons along a line-of-sight (LOS) between a satellite and a receiver. TEC can be estimated from phase and code measurements. For our purposes, only phase measurements can be used:

\[
\text{slant } \text{TEC}_{ij}(\text{phase}) = \frac{1}{\lambda} \times \frac{f_2^2 f_1^2}{f_1^2 - f_2^2} \times (L_i \lambda_i - L_j \lambda_j)
\]  

(1)

Where A = 40.308 m³/s², L_i and L_j are phase measurements, \(\lambda_i\) and \(\lambda_j\) are wavelengths at the GNSS frequencies (for instance, \(f_1\) and \(f_2\) for Global Positioning System (GPS) are 1575.42 and 1227.60 MHz, respectively). The TEC is measured in TEC units (TECu), where 1 TECu = 10^{16} \text{ electrons/m}^2 [Rideout & Coster, 2006; Hofmann-Wellenhof et al., 2008].

In order to estimate geographic positions of detected ionospheric disturbances, we assume the ionosphere to be a thin shell located at a fixed altitude (H_{im}) around the maximum ionisation altitude hmF2. The intersection points between the LOS between a satellite and a receiver, and the
ionospheric shell are called ionospheric piercing points (IPP), and their projection on the Earth surface will show the coordinates [Afraimovich & Perevalova, 2006].

TEC data series contain not only variations due to TID, but also trend due to satellite orbit motion, and also unknown bias. In order to remove the trend and the bias, in our NRT approach, we use TEC time derivative [Maletckii & Astafyeva, 2021a; Maletckii & Astafyeva, 2021b; Maletckii & Astafyeva, 2022].

Spatio-temporal parameters of TID, such as velocity and direction of propagation of TID, were estimated by using NRT-compatible interferometric method called D1-GNSS-RT [Maletckii & Astafyeva, 2021a], and/or by calculating travel-time diagrams (TTD, Figure S1, Maletckii & Astafyeva, 2021a; Maletckii & Astafyeva, 2022). The first method can calculate the horizontal propagation speed and the azimuth of TID propagation from known arrival times and positions of TID arrivals at three detection points (LOS). To detect TID, the “D1-GNSS-RT” method first analyses TEC data series to find the local maximum value (LMV). Further, it calculates the cross-correlation function for each pair of time series around the LMV, and the time shift in TID arrivals. Finally, based on these time shifts, it estimates the horizontal velocity and the direction of TID propagation. For this work, we updated the parameters of detection of LMV to improve the D1-GNSS-RT method: the analysing window was shortened to 3 minutes for both 1-sec and 30-sec data, the additional conditions of presence in the analysing window of dTEC/dt values exceeding the threshold of 0.06 TECu/min was added.

The main disadvantage of the D1-GNSS-RT technique is that it is not applicable to sparse GNSS networks. In such a case, the apparent horizontal velocity of TID can be estimated from TTD, a diagram showing the time vs distance from the source of TID [Maletckii & Astafyeva, 2021a; Maletckii & Astafyeva, 2022]. To estimate the velocity automatically, an automatic and NRT-compatible fitting technique was developed by Maletckii & Astafyeva (2022). The fitting technique consists of two stages (Figure S2): 1) the first maximum “picker” and 2) the “fitter” based on these maxima. To select the maximum of dTEC/dt data, we pick those values that exceed the standard deviation of the series and a threshold of 0.08 TECu. In the case if multiple points satisfy the conditions in a 120-second window, we chose those centered in the current window. Finally, the outliers are removed from the final list of maxima (values that can appear only with velocities exceeding 5 km/s).

One other disadvantage of the D1-GNSS-RT method is in the fact that previously it only performed successfully when the amplitude of dTEC/dt disturbances exceeded the noise level by a factor of 4 [Maletckii & Astafyeva, 2021a]. In the case of high noise level (e.g., the 2023 Turkey and the 2016 New Zealand earthquakes), TID were not detected automatically. Therefore, to further improve the method, additional adjustment was made: all TEC data series were smoothed by using a central moving average (CMA) with a 25-sec window. This procedure significantly reduced the noise level without significantly altering the amplitude of the signal, so the signal-to-noise threshold increased and this enabled the automatic detection of TID. It should be noted that such an adjustment does not require significant additional stacking of the data (only extra 12 seconds as compared to the initial methods), and, therefore, it can be applied in NRT conditions.
The obtained instantaneous velocities and ionospheric centres of disturbances are also suitable for the automatic characterization of the “spatial resolution” of a TID. Two spatial characteristics are available: 1) the distance between the first estimated instantaneous velocity of the disturbance and the further instantaneous velocities; (Figure 2a) 2) the distance between the first estimated ionospheric centre of the disturbance and the further ionospheric centres; (Figure 2b). For more localised TID, the velocity vector distribution is more “compact” around the first estimated vector.

The main disadvantage of this approach is the dependence on the spatial resolution of the network of receivers used in a detection of TID and their spatial configuration relative to each other (Figure S3). In the “good” case, these receivers are located along the propagation of TID, hence it is detected and characterised in more LOS. In addition, a less dense network could not provide a sufficient number of observations, which leads to underestimations of spatial characteristics of TID. These data gaps could affect the automatic analysis. In addition, these estimations can be affected by the initial forcing of the source of the disturbances. Moreover, even inside one class of TID, sources with different magnitudes (e.g., earthquakes - Mw, volcanic eruptions - VEI) would generate disturbances which propagate to smaller or larger distances (e.g., Astafyeva et al., 2009; Astafyeva & Shults, 2019; Heki, 2022).

Besides, spectral characteristics of TID were also estimated after switching to dTEC/dt. Figure S4 shows TEC data with the CSID signatures produced by the Sanriku earthquake of 9 March 2011. The Fast Fourier Transformation (FFT) procedure can be used in the near real-time since it requires a short series of data and is a reasonably easy and fast procedure to perform. This FFT data is suitable for retrieving the dominant frequencies in the signal, which correspond to a TID. If the Fast Fourier Transformation was applied to the TEC time series, the “slow” periods (< 2 mHz) would dominate in the frequency domain, and it would be impossible to observe signatures of any TID. It is explained by the fact that the amplitude of a trend is more significant than that of TID [Maletckii et al., 2020]. The latter problem is solved by the dTEC/dt procedure, and the methodology is still near-real-time applicable.

However, the spectral components of the dTEC/dt parameter differ from those obtained from the detrended data, because of the effects of the first order high-pass filter. Hence, the frequencies obtained by dTEC/dt approach will be different from the post-processing ones and it is not correct to compare them with one another.

3 Results

Different phenomena and events generate disturbances with different spatio-temporal characteristics because of the difference in physical mechanisms and drivers that impact the ionosphere. Figure 3 illustrates TID signatures driven by various impacts from above and from below. One can see that these disturbances exhibit differences in frequency band/periods of disturbances, amplitudes, waveform type, and duration. Also, previous research works showed that the waveform, propagation speed and the spatial characteristics such as the propagation distance can also differ significantly, depending on the origin of a TID (Table 1).
Table 1. Characteristics of TID generated by different phenomena and events

<table>
<thead>
<tr>
<th>Origin</th>
<th>“Conventional” velocities [m/s]</th>
<th>“Conventional” frequencies [mHz]</th>
<th>Source type</th>
<th>Wavefront type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earthquake</td>
<td>~600–1,500</td>
<td>~3.7 &amp; 4.4</td>
<td>Point source</td>
<td>Concentric Circular waves</td>
</tr>
<tr>
<td>Tsunami</td>
<td>~100–250</td>
<td>~0.5–2.5</td>
<td>Moving extended source</td>
<td>Plane waves</td>
</tr>
<tr>
<td>Volcanic Eruption</td>
<td>~400–500 (the gravity component)</td>
<td>~1 (the gravity component)</td>
<td>Extended point source</td>
<td>Concentric Circular waves</td>
</tr>
<tr>
<td></td>
<td>~600–1,200 (the acoustic components)</td>
<td>~3.7 &amp; 4 (the acoustic components)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tornado</td>
<td>~150–200 (the gravity waves)</td>
<td>~1–1.5 (the gravity waves)</td>
<td>Moving localised source</td>
<td>Concentric Circular waves</td>
</tr>
<tr>
<td></td>
<td>~1,300–1,400 (the short-period oscillation)</td>
<td>~4–4.5 (the short-period oscillation)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rocket launch</td>
<td>~700–1,200</td>
<td>~1.5–4.5</td>
<td>Point source</td>
<td>Concentric Circular waves &amp; Concentric V-shape waves</td>
</tr>
<tr>
<td>Explosion</td>
<td>~800–1,200</td>
<td>~1.5–4.5</td>
<td>Point source</td>
<td>Concentric Circular waves</td>
</tr>
</tbody>
</table>

Therefore, once we learn the features of TID coming from known sources, we create a database, or a “dictionary”, containing the information about characteristics of TID generated by different phenomena. Then, in NRT, we detect TID, we analyse their characteristics in NRT and, by using our predefined dictionary, we can understand their origin (Figure 4). It should be noted that in such an approach, all TID characteristics must be estimated and analysed identically during both the preparation phase and in NRT.

At the first stage, it is necessary to collect a database of different types of TID, with multiple examples for each type, and then to analyse their characteristics. Table 2 presents the list...
of events that we analysed in this work, and cites previous works that studied the ionospheric responses to these events by using a post-processing approach. Figures S5-S11 demonstrate examples of application of our NRT approach to each type of event - earthquake, tsunami, volcanic eruption, tornado, rocket launch and plasma bubble occurrence.

**Table 2. List of Events used for the NRT analysis**

<table>
<thead>
<tr>
<th>Type of event</th>
<th>Events (Time of the Event) [Reference for Retrospective Analysis of Ionospheric Response]</th>
<th>Total Number of LOSes</th>
</tr>
</thead>
</table>
| Earthquake (Onset time, UT)   | - The Chuetsu earthquake (2007-07-16T01:13:22) [Cahyadi & Heki, 2015]  
- The Sanriku earthquake (2011-03-09T02:46:23) [Thomas et al., 2018]  
- The Tohoku earthquake (2011-03-11T05:46:23) [Liu et al., 2011]  
- The Iquique earthquake (2014-04-01T23:46:47) [Shrivastava et al., 2021]  
- The Illapel earthquake (2015-09-16T22:54:33) [Reddy et al., 2016]  
- The Kaikoura earthquake (2016-11-13T11:02:56) [Inchin et al., 2021]  
- The Türkiye earthquake, first (2023-02-06T01:17:00) [Maletckii et al., 2023]  
- The Türkiye earthquake, second (2023-02-06T10:29:00) [Vesnin et al., 2023] | 8,351                 |
| Tsunamis (Approx. arrival time, UT; Arrival region) | - The Tsunami produced by the southern Peru Earthquake (2001-06-24T17:30:00; The east coast of Japan) [Artru et al., 2005]  
- The Tsunami produced by the Mentawai Earthquake (2010-10-25T14:42:22; The west coast of Sumatra in Indonesia) [Manta et al., 2020]  
- The Tsunami produced by the Tohoku Earthquake (2011-03-11T15:30:00; The west coast of Continental US) [Azeem et al., 2017]  
- The Tsunami produced by the Iquique Earthquake (2014-04-01T23:46:47; The coast of Chile) | 19,482                |
<table>
<thead>
<tr>
<th>Event Type</th>
<th>Description</th>
<th>Time/Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tsunami produced by the Illapel Earthquake</td>
<td>(2015-09-16T22:54:33; The coast of Chile)</td>
<td>[Shrivasta va et al., 2016]</td>
</tr>
<tr>
<td>Volcanic Eruptions and Volcanic Explosions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>First Calbuco eruption</td>
<td>(2015-04-22T21:04:00) [Shults et al., 2016]</td>
<td></td>
</tr>
<tr>
<td>Second Calbuco eruption</td>
<td>(2015-04-23T04:00:00) [Shults et al., 2016]</td>
<td></td>
</tr>
<tr>
<td>Fukutoku-Okanoba eruption</td>
<td>(2021-08-13T05:16:00) [Heki &amp; Fujimoto, 2022]</td>
<td></td>
</tr>
<tr>
<td>Hunga-Tonga eruption</td>
<td>(2022-01-15T04:15:00) [Themens et al., 2022]</td>
<td></td>
</tr>
<tr>
<td>Tornadoes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Super Outbreak Tornado</td>
<td>(2011-04-27T18:45:00)</td>
<td></td>
</tr>
<tr>
<td>Joplin Tornado</td>
<td>(2011-05-22T22:35:00)</td>
<td></td>
</tr>
<tr>
<td>Moore Tornado</td>
<td>(2013-05-20T19:35:02) [Nishioka et al., 2013]</td>
<td></td>
</tr>
<tr>
<td>El Reno Tornado</td>
<td>(2013-05-31T23:03:00)</td>
<td></td>
</tr>
<tr>
<td>Rocket Launches and Explosions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Korea Taepodong-2 launch</td>
<td>(2009-04-05T02:30:00) [C. H. Lin et al., 2014]</td>
<td></td>
</tr>
<tr>
<td>SpaceX Falcon 9 JASON-3 launch</td>
<td>(2016-01-17T18:42:18) [C. H. Lin et al., 2017a,b]</td>
<td></td>
</tr>
<tr>
<td>North Korea Kwangmyongsong-4 launch</td>
<td>(2016-02-07T00:30:00) [Chou et al., 2018]</td>
<td></td>
</tr>
<tr>
<td>SpaceX Falcon 9 FORMOSAT-5 launch</td>
<td>(2017-08-24T18:51:00) [Savastano et al., 2019]</td>
<td></td>
</tr>
<tr>
<td>2020 Beirut Explosion</td>
<td>(2020-08-04T15:08:18) [Kundu et al., 2021]</td>
<td></td>
</tr>
<tr>
<td>Tonga Eruption-Explosion</td>
<td>(2022-01-15T04:12:00) [Astafyeva et al., 2022]</td>
<td></td>
</tr>
<tr>
<td>Equatorial Plasma</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015-06-22/23 EPB</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Total Count:**

- Tsunami: 21,068
- Volcanic Eruptions: 21,068
- Tornadoes: 12,788
- Rocket Launches and Explosions: 31,072
- Equatorial Plasma: 2,158
3.1 Earthquakes

Vertical displacements of the ground due to earthquakes can produce disturbances in the ionosphere, known as co-seismic ionospheric disturbances (CSID). The CSID have been extensively studied by using GNSS-sounding and by post-processing approaches (e.g., Calais & Minster, 1996; Afraimovich et al., 2011; Heki and Ping, 2005; Astafyeva, 2019). Their main parameters are summarised in Table 1.

In this work, in order to characterise CSID in NRT scenario, we analysed 8,351 TEC time series containing TEC response to 8 earthquakes of different magnitudes. Figure 5 shows distributions of spatio-temporal characteristics, including the mean (black vertical line) and standard deviation (grey vertical span) values for each type of spatio-temporal characteristics.

Distributions of spatial characteristics (distances between the velocities and the distances between the ionospheric centres) are located close to the CSID source regions. They are concentrated around the first velocities and/or centres and rarely cover distances larger than ~500 km. The mean value of the distances between centres is ~128 km, and the distance between velocities is ~223 km. Generally, for the point source, we expect the last value to be smaller than the first one. However, we used the Tohoku earthquake case for our database, which had two centres of the CSID. Hence, it could affect our estimations.

Frequencies' distribution illustrates that most of the dTEC/dt parameter of disturbances are characterised by values between 2.5-7.5 mHz.

The last panel presents the distribution of velocities. Most velocities have values below ~1.2 km/s, which corresponds well to the retrospective results for the chosen events. This value can be attributed to the acoustic or shock-acoustic waves. However, there are values exceeding 1.8-2 km/s, which exceed the sound speed values at the ionospheric altitudes. Mainly, we obtain such velocities for the Tohoku event. We observed the first vectors with velocities of about 4 km/s for this event. Such values might correspond to the propagation of the primary (P-) seismic waves (i.e., the rupture propagation) or the propagation of the Rayleigh surface waves. These waves are often detected after large earthquakes, Mw >= 7.8 (e.g., the 2002 Denali earthquake, Ducic et al., 2003; the 2011 Tohoku earthquake, Rolland et al., 2011b; the 2012 Haida Gwaii earthquake, Jin et al., 2017; the 2018 Gulf of Alaska Earthquake, Lay et al., 2018).

3.2 Tsunamis

Tsunamis propagating along the surface generate gravity waves that propagate into the atmosphere and ionosphere and induce so-called co-tsunamic ionospheric disturbances (e.g., Occhipinti, 2015; Komjathy et al., 2016; Astafyeva, 2019).
Here we use 19,482 TEC time series from our database to analyse the spatio-temporal features of CTID generated by 5 tsunami events. Figure 6 shows the distributions of their spatio-temporal characteristics, including the mean (black vertical line) and the standard deviation (grey vertical span) values for each type of spatio-temporal characteristics.

In contrast to earthquakes, the travelling tsunami front, especially in the far field, represents an extended source, and not a point source. Consequently, the distributions of CTID spatial characteristics show that CTID covers significantly larger distances. They can propagate up to 1000-1250 km and even farther, depending on the relative position of the GNSS receivers and the CTID wave front. The mean value of the distance between the centres is ~354 km, but there are values up to 1000 km. The mean value of distances between velocities is ~359 km.

Frequencies' distribution illustrates that most of the dTEC/dt variations are characterised by values below 5 mHz, with the most common value below 2.5 mHz. Despite the fact that we obtained these values for dTEC/dt parameter, we note that they correspond to the frequencies of tsunami-driven gravity waves detected in band-passed filtered TEC data in the post-processing.

The distribution of velocities shows the dominance of values under 270 m/s, which is in the range of the known tsunami propagation speeds. Almost ~90% of the velocities are below 500 m/s. The presence of higher values in the distribution can be explained by limitations of our methods. The D1-technique conditions could be violated by such long period/wavelength disturbances. For instance, the distance between the receivers could be smaller than the horizontal dimensions of CTID, or the wavefront could be not plain at all different receivers.

### 3.3 Volcanic Eruptions and Explosions

Disturbances generated by volcanic explosions and eruptions are often referred to as Co-Volcanic Ionospheric Disturbances (CVID). The CVID can be of acoustic and gravito-acoustic origin [Shults et al., 2016; Astafyeva, 2019]. Figure 7 shows distributions of spatio-temporal characteristics of CVID based on analysis of 21,068 TEC data series.

Regarding the propagation distance, CVID are closer to CSID than to CTID, since they have a point or a more “localised” and stationary source (i.e., the ash plume). Spatio- temporal characteristics distributions show that velocities and ionospheric centres are localised well around the first values. However, there are values that identify the disturbances far away from the source, up to 1,500-2,000 km, which are mostly due to the Tonga eruption. However, it should be reminded that the HTHH volcano explosive eruption was an extraordinary geophysical event that generated large-amplitude Lamb waves, in addition to “conventional” shock-acoustic, acoustic and gravity waves. Therefore, most likely, this case has altered the distributions. Further discussion is presented in Section 5. The mean value of the distances between centres is ~302 km, and the distances between velocities are ~759 km.

The distribution of frequencies does not show any pattern. This could be explained by the fact that volcanoes can generate a wide spectrum of atmospheric and ionospheric disturbances, between low frequency (gravity) and higher frequency (acoustic and shock-acoustic) components [Heki, 2006; Dautermann et al., 2009a, 2009b; Nakashima et al., 2016; Shults et al., 2016; Heki &
Fujimoto, 2022]. Also, it should be reminded that we estimate these spectral characteristics for the dTEC/dt parameter, so these results are not directly comparable with band-passed TEC data series. The distribution of velocities shows the dominance of values between 250 and 1,000 m/s, which can also be attributed to gravity and acoustic waves, and it is in agreement with the post-processing results. Higher values in the distribution could be explained by the key assumptions of our methods in the subsequent calculations.

3.4 Tornadoes

Tornadoes can generate gravity waves that further generate quasi-periodic signatures in the ionosphere (e.g., Nishioka et al., 2013). For this source type, we separated the ionospheric response into two groups: gravity waves (in blue) and short-period oscillations (in navy). Figure 8 shows distributions of spatio-temporal characteristics based on analysis of 12,788 time series.

As in the case of CTID, the source of tornado-driven TID is a moving one. The formation, initial intensification, weakening and dissipation were in the different areas for all the events in our database. Hence, we observed TID over a large region, which corresponds well to the obtained distribution of spatial characteristics. Despite having a lower mean value for the velocities (~427 km vs. ~591 km), the ionospheric centres of TID generated by gravity waves were detected farther than those of TEC short-period oscillations (~393 km vs. ~329 km). Our results could be explained by the fact that the gravity waves are concentric, which better fits the assumption used for estimating the ionospheric centres in the far field of the source.

In addition, these two types of responses have different distributions of frequencies: gravity waves have lower values than short-period oscillations.

The distribution of velocities shows explicitly the split between the fast and the slow variations. The mean value of the velocity of gravity waves is ~226 m/s, and of short-period waves is ~1,400 m/s, which is in agreement with post-processing results [Nishioka et al., 2013]. These results validate the demarcation of the response to tornadoes into two groups because they have entirely different spatio-temporal characteristics.

3.5 Rocket Launches and Explosions

We combined these types of sources in one because of the similar physical mechanism. Therefore, they should have similar spatio-temporal features.

To characterise these TID, we analysed 31,072 time series. Figure 9 shows distributions of spatio-temporal characteristics. We should expect this source type to be a nearly point one, which agrees well with the distributions of spatial characteristics. The distribution of the centres shows that 100% of the obtained locations of the ionospheric source of disturbances are under 250 km from the first estimations, with the mean value of ~89 km. However, the distribution of the velocities demonstrates its propagation of TID to further distances. We obtained velocities up to ~500 km, with the mean value of ~139 km.
Distribution of temporal characteristics illustrates that ~70-75% of values have frequencies below 7.5 mHz. The lower values can be attributed to the plasma hole generated by the emission of the rocket, while the higher ones - to the shock-acoustic waves produced by the explosions or/and the rocket engine.

The distribution of velocities shows the dominance of values ~1,500 m/s, which can also be attributed to the acoustic and shock-acoustic waves. About 50% of them are between 600-1,200 m/s, having the mean value of about 1,080 m/s, which is in agreement with retrospective results.

3.5 Equatorial Plasma Bubbles

We consider Equatorial Plasma Bubbles to be non-conventional TIDs that can create an apparent propagation effect. The EPB occur quite often at low latitudes in the post-sunset region, therefore, one can easily collect data series containing this type of disturbance. Here, we analysed 2,158 time series. Figure 10 shows distributions of spatio-temporal characteristics.

The apparent effect of EPB is challenging to interpret and even to analyse, because its manifestation in the ionosphere depends on a wide range of factors. Generally, we observe them after the sunset. Hence, we should expect them to occur after the solar terminator, which would create an apparent effect with corresponding velocities. However, magnetic and thermospheric activities play an important role in EPB generation and their spatio-temporal characteristics.

The distribution of the distances between velocities shows that they “propagate” to a limited area. However, the distribution of the distances between the centres demonstrates that this type of disturbance should not be considered as a point source. Indeed, we should expect disturbances around the whole front of the solar terminator in the equatorial area.

The distribution of temporal characteristics illustrates the very fast changes in the dTEC/dt parameter. These values vary significantly from the ones of conventional TID.

For the velocities, we should expect values between ~90-130 m/s [Tsunoda et al., 1982; Abdu et al., 2003; Huba & Joyce, 2010; Huang & Hairston, 2015; Abdu, 2019]. However, the velocities distribution shows that most values are in the range below 500 m/s, with a mean value of ~243 m/s. One of the possible explanations can be the limitations of our methods of estimations, which needed to be adapted to analyse this type of disturbance.

3.6 NRT Clustering of TID

We use the previously obtained four spatio-temporal characteristics to create 6 unique pairs of their combinations in order to cluster TID depending on their sources. We use the mean (as a centre position of the ellipse) and half of standard deviations (as a width/height of the ellipses) of distributions to locate a particular type of disturbance (as an ellipse; Figure S12).

Figure 11 shows all possible combinations of TID characteristics and positions of different TID classes based on their distributions. The best TID origin discrimination results are obtained by using velocities (panels a-c). These results again emphasise the importance of developing methods of estimations of velocities of ionospheric disturbances in NRT. There is only one small
intersection of types of TID between rocket launches/explosions and earthquakes. This can be explained by the resemblance of spatio-temporal characteristics (e.g., velocities, frequencies) of acoustic waves that generate TIDs associated with these types of sources (Table 1). However, they can be separated by the spatial characteristics, since TIDs of rocket launches/explosions propagate to shorter distances compared to CSIDs.

The spatial characteristics agree well with post-processing results: the ionospheric disturbances due to gravity waves propagate to larger distances compared to acoustic and shock-acoustic waves; the point source approximation performs better for earthquakes, rocket launches/explosions, resulting in shorter distances between the first estimated ionospheric centre of the disturbance and the further ionospheric centres. We conclude that TIDs with extended sources share the similar “trend” of spatial characteristics - the mean values of distributions of distances between the velocities are close or almost equal to the mean values of distributions of distances between the ionospheric centres. However, for the localised sources, the mean values of distributions of distances between the velocities are higher than the mean values of distributions of the distances between the centres. In addition to this feature, the moving point sources have less localised values compared to the not-moving point sources. These comparisons between the degree of localisation of centres and velocities can be used to discriminate types of the source of TIDs. These evaluations justify the chosen approach to characterise spatial properties even despite the fact that the spatial resolution of the used GNSS network affects the obtained results.

4 Application of the NRT source identification methods for ionospheric disturbances generated by the 2024 Noto Earthquake.

On January 1, 2024, at ~07:10 UT, a Mw 7.5 earthquake struck 6 km north-northeast of Suzu, located on the Noto Peninsula of Ishikawa Prefecture, Japan. This event led to Japan's first major tsunami warning since the 2011 Tōhoku earthquake, and a 6.58 m tsunami along the Sea of Japan coast (by the Japanese Meteorology Agency, https://www.jma.go.jp/jma/en/2024_Noto_Peninsula_Earthquake/index.html). According to the US Geological Survey (The National Earthquake Information Center (NEIC); http://earthquake.usgs.gov), the epicentre of this earthquake was located at 37.488°N and 137.271°E.

Animation S1 (supplementary material) presents the evolution of ionospheric TEC disturbances obtained by using all available satellites and all receivers of the Japanese GEONET data. The first signature of CSID is seen at ~07:18-07:19 UT, i.e. 8-9 minutes after the main shock. However, the ionosphere is characterised by a series of disturbances of different nature observed simultaneously to CSID related to the earthquake. This emphasises, once again, the difficulty of distinguishing the source of TID task, especially in NRT.

Figure 12 shows the timeline for the NRT detection, characterization and source identification for ionospheric disturbances generated by the Noto earthquake. Based on the sound
speed profile (Figure 12a), the CSID would take ~8.5 minutes to reach the altitude maximum ionization altitude of 300 km (according to IRI-2016 [Bilitza et al., 2017], red line) and to ~250 km according to the JJ433 ionosonde, green line). The earliest instantaneous velocity fields are estimated at 07:19:30-07:20:00 UT, i.e. 9.5-10 min after the earthquake onset time (Figure 12b, blue arrows). In the NRT scenario, they are estimated to be about ~1.2-1.3 km/s, which correspond to acoustic waves. Further, 12-15 min after the earthquake onset time, our methods place the Noto EQ driven disturbances very close to other previous earthquakes (Figure 12c). We chose this combination of spatio-temporal characteristics as the earliest to construct in the NRT scenario. This timing is very close to the time when the Japan Meteorological Agency (JMA) issued the first tsunami warning.

As shown before, coseismic ionospheric disturbances can be used in future for estimations of magnitude, seismic fault dimensions and for the localisation of the source [Heki, 2006; Afraimovich et al., 2006; Liu et al., 2010; Astafyeva et al., 2011; Astafyeva et al., 2013a,b; Cahyadi & Heki, 2015; Shults et al., 2016; Manta et al., 2020; Maletckii & Astafyeva, 2021]. These characteristics are crucial earthquake parameters that are needed to evaluate its tsunamigenic potential. Hence, in the near-field of tsunami, like in this case or the 2011 Tohoku-oki earthquake, it is absolutely necessary to first automatically detect, identify, and, then, characterise the ionospheric response to CSID in NRT. The usage of high-rate 1-sec data can shorten the time of the discrimination of the source to 10 minutes, which shows a great potential for Tsunami Early Warning Systems based on the ionospheric data or to make more reactive and precise already existing ones.

5 Discussions. Conclusions. Future work.

In this work, we presented the first and preliminary results of identification of TID origin in NRT based on their spatio-temporal characteristics. Our work opens opportunities and is the first step toward building an NRT Automatic Global Detector-Distinguisher of ionospheric disturbances of different origins. However, a series of adjustments are yet to be made in the methodology to solve this fundamental scientific challenge. The following improvements can be suggested in this direction:

- enlargement of the database of events;
- diversification of some types of a source into more specific subgroups;
- adding other TID characteristics for the discrimination task.

The database enlargement will help to minimise possible outliers in the distribution of the spatio-temporal characteristics. It reduces the biases, variances, and the possibility of an influence of random fluctuations in one case of a specific type of source. It can improve the validity and generalizability of the analysis.

A more complete database would also allow to separate some types of events into more subgroups:
- Explosive volcanic eruptions and effusive volcanic eruptions should be separated, since they produce different types of atmospheric waves. Explosive eruptions are more violent
and produce hazardous flows, fast-moving hot gas and ash mixtures that can travel up to hundreds of kilometres per hour. They also send ash high into the atmosphere, forming plumes that can affect it. Explosive eruptions are usually associated with more viscous magma with a higher gas content [Fisher et al., 1997; Sigurdsson et al., 1999; Scarth, 1999]. These magmas tend to trap the gas bubbles within them, creating a high pressure that eventually leads to a violent explosion, which makes them closer to the general explosion/rocket launch type of source of TID in terms of the spatio-temporal characteristics. This evaluation applies especially to explosive eruptions with VEI >= 5. Effusive eruptions, on the other hand, are less powerful; they generate gravito-acoustic waves with quasi-periodic waveforms.

- Disturbances generated by rocket launches can be divided into shock-acoustic waves by the booster trajectory and Plasma depletions by the emission of the exhaust plume. These two types of signatures have quite different physical mechanisms and, therefore, different parameters. Generally, shock-acoustic and acoustic waves are more common/standard responses, while plasma depletion would only appear in the case of rocket fuel that leads to the injection of large amounts of neutral molecules in the ionosphere [Furuya & Heki, 2008; Ozeki & Heki, 2010].

- Our current database does not contain ionospheric disturbances generated by geomagnetic storms. Storm-time intense Joule heating and auroral particle precipitation in the auroral zone are known to generate TID of different scales (e.g., Richmond, 1978; Ho et al., 1996; Nicolls et al., 2004; Shiokawa et al., 2007; Borries et al., 2015; Pradipta et al., 2016; Zhou et al., 2016; Zakharenkova et al., 2016; Cherniak & Zakharenkova, 2018; Jonah et al., 2018; Pradipta et al., 2023).

- Finally, the current “earthquakes” group could be discriminated into Earthquakes and Rayleigh waves, if the amount of data related only to ionospheric disturbances generated by earthquakes is sufficiently vast. However, finding ionospheric signatures of Rayleigh wave propagation will be more challenging because it is a rarer phenomenon in the ionosphere [Ducic et al., 2003; Astafyeva et al., 2009; Rolland et al., 2011; Maruyama et al., 2012; Jin et al., 2017; Lay et al., 2018; Liu & Jin, 2019].

Besides, an extended database could also help to examine more TID features for the clustering. In our work, we used only four spatio-temporal characteristics to identify the source of the disturbances. These characteristics were considered for the discrimination task based on the previously known fact that the chosen sources of disturbances should show variability in them. However, we can extract more features from the TEC time series, spectra, and spectrograms in NRT. Brissaud & Astafyeva (2022) analysed 46 features commonly used for signal classification tasks (e.g., Hammer et al. 2013; Hibert et al. 2014; Wenner et al. 2021). Not all of them can be used for the discrimination and classification, because a series of these features showed a correlation, which means they would provide similar results. However, it would be a significant upgrade from only 4 characteristics used in this work.
Further, unfortunately, our TEC time derivative approach cannot automatically detect disturbances produced by solar eclipses, gravity waves driven by typhoons, lower atmosphere events, hurricanes and solar terminator [Vadas, 2007; Vadas & Liu, 2009; Afraimovich, 2009; Perevalova & Ishin, 2011; Polyakova & Perevalova, 2013; Chou et al., 2017; Zhang et al., 2019]. Most of them are characterised by the long-period TEC variations, which are almost entirely removed after applying the TEC derivative procedure. Hence, new more sophisticated methods that will detect other TID with smaller dTEC/dt, amplitude and longer periods, are necessary. The AIDE algorithm developed by Brissaud & Astafyeva (2022), does not have amplitude or dTEC/dt limitations, and it currently captures CSID, but also disturbances driven by volcanic eruptions, and tornadoes. The algorithm is currently being improved and will further be upgraded in order to better perform on different kinds of disturbances. Once the detection is done by the AIDE, spatio-temporal characteristics can be estimated by our techniques.

Our developments are crucial for the future NRT assessment of natural hazards from the ionosphere and for NRT Space Weather applications. The latter aim at nowcasting and forecasting solar-terrestrial interactions on the ionosphere and upper atmosphere that may seriously impact technology. TIDs are known to severely affect the propagation of radio-signals and they often lead to disruption of radio-communication and degradation of precise positioning applications. Therefore, it is utterly important to be able to detect such ionospheric disturbances and to forecast their propagation. In this regard, our methods already provide a very valuable contribution to this applicative domain since they reliably detect small- and medium-scale TID with high TEC derivative that are the most threatening for the propagation of radiowaves.

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Open Research

CDDIS GNSS data are available from the CDDIS data archives (https://cddis.nasa.gov/archive/gnss/data/daily/). UNAVCO GNSS data are available from the UNAVCO data archives (https://data.unavco.org/archive/gnss/rinex/obs). UNAVCO GNSS data are available from the UNAVCO data archives (https://data.unavco.org/archive/gnss/rinex/obs). CORS GNSS data are available from the CORS data archives (https://data.unavco.org/archive/gnss/rinex/obs/). The Japan GNSS data are available from the GeoSpatial Authority of Japan (GSI, http://datahouse1.gsi.go.jp/terras/terras_english.html). New Zealand GNSS data are available from the Geological Hazard Information for New Zealand (GeoNet) database (https://data.geonet.org.nz/). The South America West Coast data are available from the Centro Sismológico Nacional Universidad de Chile data archives
Figures 3-12 and S4-12 were plotted by using Python (ver. 3.7, libraries “matplotlib.pyplot”: https://matplotlib.org/3.5.0/api/_as_gen/matplotlib.pyplot.html and “cartopy”: https://scitools.org.uk/cartopy/docs/latest/).


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plasma irregularities during the 17–18 March 2015 event, J. Geophys. Res. Space Physics,
Figure 1. Scheme explaining the concept and temporal resolution requirements for TID analysis in NRT by our definition. The Real-Time (RT) block corresponds to the Technical/Engineering part of an automatic Detector-Distinguisher of Ionospheric Disturbances. It consists of RT collection of GNSS phase data and orbit parameters. NTRIP could be used to provide the real-time dual-frequency phase and pseudo-range data stream from GNSS stations [GNSS Science Support Centre, 2020]. RTKLib software could be used to convert binary information from NTRIP data streams [Takasu, 2013]. The International GNSS Service (IGS) ultra-rapid orbit is used to obtain the information about the elevation angle and the azimuth [Noll et al., 2010]. The examples of such local and global RT products are given: Hernández-Pajares et al. [2009], Savastano et al. [2017], Liu et al. [2021], Cesaroni et al. [2021], Ravanelli et al. [2021], Yasyukevich et al. [2022], Martire et al. [2023]. The NRT block corresponds to the analysis part of an automatic Detector-Distinguisher of Ionospheric Disturbances. It consists of methods for the automatic detection and characterization in NRT (the 1-sec and 30-sec D1-GNSS-RT [Maletckii & Astafyeva, 2021, 2022], the NRT TTD fitting technique [Maletckii & Astafyeva, 2022]), and an automatic approach allowing to discriminate the TID origin in NRT based on the distributions of spatio-temporal characteristics obtained by using dTEC/dt and automatic methods.

Figure 2. Scheme explaining spatial characteristics of TID. a) Distance between the first estimated instantaneous velocity of the disturbance and the further instantaneous velocities. b) Distance
between the first estimated ionospheric centre of the disturbance and the further ionospheric centres

**Figure 3a.** Examples of TID signatures driven by different sources. The list of the sources includes (from top to bottom) earthquakes, rocket launches, volcanic eruption, tsunamis and plasma bubble.
Figure 3b. Examples of the TID signatures in dTEC/dt data driven by different sources. The list of the sources includes (from top to bottom) earthquakes, rocket launches, volcanic eruption, tsunamis and plasma bubble.
Figure 4. Scheme illustrating the concept of the suggested automatic NRT Detector-Distinguisher of TID.
Figure 5. The distribution of spatio-temporal characteristics of ionospheric disturbances produced by earthquakes (CSID). Panels from top to bottom: the distances between the first estimated ionospheric centre of the disturbance and the further ionospheric centres; the distances between the first estimated instantaneous velocity of the disturbance and the further instantaneous velocities; the dominant frequencies in the dTEC/dt time series; the instantaneous velocities. The
black vertical line depicts the mean value, and the grey vertical span - standard deviation for each parameter.
Figure 6. The distribution of spatio-temporal characteristics of ionospheric disturbances produced by tsunamis.
Figure 7. The distribution of spatio-temporal characteristics of ionospheric disturbances produced by volcanic eruptions.
Figure 8. The distribution of spatio-temporal characteristics of ionospheric disturbances produced by tornadoes.
**Figure 9.** The distribution of spatio-temporal characteristics of ionospheric disturbances produced by rocket launches and explosions.

a) 

b) 

c) 

d) 

- Mean: 89.260, STD: 56.274
- Mean: 138.998, STD: 111.147
- Mean: 4.415, STD: 3.084
- Mean: 1079.940, STD: 487.019
Figure 10. The distribution of spatio-temporal characteristics of ionospheric disturbances produced by equatorial plasma bubbles.
**Figure 11.** Clustering of ionospheric disturbances driven by six sources based on their spatio-temporal features. We analyzed the following six combinations: a) the dominant frequencies - the instantaneous velocities; b) the distance between the ionospheric centres - the instantaneous velocities; c) the distance between instantaneous velocities - the instantaneous velocities; d) the distance between the ionospheric centres - the dominant frequencies; e) the distance between instantaneous velocities - the dominant frequencies; f) the distance between instantaneous velocities - the distance between the ionospheric centres. The centres of ellipses are the mean values of the given type of TID, and the width/height of the ellipses are half of the standard deviation of the given type of TID. EA - earthquakes (in red), VE - volcanic eruptions (in orange), TR\_GW - gravity waves generated by tornadoes (in blue), TR\_Osc - oscillations generated by tornadoes (in navy), BU - plasma bubbles (in grey), RL+EXP - rocket launches and explosions - explosions (in yellow), TS - tsunamis (in green).
Figure 12. The timeline for the automatic NRT analysis of ionospheric disturbances generated by the 2024 Noto earthquake: a) the sound speed profile (blue) for the time and the location of the earthquake’s epicenter and the average velocity of acoustic wave to reach hmF2 estimated based on the IRI-2016 model (300 km, red line) and the JJ433 ionosonde (250 km, green line), respectively. The empirical NRLMSISE-2 model was used to compute the sound speed profile [Emmert et al., 2020]; b) the first instantaneous velocities obtained by using the D1-GNSS-RT method in the NRT scenario. The grey arrow corresponds to 1.1 km/s velocity, the blue arrows - obtained velocities of TID, the red star depicts the epicentre of the earthquake; c) NRT clustering of TIDs generated by the Noto earthquake (in purple) in the distance between instantaneous velocities (y-axis) - the instantaneous velocities (x-axis) coordinate system (similar to Figure 10c). The transparent ellipses show the width/height of standard deviations. The timeline on the bottom shows the timing of the main steps of TID detection and characterization during this earthquake. We note that the first tsunami warning was issued by the JMA ~12 min after the earthquake.
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Additional Supporting Information (Files uploaded separately)

Animation S1
Animation S2
Animation S3

Introduction

The supplementary material consists of Figures S1-S12 and the List of References.

Figures S1-S2 present the scheme how to build a Travel Time Diagram and use it for the velocity slope fitting technique.

Figure S3 shows the scheme of dependence of spatial GNSS network - TID configuration on obtained results.

Figure S4 demonstrates the CSID signatures by the Sanriku earthquake of 9 March 2011. Panel (e) presents slant TEC. The time series start 2.8 minutes before the detection of CSID. Panel (c) illustrates the dTEC/dt parameter computed based on
the panel (e) data. Panel (d) shows the detrended TEC variations by sixth order polynomial fitted in TEC data from the panel (e) data. The signatures are characterized by the initial fast growth of the TEC in a short period and then continued by the significant depletion (i.e., N-shape signal). Panel (a) presents the Fast Fourier Transformation (FFT) of the dTEC/dt parameter from panel (c) and panel (b) presents the FFT of the detrended TEC variations from panel (d).

Figures S5-S11 present examples for each type of event that can be detectable by the dTEC/dt approach. The first panels show the GNSS network used for the analysis of a particular case. We show the cases of TID generated by:

- the 2011 Great Tohoku earthquake (Figures S5-S6);
- the tsunami produced by the 2011 Great Tohoku earthquake on the West Coast of Continental Coast of the US (Figure S7);
- the 2022 Tonga Hunga eruption (Figure S8);
- the 2011 Moore tornado (Figure S9);
- the 2016 SpaceX Falcon 9 Jason-3 launch (Figure S10);
- equatorial plasma bubbles during the 22-23 June 2015 Geomagnetic Storm (Figure S11)

Figure S12 shows how to locate a particular type of the source in a coordinate system based on the spatio-temporal characteristics.

Animation S1 illustrates TEC variations during the 2024 Noto Peninsula Earthquake. Animation S2 demonstrates the instantaneous velocity fields for the CSID detected after the 2024 Noto Peninsula Earthquake. Animation S3 presents the obtained ionospheric centers for the CSID detected after the 2024 Noto Peninsula Earthquake. The first estimation provides the point source, while later we obtain the location of the CSID circular wavefront that acts as a secondary source.

**Figures**
Figure S1. Scheme explaining the concept of a TTD. The disturbance is plotted in colour with respect to the time after the source onset (X-axis; \( t_0 \) – the onset time, \( t_1, t_2, t_3 \)) and distance from the source (Y-axis; Dist\(_0 \) – the location of the source, Dist\(_1\), Dist\(_2\), Dist\(_3\)).
**Figure S2.** Scheme explaining the concept of the NRT TTD velocity slope (in grey) fitting technique. The first maximum “picker” conditions are presented in the green box below the NRT TTD, the “maxima fitter” conditions are shown to the left of the NRT TTD.

\[ 1/\cos(\alpha_i) = v_i \]

1. \( 0.1 < v_i < 5 \text{ km/s} \)
2. \( \frac{|v_i - v_{i-1}|}{v_i} \leq 20\% \)
3. \( \frac{|v_{av} - v_i|}{v_{av}} \leq 50\% \) for \( i > 8 \)

where, \( v_{av} = \frac{|d_i - d_0|}{|t_i - t_0|} \)

**Figure S3.** Scheme explaining the importance of a “favourable” spatial GNSS network - TID configuration. The GNSS network in both cases consist of 10 receivers over the similar area of observations (lat\(_1\), lon\(_1\); lat\(_2\), lon\(_2\)).
Figure S4. The Fast Fourier Transformation of (a) the dTEC/dt parameter and (b) detrended TEC, (c) the dTEC/dt parameter, (d) the detrended TEC and (e) slant TEC by using data from the G07 satellite for the CSID produced by the Sanriku earthquake of 9 March 2011.
Figure S5. a) Map of the Tohoku Earthquake (red star, 38.3°N; 142.3°E) and GNSS receivers (yellow dots) network. Map background was produced by using Blue Marble: Next Generation by Reto Stöckli, NASA Earth Observatory (NASA Goddard Space Flight Center) [Stöckli et al., 2006]; b) Examples of the dTEC/dt approach application results on the Great Tohoku-oki Earthquake. The instantaneous velocity
fields were calculated from the first CSID detected by GPS satellite PRN 26 after the Tohoku earthquake. The dotted curve shows the position of the Japan Trench; the black star depicts the epicentre. The gray arrow corresponds to 1.1 km/s. c) Examples of the dTEC/dt approach application results on the Great Tohoku-oki Earthquake. The localization of the seismic source is estimated from the first velocity vectors shown in the red dots. Adapted from: Maletckii and Astafyeva [2021]

**Figure S6.** Examples of the dTEC/dt approach application results on the Great Tohoku-oki Earthquake. The NRT-TTD panels show the TTD build by using dTEC/dt parameter: on panel (b), the distance is calculated with respect to the earthquakes’ epicentres as estimated by the USGS (shown on panel a as a black star); on panel (c) — with respect to the ionospheric localization (shown on panel a as a red dot). The colour scale is shown on the top. Adapted from: Maletckii and Astafyeva [2021]
Figure S7. a) NOAA National Geophysical Data Center's map of tsunami arrival time (in hours) during the 2011 Japan tsunami (http://www.ngdc.noaa.gov/hazard/11mar2011.html) b) GNSS receivers (yellow dots) network used for the tsunami produced by the Tohoku Earthquake on the west coast of Continental US. Map background was produced by using Blue Marble: Next Generation by Reto Stöckli, NASA Earth Observatory (NASA Goddard Space Flight Center) [Stöckli et al., 2006] c) The instantaneous velocity fields calculated from the co-tsunamic ionospheric disturbances detected by GPS satellite PRN 22. The gray arrow corresponds to 0.1 km/s; d) The localization of the ionospheric centres is estimated from the velocity vectors shown in the blue dots.
Figure S8. **a)** map depicting the position of the Hunga Tonga volcano (red star, 175.382 W; 20.53S) and GNSS receivers (yellow dots). The map background was produced by using Blue Marble: Next Generation by Reto Stöckli, NASA Earth Observatory (NASA Goddard Space Flight Center) [Stöckli et al., 2006]; **b)** Example of dTEC/dt approach application to the Tonga eruption. The first instantaneous velocity field was obtained by the "D1-GNSS-RT." The gray arrow denotes the velocity vector of 1,000 m/s. The blue arrows correspond to the instantaneous velocities' field of
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**Figure S9.** a) Map showing the Moore Tornado origin (red star, 35.3° N; 97.7° W) and GNSS receivers (yellow dots). The map background was produced by using Blue Marble: Next Generation by Reto Stöckli, NASA Earth Observatory (NASA Goddard Space Flight Center) [Stöckli et al., 2006]; b) Example of the results of dTEC/dt approach application to the May 2013 Moore Tornado. The slant TEC time series
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Figure S10. a) The SpaceX Falcon 9 Jason-3 launch (Vandenberg Air Force Base - red star, 34° N; 120° W) and GNSS receivers (yellow dots) network. Map background was
produced by using Blue Marble: Next Generation by Reto Stöckli, NASA Earth Observatory (NASA Goddard Space Flight Center) [Stöckli et al., 2006]; **b)** Example of the dTEC/dt approach application to the analysis of the SpaceX Falcon 9 JASON-3 launch. Slant TEC time series was obtained using the satellite PRN R19 and multiple stations. **c)** dTEC/dt data plotted based on the panel (b) data. **d)** The NRT-TTD was plotted by using dTEC/dt parameter with respect to the launch location. The vertical grey line is the onset time of the event. The vertical grey box highlights the response produced by the launch.
**Figure S11.**  
**a)** GNSS receivers (yellow dots) network used for the EPB in the equatorial regions of Southern/Mediterranean Europe and Northern Africa. Map background was produced by using Blue Marble: Next Generation by Reto Stöckli, NASA Earth Observatory (NASA Goddard Space Flight Center) [Stöckli et al., 2006];  
**b)** Example of the results of dTEC/dt approach application to the Equatorial Plasma Bubbles. Slant TEC time series obtained by using the satellite PRN G32 and the station “mas1”;  
**c)** dTEC/dt data plotted based on panel (b) data;  
**d)** The NRT-TTD was plotted using the dTEC/dt parameter by the satellite PRN G32 concerning the solar terminator location.

**Figure S12.** An example based on spatio-temporal characteristics of Co-Tsunamic Ionospheric Disturbances how to use the mean (as a center position of the ellipse, black lines) and standard deviations (as a width/height of the ellipses, gray spans) of distributions to locate a particular type of disturbance (as an ellipse, in green). 
Upper panel - distribution of frequencies, right panel - distribution of velocities. Center panel corresponds to the spatio-temporal coordinate system based on these distributions.

**Animation S1.** Evolution of TEC variations (in color) observed during the Noto Peninsula 2024 Earthquake. All satellites and all receivers of the Japanese GEONET data were used. We utilized a 6th order polynomial to detrend vTEC and retrieve TEC variations. The cut-off of elevation angle is 20°. The gray shadow corresponds to
the solar terminator, the magenta star depicts the earthquake epicenter, the green lines show the iso-distances at 150, 350, and 550 km from epicenter.

**Animation S2.** Evolution of the instantaneous velocities for CSID after the 2024 Noto Peninsula Earthquake. All satellites and all receivers of the Japanese GEONET data were used. The gray arrow corresponds to 1.1 km/s velocity, the blue arrows - obtained velocities of CSID, the red star depicts the epicentre of the earthquake.

**Animation S3.** Evolution of the obtained ionospheric centers of CSID during the 2024 Noto Peninsula Earthquake. All satellites and all receivers of the Japanese GEONET data were used. The blue squares - ionospheric centers of CSID, the red star depicts the epicentre of the earthquake.

**Supporting Information References**

