The 2021 volcanic eruption in La Palma Island and its impact on ionospheric scintillation as measured from GNSS reference stations, GNSS-R, and GNSS-RO

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Abstract. Ionospheric disturbances induced by seismic activity have been studied in the last years by many authors, showing an impact both before and after the occurrence of earthquakes. In this study, the ionospheric scintillation produced by the 2021 La Palma volcano eruption is analyzed. The "Cumbre Vieja" volcano was active from September 19th to December 13th, 2021, and many magnitude 3-4 earthquakes were recorded, with some of them reaching magnitude 5. In this study the three

5   methods: GNSS reference monitoring, GNSS Reflectometry (GNSS-R) from NASA CYGNSS, and GNSS Radio Occultation (GNSS-RO) from COSMIC and Spire constellations, are used, allowing us to compare and evaluate their performance in the same conditions. To compare the seismic activity with ionospheric scintillation, earthquakes' generated energy, and percentile 95 of the intensity scintillation parameter (S_4), measurements have been computed every 6 h intervals for the whole duration of the volcanic eruption. GNSS-RO has shown the best correlation between earthquakes' energy and S_4, with values up to 0.09

10   when the perturbations occur around 18 h after the seismic activity. GNSS reference monitoring stations data also shows some correlation 18 h after and 7-8 days after. As expected, GNSS-R is the one that shows the smallest correlation, as the ionospheric signatures get masked by the signature of the surface where the reflection is taking place. Additionally, as expected as well, the three methods show a smaller correlation during the week before earthquakes.

1 Introduction

15   Ionospheric disturbances such as scintillation constitute a notable problem for satellite communications, global navigation satellite systems (GNSS), and Earth observation systems, notably at P and L-bands. They can disturb the signals making it difficult or even impossible to transmit the correct information through the ionosphere. Nevertheless, they can also be seen as an opportunity to detect, measure or infer other physical phenomena, not necessarily related to the ionosphere itself. For example, in the last decades, several studies have shown that ionospheric disturbances can occur during solar eclipses Das et al.

20   (2022), or geomagnetic storms Ding et al. (2007); Li et al. (2008), which are due to causes external to the Earth, coming from the Sun or near space weather.

In addition, other "internal" causes have recently shown that they can impact the ionosphere too. There are studies relating severe atmospheric phenomena such as cyclones or hurricanes to ionospheric anomalies Ke et al. (2019); Xu et al. (2019); Kamogawa (2006). Anomalous variations in the Total Electron Content (TEC) and peaks in the ionospheric scintillation have been detected during the passage of a large cyclone or hurricane, which creates gravity waves that couple to the lower iono-sphere, yielding to ionospheric disturbances.

Another source of perturbations in the ionosphere is related to the lithosphere, and the seismic activity, as supported by many studies that are being published in the last years Kamogawa (2006); Pulinets et al. (2021); Molina et al. (2021); Pulinets and Davidenko (2014); Molina et al. (2022); Liu et al. (2004); Pulinets (2004). The physical mechanisms behind this interaction are still not very clear, but there are several research paths open. Some of them explain this interaction by the generation of low-frequency electromagnetic signals from the underground rock under huge pressures during the earthquake preparation period. Other authors explain the interaction by changes in the surface electric potential due to the piezoelectric effect in the underlying rocks, which can induce changes in the ionosphere's TEC.

This study looks for ionospheric anomalies related to the seismic activity generated by a recent volcano eruption on the Spanish island of La Palma (Canary Islands). In the past, other studies have analyzed the impact of volcanic eruptions on the ionosphere De Ragone et al. (2004); Shults et al. (2016); Astafyeva (2019); Yong-Qiang et al. (2006). For example, the recent Tonga submarine eruption on January 12th 2022 created traveling ionospheric disturbances (TID) from the eruption site Themens et al. (2022). In this case, the eruption was so strong that the gravity waves generated within the atmosphere traveled to the ionosphere, and then propagated concentrically all around the globe producing these perturbations. The La Palma eruption that happened last year, wasn't as explosive as the Tonga one, but it was much longer in time, and it had significant seismic activity associated with it.

1.1 The September 2021 "Cumbre Vieja" Volcanic eruption in La Palma (Spain)

La Palma is a volcanic island located in the North West of the Canary Islands archipelago (Spain) in the Atlantic Ocean, at ~500 km from the coast of Africa. The island has a relatively low volcanic activity with only 5 eruptions in the last century, and 7 in the last 500 years, even though it is one of the islands in the archipelago with the highest potential risks Fernández et al. (2021).

The last eruption started at 13:43 UTC on September 19th, 2021, near the former volcano "Cumbre Vieja", and it lasted for 85 days until December 13th, 2021, when it was declared finished.

Preceding the eruption, for 8 days since September 11th a series of earthquakes were registered in the region where the eruption took place. There were around 6000 earthquakes with magnitudes from 1 mbLg to 3.8 mbLg and decreasing depths from 15 km to almost the surface, and their epicenters were getting closer to the eruptive cone. mbLg is the magnitude unit used by the IGN (IGN) to characterize the earthquakes on the island. The evolution of the position and depth of this preparation earthquake swarm can be observed in Fig. 1.
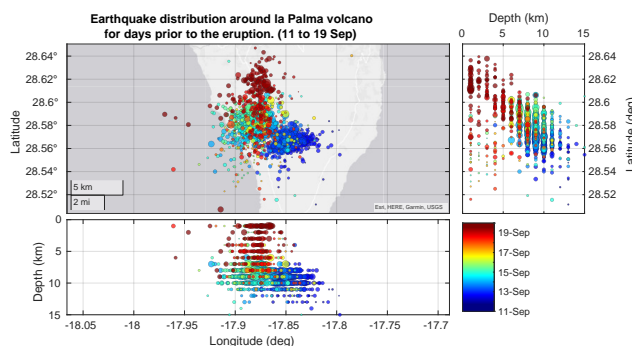
Figure 1. Series of earthquakes preceding the volcanic eruption from September 11th, indicating their position, depths and date.

During the 10 days following the start of the eruption, while the lava, gasses, and ashes were being expelled from the volcano,

55 the seismic activity was relatively low. At the begging of October, around 15 days after the start of the eruption, the seismic

activity increased again and remain stable until the end of the eruption, which was declared to be on December 13th.

2 Data sources and methods

This study is focused on the simultaneous analysis of several sources of data measuring the ionospheric scintillation with GNSS

signals and correlating them with the seismic activity related to the eruptive event in La Palma in 2021.

60 The same physical mechanism is involved in the three techniques used to measure the ionospheric scintillation through

GNSS signals, and it is based on the fact that in the ionosphere, when the electron density is perturbed, the propagation of

electromagnetic waves gets affected, in particular in the GNSS bands and at lower frequencies.

Ionospheric scintillation refers to the rapid fluctuations in phase and/or intensity of the electromagnetic signal received after

crossing the ionosphere. From now on, the study will be centered only on the intensity, also called "amplitude scintillation".

65 The three ways of measuring this ionospheric amplitude scintillation with GNSS signals are: (1) by static ground-based GNSS

reference monitoring, (2) by GNSS-R (GNSS Reflectometry), and (3) by GNSS-RO (GNSS Radio Occultation). The novelty

and interest of this work is the analysis of the effects that the same physical phenomenon, a volcanic eruption, produces in the

ionosphere, as observed by three different techniques measuring the same magnitude at the same frequency.

2.1 Ground stations data

70 Since the appearance of GNSS, ground-based monitoring GNSS stations have been operating and continuously monitoring the

signals emitted by these satellites. GNSS monitoring ground station networks have been sensing the behavior of the ionosphere

for many years, providing TEC and scintillation data required to make the ionospheric corrections needed for navigation, and

to assess the quality of the service.

One of the weaknesses of his technique is its relatively small coverage. Because the stations must be placed on a fixed ground

75 location, only the region close to them are prone to be studied. Fortunately for this study, there are two ground stations close to

the volcano, one is located on the same island (La Palma), which from now on, will be identified as LPAL, and the second one in Maspalomas (MAS1), a town South of the Gran Canaria Island, which is around 250 km southeast of the volcano. Figure 2 shows a map displaying the two ground stations.
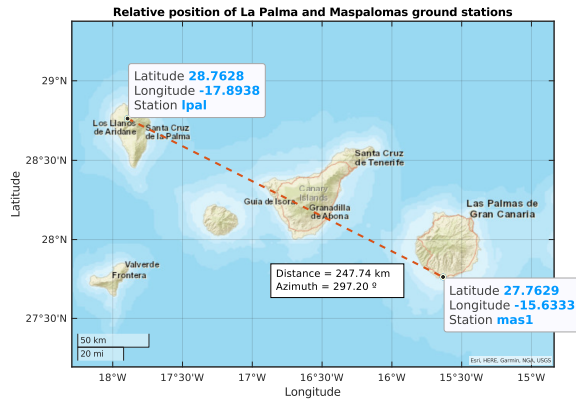
Figure 2. Relative position of LPAL and MAS1 ground stations with respect to the La Palma Island, which is the top left one. Map: Esri, HERE, Garmin, NGA, USGS.

The GNSS monitoring ground station data contains the measurement for every minute of all the GNSS satellites in view for
80 each station. The database has been pre-processed, and it includes the variables in Table 1:

A clear trend between the elevation angle and the measured scintillation has been observed. The smaller the elevation, the larger the S_4, which can be attributed to the longer path within the ionosphere of the lower elevation rays, which may suffer from stronger scintillation and multipath propagation. This behavior is displayed in Fig. 3. Therefore, data with an elevation lower than 30º has been discarded.
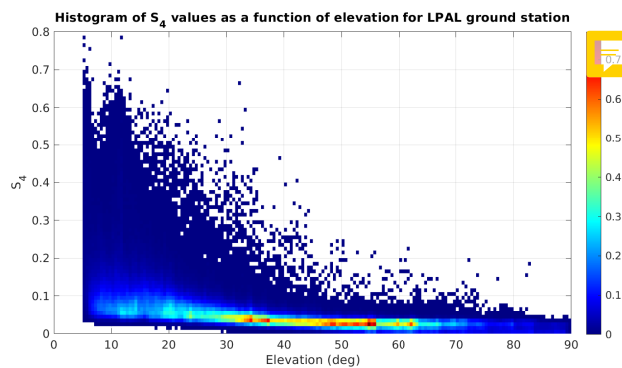
Figure 3. Histogram of S_4 values with respect to the elevation angle for La Palma ground station data.

Table 1. GNSS monitoring ground stations database variables

Variable Name	Description
Year	Year of the measurement
DoY	Day of the Year
Seconds	Second of the day
Satellite	Satellite number
	1 to 33: GPS
	37 to 70: GLONASS
	71 to 120: GALILEO
	121+: discarded in this study
Azimuth (deg)	Azimuth from the station (North at 0º)
Elevation (deg)	Elevation from the station (0º – 90º)
S4	Amplitude scintillation calculated over 60 s
Sigma_phi	σ_ϕ from the L1 signal calculated over 60 s
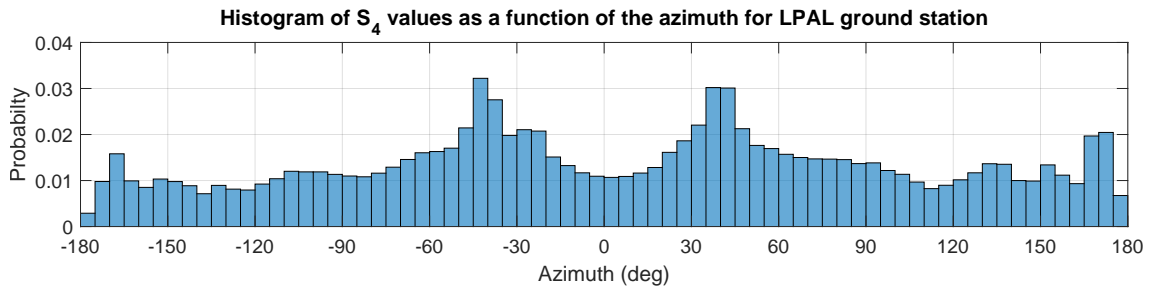
Figure 4. Histogram of the amount of S_4 measurements as a function of the azimuth.

85   Also, the dependence on azimuth has been studied. A certain dependence of the number of measurements vs. the azimuth has also been found. As shown in Fig. 4, the most probable azimuths for receiving GNSS signals at the LPAL station are +45º and -45º.

Figure 5 shows the percentile 95% of S_4 values as a function of time and azimuth, and it can be observed that the largest values are obtained, for both stations, mostly when the GNSS satellites are located southwards, near 180º azimuth.
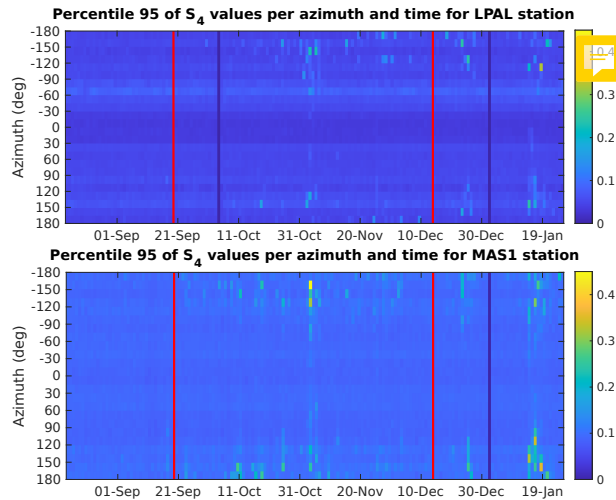
Figure 5. Percentile 95% of S_4 values as a function of the azimuth (in vertical axis) and time (in horizontal axis) for LPAL and MAS1 ground stations respectively.

90 ## 2.2 GNSS-R data

GNSS-Reflectometry has also proven to be a good way to detect ionospheric scintillation over calm oceanic regions Molina and Camps (2020). In this study, the NASA CYGNSS GNSS-R constellation has been used, which started providing science data in March 2017 and it is open-access. CYGNSS orbit's inclination is around 35º, so the coverage is from 40ºS to 40ºN, which includes the latitude of the islands (28.5ºN).

95 The eight satellites comprising the CYGNSS constellation are continuously tracking up to 4 GPS satellites in view, taking measurements at a sample rate of 2 Hz, providing a relatively good availability of data in the region close to La Palma. There have been recorded almost 65.000 points inside a circle of 100 km centered on the island during the whole period of 139 days.

The location of each point corresponds to the specular reflection point of each trajectory between the GPS satellite and the CYGNSS receiver, as shown in Fig. 6. The track of these reflected signals crosses the ionosphere twice because the height of

100 the CYGNSS satellites is around 520 km, which is above the typical height of the ionosphere's maximum density (~350 km). As GNSS-R cannot distinguish if the scintillation was generated in the ascending or descending paths, the specular reflection point is used to locate the measurements.

GNSS-R data has been processed as detailed in Molina and Camps (2020), doing the moving average and standard deviation of 10 s of samples around each point, and then computing the S_4 index as:

105 $$S_4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}}, \qquad (1)$$
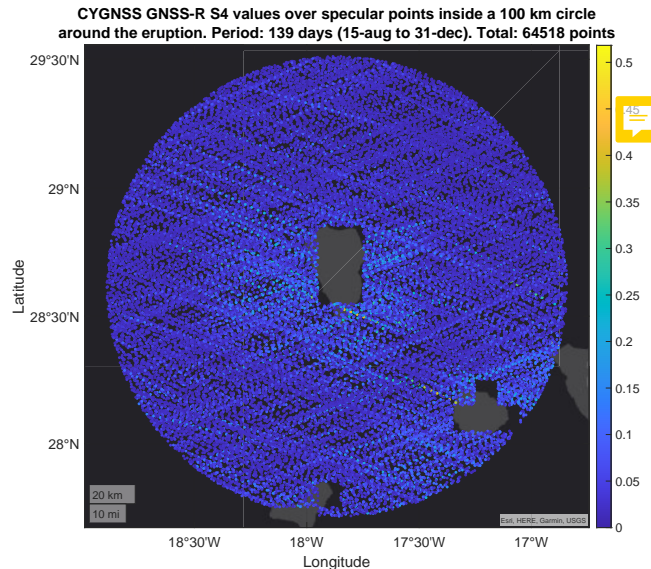
Figure 6. Position of CYGNSS GNSS-R specular refelction points inside a cicrle of 100 km around La Palma Island for the whole period studied, indicating the S_4 in colors. Map: Esri, HERE, Garmin, USGS.

where I is the signal's intensity in linear units derived from the SNR provided in the CYGNSS database and stands for the moving average of all samples within 10 seconds around the central measurement.

As the performance of the GNSS-R technique to estimate the scintillation is affected by the sea surface roughness, another filter has been applied. A wavy water surface destroys the signal coherence, making it impossible to infer the scintillation suffered along the path. Using data from maritime buoys around the islands, the model SIMAR Puertos del Estado (2020) extrapolates the wave height in a grid of points along the ocean. Figure 7 shows the position of these points around La Palma Island and the ones selected to estimate the wave height during the eruptive period. The wave height extracted from them is compared to the detected scintillation from CYGNSS in Fig. 8. It can be observed that the high values of scintillation can appear only when the sea roughness is small, as indicated by the color-shaded areas. For example, the peaks around Sep, 4th appear during a period of waves lower than 1.5 m. Similar behavior is observed around Sep, 25th, Oct, 16rd, or Nov, 23rd.

Figure 9 shows the comparison between the Significant Wave Height (SWH) in the horizontal axis vs. the detected value of S_4, confirming what was observed in the timeline in Fig. 8. In this correlation, we can define a noise floor at 0.02 to remove all the values that are prone to be affected by the sea surface roughness. In the study, we compare the results for both cases: when using all data without filtering and when using only S_4 values above 0.02.

2.3 GNSS-RO data

The GNSS Radio-occultation method is another way to retrieve information about the ionosphere using GNSS signals. In this case, the signal emitted by the GNSS satellites is received by the receiver onboard a LEO satellite when they are setting under

Figure 7. Set of SIMAR model points around the island, indicating the ones selected to extract the Significant Wave Height (SWH) around La Palma. Dataset downloaded from Puertos del Estado (2022) website. Map: Sentinel-2 cloudless 2021 by EOX IT Services GmbH.
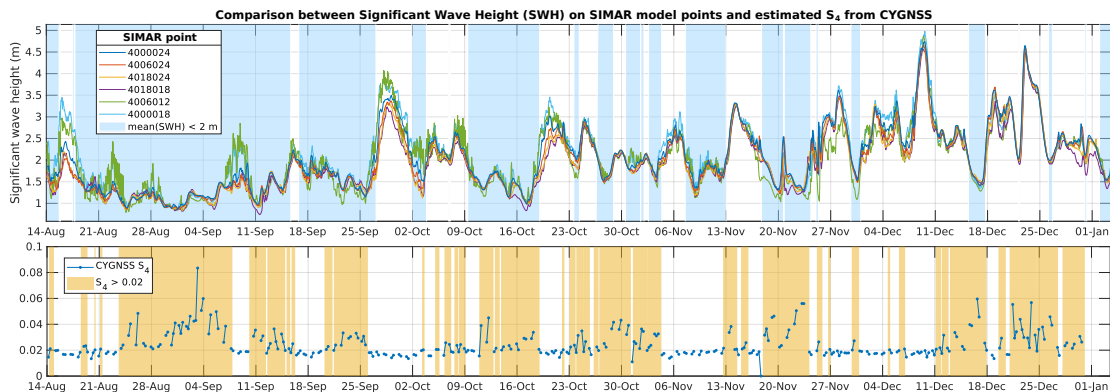
Figure 8. Significant Wave Height (SWH) from 6 SIMAR model points every hour around La Palma, compared to the estimated S_4 from CYGNSS GNSS-R data. Light blue shaded area marks the periods with an average SWH less than 2 m and the yellow area marks the intervals in which the S_4 is larger than 0.02, showing that most of the S_4 peaks only appear when the SWH is low.

or rising above the horizon. The use of this technique has the advantage of not being affected by ground reflection disturbances as in GNSS-R. For the same reason, land and oceanic regions can be studied indistinctly.

125   For this study, Spire and open-access data from COSMIC-2 COSMIC (2019) have been used. Spire Global Jales et al. (2020); Irisov et al. (2018) operates a constellation of more than 80 3U CubeSats that can perform GNSS-RO, and more recently GNSS-R as well. From Spire, data from around 58000 GNSS-RO occultations recorded in the region around La Palma Island from August 15th to October 31th, 2019 has been used.

     Cosmic data includes all the occultations of GPS satellites as seen from the constellation of COSMIC-2 LEO satellites.
130   COSMIC-2, also known as FORMOSAT-7, is a constellation of 6 LEO mini-satellites (300 kg) that were launched on June
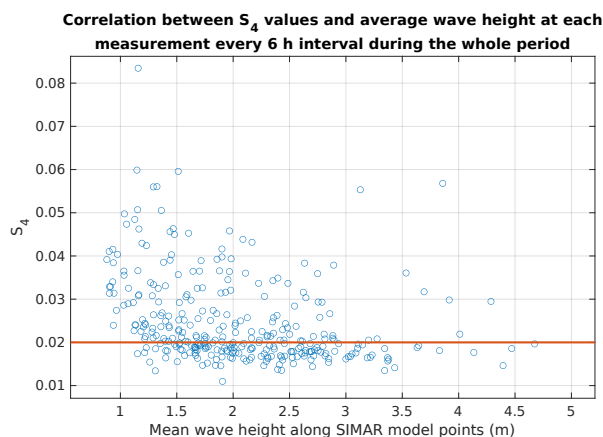
Figure 9. Correlation between the waveheight and the detected scintillation index S_4 using GNSS-R from CYGNSS.

25th 2019 into a 24° inclination orbit. The Level 1b podTc2 dataset contains the information that has been used in this study. Particularly, it contains the variables detailed in Table 2.
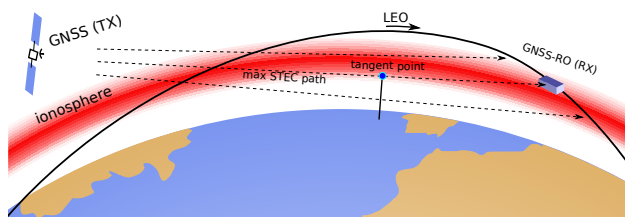
Figure 10. Schematics of the GNSS-RO technique to measure the ionosphere, indicating the location of the tangent point in the path with maximum STEC value.

With these data, the tangent point, (i.e., the point in the trajectory which is closer to the Earth), can be computed from the GPS and LEO satellite positions. For each of these points, the corresponding S_4 value has been computed, and their coordinates

135   will be used later to filter by distance around the volcano. Given that the occultations have been recorded during a long period, including high elevation angles (almost 90° in some cases), a method has been applied in order to filter the data points that correspond to the rays ~~actually~~ traversing the ionosphere.

Using the slant TEC (STEC) value during the occultation, we can assume that the maximum value coincides with the path in which the ray crosses its longest path in the ionosphere, as shown in Fig. 10. Then, selecting the points that have a STEC

140   larger than 80% of the maximum TEC in each occultation will leave the points that are inside the ionosphere, more likely to suffer from scintillation, as show in Fig. 11.

Figure 12 shows the location of the points with STEC larger than the 80% of the maximum one and within a circle of 1000 km radius around the eruption coordinates.

Table 2. Level 1b "podTc2" database variables available from COSMIC-2 database.

Variable Name	Description
Time (GPS seconds)	GPS time of the measurements (seconds from 1-Jan-1980)
TEC (TECU)	Total Electron Content along LEO-GPS link (slant TEC)
caL1_SNR (V/V)	Signal to Noise ratio on the L1 channel, CA code
pL2_SNR (V/V)	Signal to Noise Ratio on the L2 channel, P code
x_LEO (km) y_LEO (km) z_LEO (km)	LEO position (ECF) at time of signal acquisition.
x_GPS (km) y_GPS (km) z_GPS (km)	GPS position (ECF) at time of signal acquisition.
S4	S_4 scintillation index
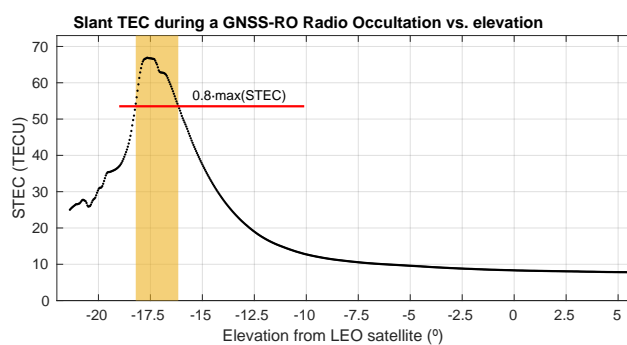
Figure 11. STEC variation during a GNSS occultation as a function of the elevation angles seen from a COSMIC-2 satellite on September 19th, 2021.
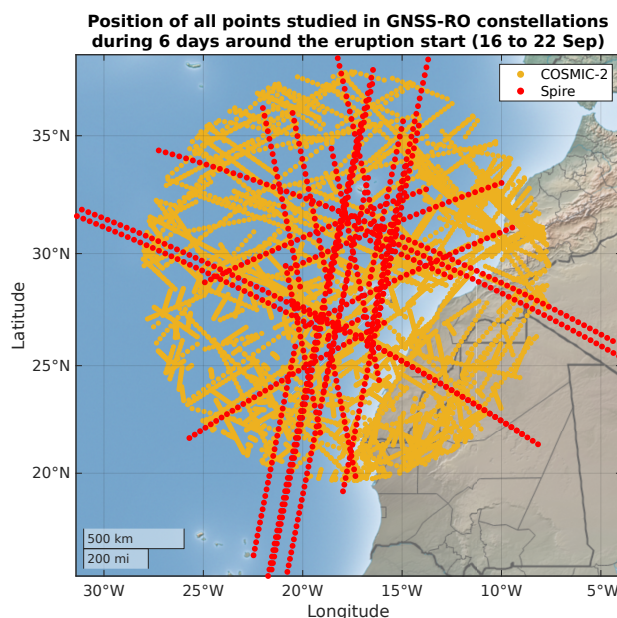
Figure 12. Location of Spire (in red) and COSMIC-2 (in yellow) measurements during 6 days (± 3 days) around the start of the volcanic eruption on Sep 19th. Map: made with Natural Earth.

2.4 Seismic activity data

145 The volcanic eruption had seismic activity associated. The database of earthquakes has been retrieved from the Spanish Instituto Geográfico Nacional (IGN) (IGN). For the whole duration of the eruption, around 9200 earthquakes have been recorded in the database, which includes information about their time, magnitude, location, and depth.

~~All the earthquakes studied~~ are represented in Fig. 13, indicating their depth in the vertical axis during the whole eruption period (yellow shade). As observed in the figure, there is a precursor seismic activity close to the surface with decreasing depths,
150 then a relatively calm period of 8-days, preceding a roughly stable activity with earthquakes at two differentiated depths, but with homogeneous magnitudes in each group. When the eruption ends, the seismic activity lasted for approximately 15 more days with decreasing magnitude and frequency.

To allow the comparison between the seismic activity and the corresponding ionospheric scintillation indicator, in this study it is proposed to use the energy generated per earthquake and then integrate all the earthquakes' energy in a time interval. The
155 rationale behind the selection of these metrics is that, whichever mechanism is involved in the perturbation of the ionosphere, the larger the energy dissipated into the environment, the larger the induced perturbations should be. The formula used to compute the energy per earthquake is taken from the work of Gutenberg and Richter Gutenberg and Richter (1955):

$$\log E = 5.8 + 2.4m, \tag{2}$$
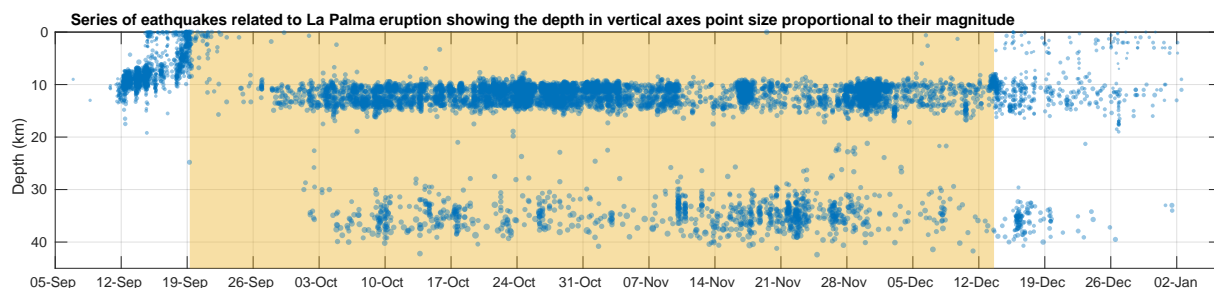
Figure 13. Series of earthquakes associated with the volcanic eruption in La Palma Island, indicating their depth in the vertical axis, and their magnitude proportional to the point size. The volcanic eruption is active during the period shaded in yellow.

where m is the magnitude of the earthquake, and E is the dissipated energy in Ergs.

160   Figure 14 shows a temporal histogram of the magnitude of earthquakes during the eruption period, indicating in vertical the magnitude, and in colors the number of earthquakes per bin. Red arrows mark the beginning and end of the eruption, respectively. The orange line represents the integrated energy every 6-hour intervals, computed for each earthquake using Eq. 2.
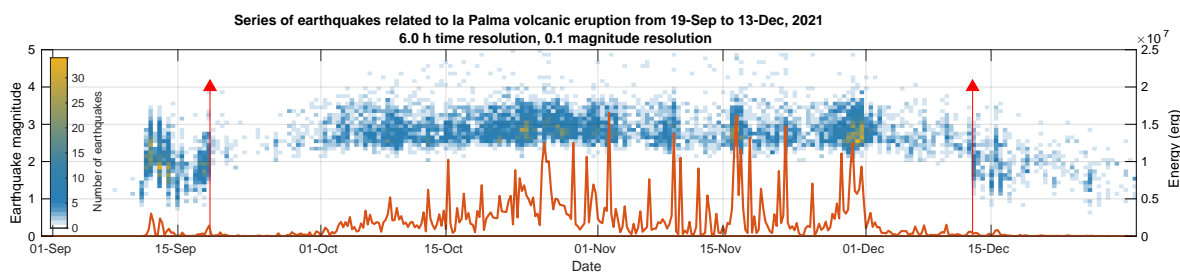
Figure 14. Seismic activity associated with the La Palma volcano eruption for the whole period, showing in colors the histogram of magnitudes and the integrated generated energy with an orange line. The red arrows mark the start and end of the volcanic eruption.

3   Results and discussion

165   The three GNSS techniques studied to measure the ionospheric scintillation are correlated to the seismic activity induced by the volcanic eruption. In each of the cases, instantaneous measurements of the S_4 index at every geographic coordinate have been recorded. To integrate this information into something comparable to the integrated energy dissipated by earthquakes, measurements were averaged and integrated into 6 h bins as the earthquake's energy ones. This 6 h period is long enough to include many measurements and reduce noise, but short enough to allow tracking possible variations within the day.

170   Figure 15 shows the comparison between the integrated energy generated by the earthquakes and the different methods to estimate the S_4 ionospheric scintillation index used around La Palma Island. Figure 15a shows the integrated earthquake energy
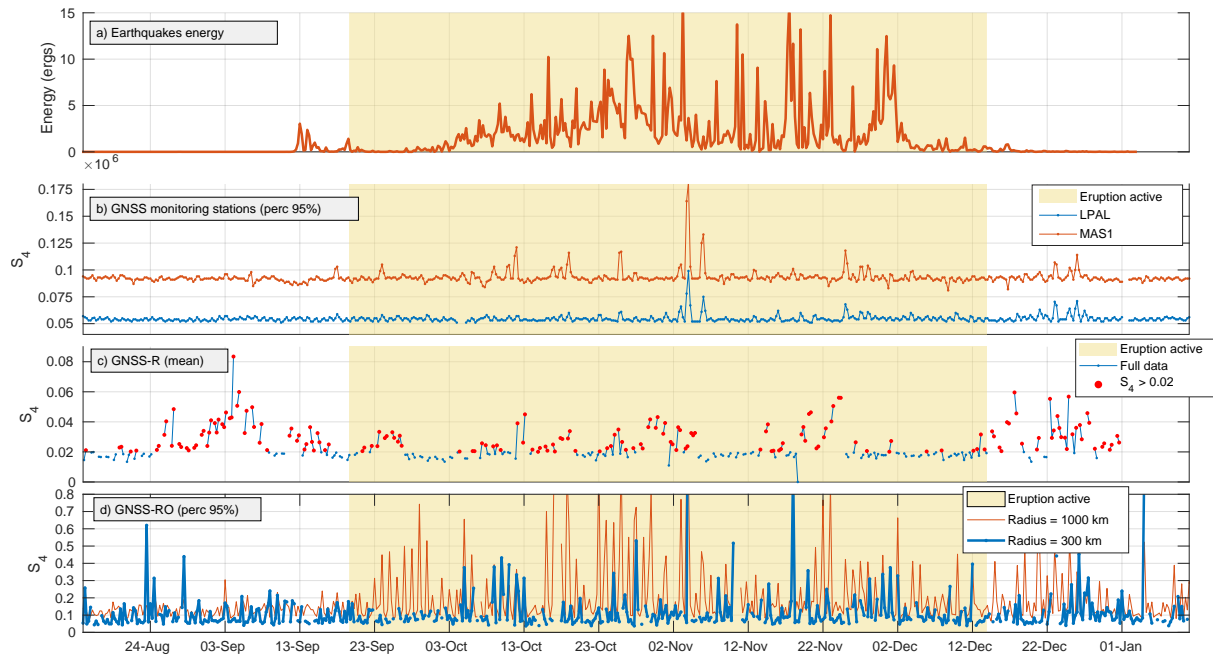
Figure 15. Comparison of a) integrated earthquake's energy every 6 h interval vs. estimated S_4 from the three sources: b) percentile 95 of S_4 obtained from ground stations in La Palma and Maspalomas, c) mean S_4 obtained from CYGNSS GNSS-R, and d) percentile 95% of S_4 obtained from GNSS-RO with two different filtering distances.

every 6 h interval over a yellow background indicating the time when the eruption was active. Figure 15b shows the ground station data obtained from LPAL and MAS1 stations, and then the percentile 95% computed every 6 h intervals. Figure 15c shows the GNSS-R data from CYGNSS, in the same 6 h intervals. And finally, Fig. 15d shows the GNSS-RO data. The percentile 95% of the S_4 values is shown in these plots after filtering them by distance to the eruption: 300 km in blue color and 1000 km in red color.

A first visual inspection of these data shows a certain correlation between the seismic energy and the estimated scintillation. For example, the largest peak in the seismic activity on November 3rd at 9 h UTC almost matches with the peaks in the GNSS monitoring ground stations and GNSS-RO measurements, both at the 6-hours interval at 0 h UTC on November 4th. Similarly, the second largest peak in the seismic activity on November 17th at 15 h UTC, has a corresponding replica in the 300 km radius GNSS-RO measurements on November 18th 0 h UTC.

It can be observed that GNSS monitoring ground stations data presents an offset between LPAL and MAS1 stations, but they are highly correlated most of the time as both stations can sense the region of the ionosphere likely to be perturbed by the eruptive activity.

Figure 15c shows the CYGNSS GNSS-R data, which seems the most uncorrelated measurement in this study. As mentioned previously, this can be explained as the GNSS-R reflectometry is affected by the sea surface conditions to correctly estimate

the ionospheric scintillation index. The red points in this Fig. 15c are the ones with an S_4 value larger than 0.02 to filter out the values that are more prone to be affected by sea roughness, as explained in Sect. 2.2.

Figure 15d shows the GNSS-RO data after being filtered by their distance to the eruption site: 1000 km in a red line, and 190 300 km in a blue line. The 1000 km one shows more and higher peaks during almost the whole period, which may be indicating that it is being affected by other sources of perturbations, different from the volcanic eruption.

To do a quantitative analysis between the different GNSS data sources, and allow a better comparison of them, a linear correlation between each pair of data (earthquakes energy vs. each of the GNSS measurement methods) has been performed. Before correlating each signal, they have been shifted by a certain amount of time from -10 days to +10 days, in steps of 6 h, 195 equal to the sampling rate for all signals. This way we can also see if the impact of earthquakes in the ionosphere is a precursor or a consequence of it.

After the temporal shift, the corresponding pair of points are plotted in a scatter plot, and a least-squares linear correlation line is computed, obtaining for each case its correlation coefficient, R. Then, for each shifted time, the values of R over time are plotted in Fig. 16. In every case, the x-axis indicates the amount of time shifted, being negative when the scintillation is a 200 precursor of the earthquakes, and the y-axis is the correlation coefficient R.
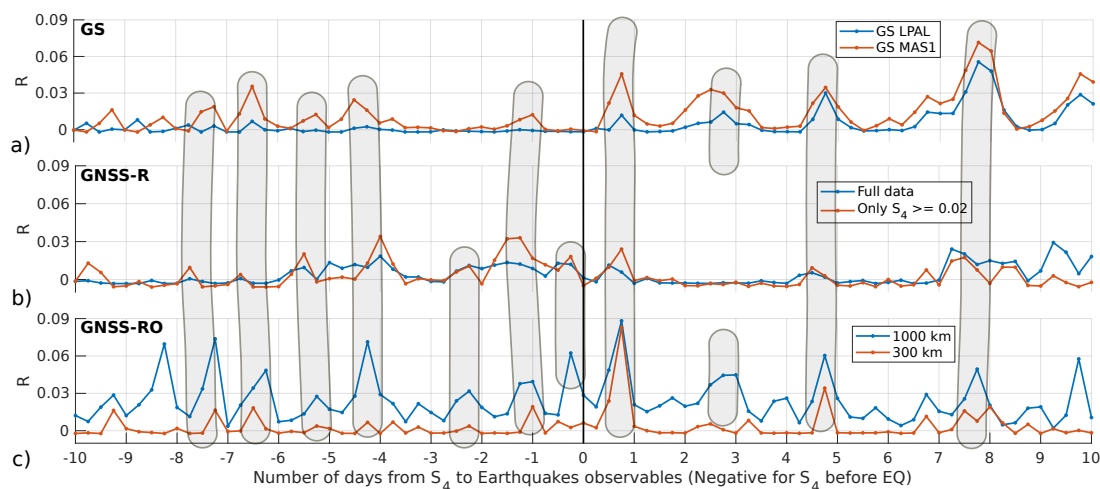
Figure 16. Results of the correlation analysis for each GNSS method and each shifted period in the x-axis: a) GNSS monitoring ground stations, b) GNSS-R data, and c) GNSS-RO data. In gray-shaded areas, a visual cross-correlation is observed between some of the methods.

These results confirm some of the features commented qualitatively in the previous paragraphs. For example, Fig. 16b proves that the GNSS-R method presents the smallest correlation for all shifting times. Even though, it presents a weak correlation in several points, which tends to be larger when using only the S_4 values larger than 0.02. GNSS-R data present peaks of correlation from -7 to -4 days, also from -2 to +1, and a last set of peaks from +7 to +10.

205   For GNSS monitoring ground stations data in Fig. 16a some peaks of correlation occur when the scintillation is produced around 8 days later, and also 5 or 3 with smaller intensity. Additionally, there is a peak, which is bigger in Maspalomas than in the La Palma monitoring station, at +18 h from the eruption, which supports the fact observed previously in Fig. 15.

Figure 16a also shows that the Maspalomas (MAS1) station always has a higher correlation than the La Palma station, even if it is on the same island. One possible explanation for this is that the lower the elevation angle, the larger the detected
210   scintillation is, increasing the possibility of detection of small ionospheric signatures. This is why larger correlations are found in the GNSS-RO measurements.

In the results for GNSS-RO in Fig. 16c it can be seen the largest correlation peak occurs at +18 h after the seismic activity, as for the GNSS monitoring ground stations data. It can also be seen that the data filtered by a 1000 km radius is noisier than the one filtered by a 300 km radius, because the last ones are more related to the eruptive activity than to other external
215   causes. Even though, for the 1000 km radius curve, there are some correlation peaks when the seismic activity precedes the ionospheric perturbations in 8, 7, or 4 days approximately. Also, another peak is found at +4.75 days after the seismic activity, with a smaller replica in the 300 km radius, being the second larger peak for this case.

In Fig. 16, vertical lines in light gray are highlighting the observed cross-correlation between two or more techniques. It has been observed, that there are several points that present correlation peaks approximately at the same time interval,
220   reinforcing the results presented and confirming that the different methods can actually detect, with a different sensibility, the same signatures related to the seismic activity.

4   Conclusions

In this study, an analysis of the impacts of the La Palma eruption on ionospheric scintillation has been made by correlating three different ways to measure it by using GNSS signals (GNSS monitoring ground stations, GNSS-R, and GNSS-RO) with
225   the seismic activity related to the eruption.

This ~~particularity~~ allows comparing the 3 methods' performance to detect tiny signals in the ionosphere produced by seismic activity. It has been found a detectable correlation for the GNSS monitoring ground stations, and the GNSS-RO methods. The GNSS-R technique ~~has shown the worst results~~, which can be due to the sea state, which was rough (SWH > 2 m) for a considerable amount of time during the volcanic eruption period. The correlation peaks found in the other two methods are
230   obtained after computing the data for the complete duration of the eruption, from September 19th to December 13th, 2021. They show the largest peaks at +18 h after the seismic activity, with a correlation coefficient R of around 0.09 and 0.05 for GNSS-RO and GNSS-GS respectively. Even though they are not very high, they are detectable and they can be related to the direct energy transfer from the earthquakes to the ionosphere by mechanical gravity waves (pressure waves coupling the atmosphere and the ionosphere), as other studies have reported in other eruptions.
235   In the case of the La Palma volcanic eruption, there is possible coupling through a piezo-electric effect caused by the severe seismic activity under La Palma during the whole duration of the eruption. This piezo-electric effect induced by the large

underground rocks' pressure can induce electric charges in the surface generating perturbations in the ionosphere's electron density during some days before the earthquakes.

Code availability. Data analysis code is not available. The analysis followed standard statistical routines and can be reproduced by the explanations given in the text.

Author contributions. All authors contributed conceptualization and manuscript revision, CM preformed data curation, software implementation, formal analysis, visualization, and original draft writing. AC was in charge of the project adminstration, funding acquisition and resources provision.

Competing interests. The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Acknowledgements. This work was supported in part by the grant PID2021-126436OB-C21 from the Programa Estatal para Impulsar la Investigación Científico-Técnica y su Transferencia, del Plan Estatal de Investigación Científica, Técnica y de Innovación 2021-2023 (Spain) and in part by the European Social Fund (ESF). GNSS-RO Spire data has been provided by the European Space Agency through the ESA TPM SPIRE project id 67176. Finally, the authors sincerly express their thanks to gAGE UPC team for pre-processing and providing the GNSS monitoring ground stations data.

References

Astafyeva, E.: Ionospheric Detection of Natural Hazards, Reviews of Geophysics, 57, 1265–1288, https://doi.org/10.1029/2019rg000668, 2019.

COSMIC, U.: UCAR COSMIC Program, 2019: COSMIC-2 Data Products, https://doi.org/10.5065/T353-C093, https://doi.org/10.5065/T353-C093, access date [20-Jun-2022], 2019.

Das, B., Barman, K., Pal, S., and Haldar, P. K.: Impact of Three Solar Eclipses of 2019–2020 on the D-Region Ionosphere Observed From a Subtropical Low-Latitude VLF Radio Station, Journal of Geophysical Research: Space Physics, 127, e2022JA030 353, https://doi.org/https://doi.org/10.1029/2022JA030353, e2022JA030353 2022JA030353, 2022.

De Ragone, A. H., De Manzano, A. N., Elias, A. G., and De Artigas, M. Z.: Ionospheric effects of volcanic eruptions, Geofísica Internacional, 43, 187–192, 2004.

Ding, F., Wan, W., Ning, B., and Wang, M.: Large-scale traveling ionospheric disturbances observed by GPS total electron content during the magnetic storm of 29–30 October 2003, Journal of Geophysical Research: Space Physics, 112, https://doi.org/https://doi.org/10.1029/2006JA012013, 2007.

Fernández, J., Escayo, J., Hu, Z., Camacho, A. G., Samsonov, S. V., Prieto, J. F., Tiampo, K. F., Palano, M., Mallorquí, J. J., and Ancochea, E.: Detection of volcanic unrest onset in La Palma, Canary Islands, evolution and implications, Scientific reports, 11, 1–15, 2021.

Gutenberg, B. and Richter, C.: Magnitude and energy of earthquakes, Nature, 176, 795–795, 1955.

(IGN): Instituto Geográfico Nacional. Catálogo de terremotos, https://doi.org/10.7419/162.03.2022.

Irisov, V., Nguyen, V., Duly, T., Masters, D. S., Nogues-Correig, O., Tan, L., Yuasa, T., and Ector, D. R.: Recent Ionosphere Collection Results From Spire's 3U CubeSat GNSS-RO Constellation, in: AGU Fall Meeting Abstracts, vol. 2018, pp. PA24B–05, 2018.

Jales, P., Esterhuizen, S., Masters, D., Nguyen, V., Correig, O. N., Yuasa, T., and Cartwright, J.: The new Spire GNSS-R satellite missions and products, in: Image and Signal Processing for Remote Sensing XXVI, edited by Bruzzone, L., Bovolo, F., and Santi, E., vol. 11533, p. 1153316, International Society for Optics and Photonics, SPIE, https://doi.org/10.1117/12.2574127, 2020.

Kamogawa, M.: Preseismic lithosphere-atmosphere-ionosphere coupling, Eos, Transactions American Geophysical Union, 87, 417–424, https://doi.org/https://doi.org/10.1029/2006EO400002, 2006.

Ke, F., Wang, J., Tu, M., Wang, X., Wang, X., Zhao, X., and Deng, J.: Characteristics and coupling mechanism of GPS ionospheric scintillation responses to the tropical cyclones in Australia, GPS Solutions, 23, 1–14, https://doi.org/https://doi.org/10.1007/s10291-019-0826-2, 2019.

Li, G., Ning, B., Zhao, B., Liu, L., Liu, J., and Yumoto, K.: Effects of geomagnetic storm on GPS ionospheric scintillations at Sanya, Journal of Atmospheric and Solar-Terrestrial Physics, 70, 1034–1045, https://doi.org/https://doi.org/10.1016/j.jastp.2008.01.003, 2008.

Liu, J., Chuo, Y., Shan, S.-J., Tsai, Y., Chen, Y.-I., Pulinets, S., and Yu, S.: Preearthquake-ionospheric anomalies registered by continuous GPS TEC, Annales Geophysicae, 22, https://doi.org/10.5194/angeo-22-1585-2004, 2004.

Molina, C. and Camps, A.: First evidences of ionospheric plasma depletions observations using GNSS-R data from CYGNSS, Remote Sensing, 12, 3782, 2020.

Molina, C., Semlali, B. B., Park, H., and Camps, A.: Possible Evidence of Earthquake Precursors Observed in Ionospheric Scintillation Events Observed from Spaceborne GNSS-R Data, in: 2021 IEEE International Geoscience and Remote Sensing Symposium IGARSS, pp. 8680–8683, IEEE, 2021.

Molina, C., Boudriki Semlali, B.-E., Park, H., and Camps, A.: A Preliminary Study on Ionospheric Scintillation Anomalies Detected Using GNSS-R Data from NASA CYGNSS Mission as Possible Earthquake Precursors, Remote Sensing, 14, 2555, 2022.

Puertos del Estado: Conjunto de datos SIMAR, https://bancodatos.puertos.es/BD/informes/INT_8.pdf, 2020.

290 Puertos del Estado: Predicción de oleaje, nivel del mar. Boyas y mareografos., https://www.puertos.es/en-us/oceanografia/Pages/portus.aspx, access date [23-sep-2022], 2022.

Pulinets, S.: Ionospheric Precursors of Earthquakes: Recent Advances in Theory and Practical Applications, Terrestrial Atmospheric and Oceanic Sciences, 15, 413–435, https://doi.org/10.3319/TAO.2004.15.3.413(EP), 2004.

Pulinets, S. and Davidenko, D.: Ionospheric precursors of earthquakes and global electric circuit, Advances in Space Research, 53, 709–723, 295 2014.

Pulinets, S., Krankowski, A., Hernandez-Pajares, M., Marra, S., Cherniak, I., Zakharenkova, I., Rothkaehl, H., Kotulak, K., Davidenko, D., Blaszkiewicz, L., et al.: Ionosphere Sounding for Pre-seismic anomalies identification (INSPIRE): Results of the project and Perspectives for the short-term earthquake forecast, Frontiers in Earth Science, 9, 610 193, 2021.

Shults, K., Astafyeva, E., and Adourian, S.: Ionospheric detection and localization of volcano eruptions on the example of the April 2015 300 Calbuco events, Journal of Geophysical Research: Space Physics, 121, 10–303, https://doi.org/10.1002/2016ja023382, 2016.

Themens, D. R., Watson, C., Žagar, N., Vasylkevych, S., Elvidge, S., McCaffrey, A., Prikryl, P., Reid, B., Wood, A., and Jayachandran, P.: Global propagation of ionospheric disturbances associated with the 2022 Tonga Volcanic Eruption, Geophysical Research Letters, 49, e2022GL098 158, 2022.

Xu, J., Ke, F., Zhao, X., and Qi, X.: Characteristics of the Ionospheric Disturbances Caused by Typhoon Using GPS and Ionospheric 305 Sounding, pp. 509–517, https://doi.org/https://doi.org/10.1007/978-981-15-6113-9_57, 2019.

Yong-Qiang, H., Zuo, X., and Dong-He, Z.: Responses of the ionosphere to the Great Sumatra earthquake and volcanic eruption of Pinatubo, Chinese Physics Letters, 23, 1955, 2006.