Characteristics of CIR-driven storm induced traveling ionospheric disturbances over mid-latitude Europe from ionosonde and LOFAR data (SUNDIAL)

1. Abstract

Magnetic storms are known to effectively generate atmospheric waves, result in negative effects on the space-based assets and require further thorough investigations. The goal of the proposed project was to search a relationship between auroral activity enhancement, initiated by corotating interaction region / high speed stream (CIR / HSS)-driven events and characteristics of traveling ionospheric disturbances (TIDs) observed over mid-latitude Europe. We thoroughly analysed both large-scale and medium-scale TID activity during CIR / HSS-driven magnetic storm on March 30 – April 6, 2023.

Thanks to the PITHIA-NRF project and the valuable support provided by the TNA program, we successfully combined the efforts of scientists from the Institute of Atmospheric Physics CAS (Czech Republic) and the Space Research Centre PAS (Poland) to jointly detect and characterize TIDs using ionosonde, GNSS, and LOFAR scintillation techniques. A unified methodology was applied and further improved for data analysis, incorporating cross-correlation, spectral analysis, and bandpass filtering to ensure consistency across the obtained results.

We detected the several time intervals with TIDs propagated from the high latitudes towards the equator associated with an enhancement in auroral activity. Ionosonde and GNSS based results show the consistency in estimation of TID characteristics. The detected large scale TIDs have the dominant periods of 50 – 80 min, horizontal phase velocities of 400 – 600 m/s and horizontal wavelengths of 1300 – 3500 km. In addition, an analysis of the LOFAR scintillation data revealed the intensification of irregularities which is likely to be caused by medium and small scale TIDs. The southward propagated TIDs in the broad range were detected and characterized during the selected magnetic storm interval. Based on this case study, we spotted that the TIDs at mid-latitudes were usually observed several (1 – 4) hours after the enhancement in the auroral activity characterized by IMAGE IE indices. We continue to analyse other CIR / HSS driven events to establish the validity of such relationship.

2. Objective

Understanding how traveling ionospheric disturbances (TIDs) are generated, propagate, and attenuate during space weather events is crucial for forecasting and minimizing their negative impacts on communication, navigation, and other ionosphere-dependent technologies. Magnetic storms triggered by coronal mass ejections (CMEs) and high-speed streams (HSSs) associated with corotating interaction regions (CIRs) can influence the ring current as well as the intensity and duration of auroral activity in distinct ways. Notably, although CME-induced storms typically involve higher energy output, CIR / HSS-driven storms often exhibit stronger magnetospheric coupling and deliver more geoeffective total energy input to the Earth's magnetosphere. Moreover, storms driven by CIRs can cause more prolonged negative impacts on space-based systems.

The intensity of TIDs at mid-latitudes is strongly influenced not only by the type of storm driver but also by factors such as the time of day, season, solar activity levels, disturbance intensity, the phase of the magnetic storm, and the presence of other sources like tropospheric convection. Therefore, a detailed analysis of mid-latitude TID behaviour allows for the collection of valuable observational data, supporting statistical analysis and improving our ability to understand and forecast TID characteristics during CIR-driven magnetic storms.

The overarching goal of this investigation was to explore the relationship between pulse-like enhancements in auroral activity, triggered by high-energy inputs from the magnetosphere into the atmosphere and ionosphere during CIR-driven events, and the TIDs observed over mid-latitude Europe. For this purpose, we conducted a detailed case study of one CIR/HSS-driven geomagnetic storm that occurred from March 30 to April 6, 2023, and identified and characterized the resulting TIDs using a number of remote sensing facilities. The broader impact of this work lies in advancing our understanding of how CIR-driven magnetic storms contribute to energy deposition in the upper atmosphere and ionosphere, and how this energy is subsequently transferred to mid-latitudes via wave processes. The findings from this case study may also support the future development and refinement of global atmospheric and ionospheric circulation models.

3. Project process

The workflow consisted of several key steps, some of which were preparatory and completed prior to the start of the current project. Additionally, several steps are planned as follow-up tasks to be carried out after the project's completion, ensuring the sustainability and further development of the outcomes.

The preparatory steps involved a comprehensive comparison between automatically and manually scaled ionograms obtained from several European ionosondes during both magnetically quiet and disturbed periods. These efforts also focused on estimating detrended slant and vertical TEC values for each satellite–receiver pair and removing pulse interferences from GNSS data using statistical criteria. A thorough data quality check was conducted based on predefined quality rules tailored to specific tasks, and statistical threshold values were established to guide effective data filtration.

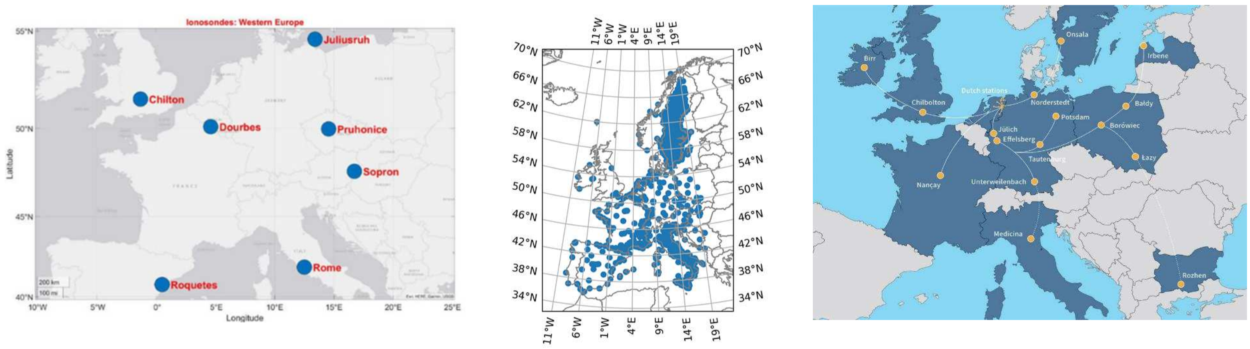
The steps undertaken during the course of the project included the selection of an appropriate CIR / HSS-driven magnetic storm event, ensuring the availability of data from all employed facilities and minimizing the influence of other high-energy natural or artificial TID sources to avoid contamination of results. These efforts also involved refining and expanding the unified methodology for TID detection and characterization. Further activities included retrieving TID characteristics, investigating the relationship between TID occurrence and auroral activity indices, and disseminating the results.

The follow-up tasks will focus on the continued integration of LOFAR, ionosonde, GNSS, and incoherent scatter data to enable a thorough statistical analysis of multiple CIR-driven events. This will support the development of a more refined TID detection methodology and facilitate a comprehensive examination of TID signatures across various ionospheric parameters in both temporal and spatial domains. The results will be disseminated through joint publications, including papers in leading international journals as well as presentations at conferences and symposia.

4. Data and analyses

Data from ionosonde, GNSS receiver, and LOFAR networks were used for the detection and characterization of TIDs (Fig. 1).

The Pruhonice, Juliusruh and Dourbes ionosonde data were utilized to detect and estimate the propagation characteristics of large-scale TIDs during the selected magnetic storm event (Fig. 1,a). Figures 2 and 3 show the main stages of ionosonde data analysis, including trend estimation, obtaining absolute and relative variations in F2 peak electron density, bandpass filtration and spectral analysis. These figures demonstrate that automatically scaled data have limited utility for TID characterization and are generally suitable only for detecting large scale TIDs (with periods over 60 minutes) over midlatitude ionosondes. The automatically scaled Pruhonice ionosonde data are appropriate for large scale TID characterization for the selected event. However, the Juliusruh automatically scaled ionosonde data suffer on underestimation even during magnetically quiet days providing wrong fluctuations in a broad period range from 10 to 240 minutes (Fig. 3).



A B C

Figure 1. Remote sensing facilities employed for the current study: a – ionosonde network, b – GNSS receiver network, c – LOFAR stations.

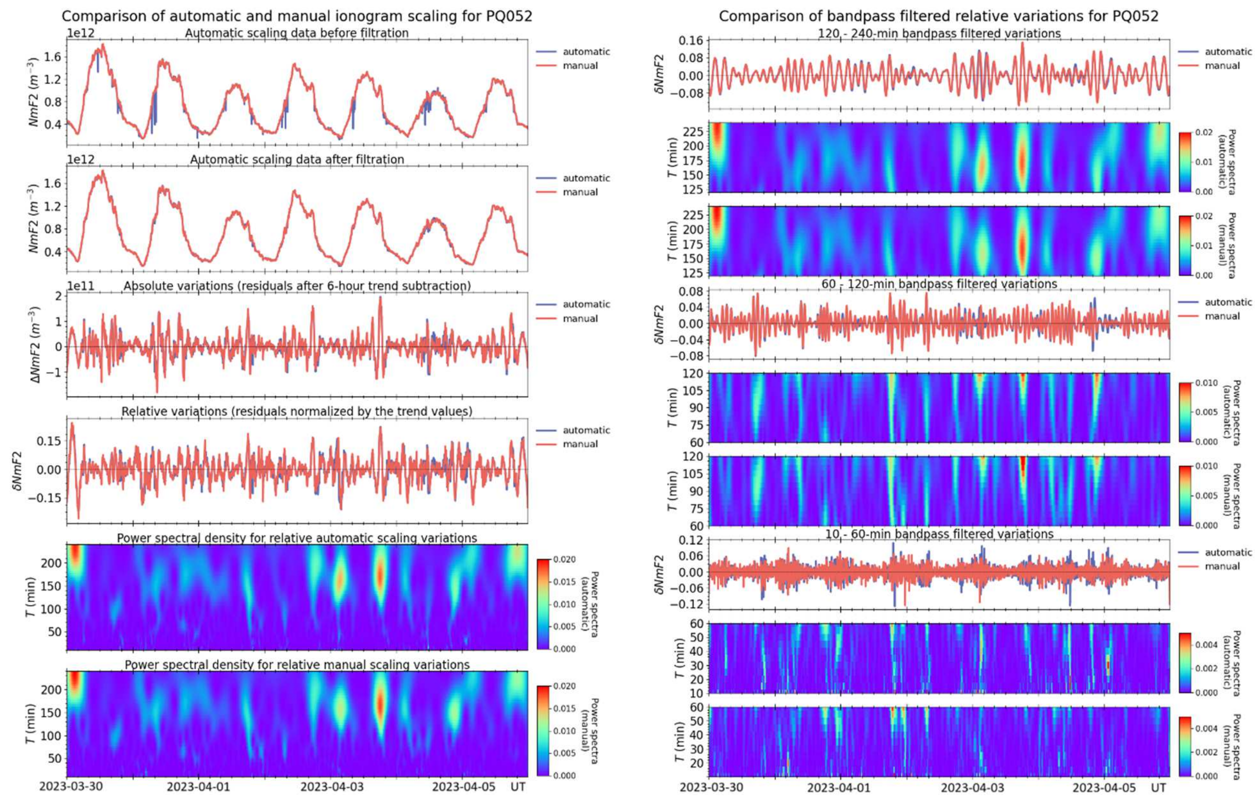


Figure 2. Stages of automatically and manually scaled Pruhonice ionosonde data analysis

We also employed GNSS data stored in Madrigal database. Time variations of the slant total electron content (TEC) derived from GPS signals were analysed with a cadence of 30 seconds. To account for the unknown shift in the slant TEC (STEC) and its long-term variations, we applied the Savitzky – Golay smoothing filter over time windows of 1 and 2 hours using a second-degree polynomial. For further analysis of dTEC variations, only data with an elevation angle of at least 30˚for each GNSS receiver-satellite direction were considered.

LOFAR data, in the form of dynamic spectra of radio power in the 25 – 65 MHz frequency range, were provided by the CBK / PAS Node and also retrieved from the LOFAR Long-Term Archive (https://lta.lofar.eu). Dr. Mevius from ASTRON – The Netherlands Institute for Radio Astronomy kindly shared Python scripts to facilitate LOFAR data access and analysis. Cross-correlation analysis of signal variations from different core and remote antennas was conducted to identify specific time intervals during which the condition of "frozen-in" ionospheric irregularities was satisfied and the movement of the diffraction pattern could be reliably observed.

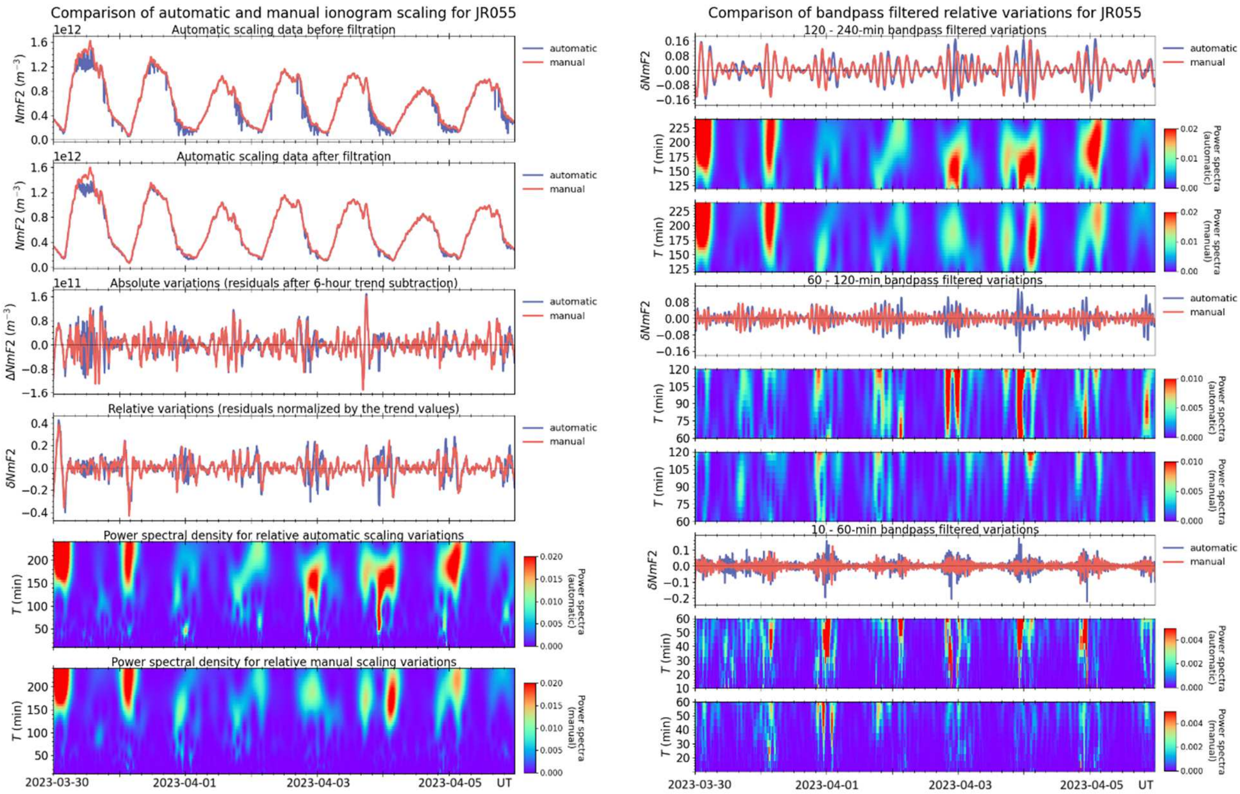


Figure 3. Same as in Figure 2, but for Juliusruh ionosonde

5. Results

During the selected magnetic storm event, three time intervals were identified in which southward-propagating TIDs were confidently detected using both ionosonde and GNSS techniques. This report focuses in detail on two such intervals (18 – 24 UT on April 1, 2023 and 16 – 20 UT on April 1, 2023).

The space weather conditions during the selected period are shown in Fig. 4. It is shown that Hp30 index usually was less than 5 and minimal SYM-H values were about – 40 nT. This CIR / HSS driven storm was minor and characterized by relatively long duration (about 6 days).

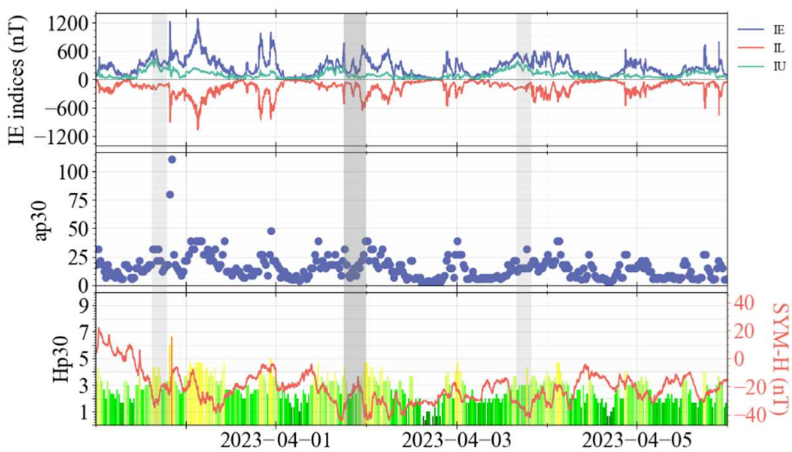
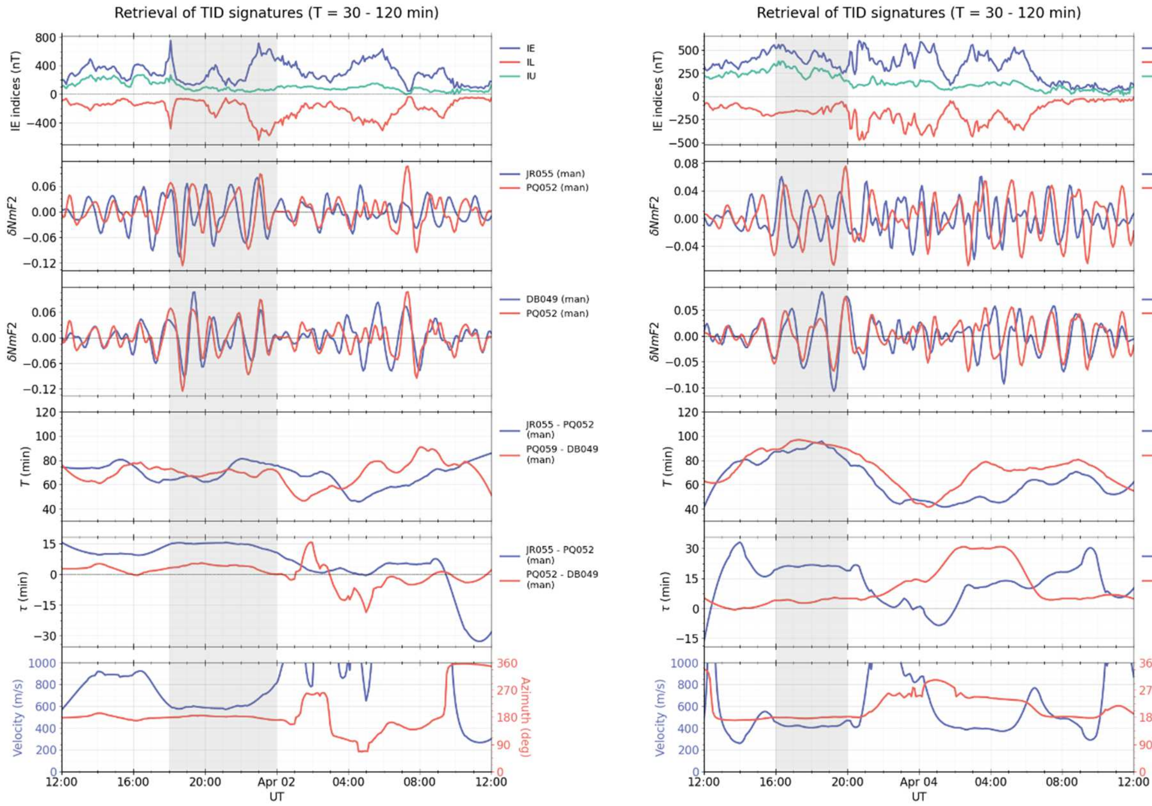


Figure 4. Variations of IMAGE IE, ap30, Hp30 and SYM-H indices during the magnetic storm on March 30 – April 5, 2023. Grey strips mark time intervals, where southward propagated TIDs were observed.

Ionosonde-derived TID characteristics. Fig. 5. presents the temporal variations of several TID characteristics, including bandpass filtered relative changes in electron density at the F2 peak altitude (δNmF2), dominant periods T, the magnitude of the horizontal phase velocity and its direction (azimuth, measured clockwise from the North). Manually scaled data from the Pruhonice Juliusruh and Dourbes ionosondes were used to estimate the horizontal phase velocity.



a b

Figure 5. TID characteristics from ionosonde data on April 1 (a) and April 3 (b), 2023. Grey strips mark time intervals, where southward propagated TIDs were observed.

Fig. 5 shows that the observed large-scale TIDs have periods of 50 – 80 minutes and horizontal phase velocities ranging from 400 to 600 m/s. The corresponding horizontal wavelengths are estimated to be between 1300 and 3500 km. This figure also illustrates a variable time delay of 1 – 4 hours between the enhancement of auroral activity and the onset of TIDs at mid-latitudes.

GNSS-derived TID characteristics. Fig. 6 presents keograms (latitude–time and longitude–time maps) illustrating the propagation of TIDs with periods of 30 – 120 minutes (mostly large-scale TIDs) and 10 – 50 minutes (mostly medium-scale TIDs) across Europe during the magnetic storm period. The reference location for both latitude and longitude was selected as the position of the Pruhonice ionosonde (50.0°N, 14.6°E). This figure clearly indicates enhanced activity of both large- and medium-scale TIDs during selected intervals. The keograms also demonstrate a predominantly southward propagation direction, suggesting that the TID sources were located at high latitudes.

To further trace the propagation of large-scale TIDs on April 1, 2023, we generated maps of detrended TEC (dTEC) across Europe at different time stamps (Fig. 7). These maps reveal wave activity propagating from high to mid-to-low latitudes. We roughly estimated the TID characteristics, identifying a dominant period of approximately 60 minutes and a horizontal phase velocity of about 400 m/s, corresponding to a horizontal wavelength of 1440 km. More accurate estimations, obtained via cross-correlation analysis (similar to that applied to ionosonde data), yielded the same dominant period (60 minutes) but a higher horizontal phase velocity of 650 m/s, resulting in a horizontal wavelength of 2340 km. These findings demonstrate good consistency between the large-scale TID parameters derived from both ionosonde and GNSS techniques.

At this stage, we have not yet estimated the propagation characteristics of medium-scale TIDs, limiting our analysis to qualitative observations. The primary limitation is that the distances between ionosonde stations often exceed the horizontal wavelengths of medium-scale TIDs. For GNSS data, such detailed estimations are planned for future work.

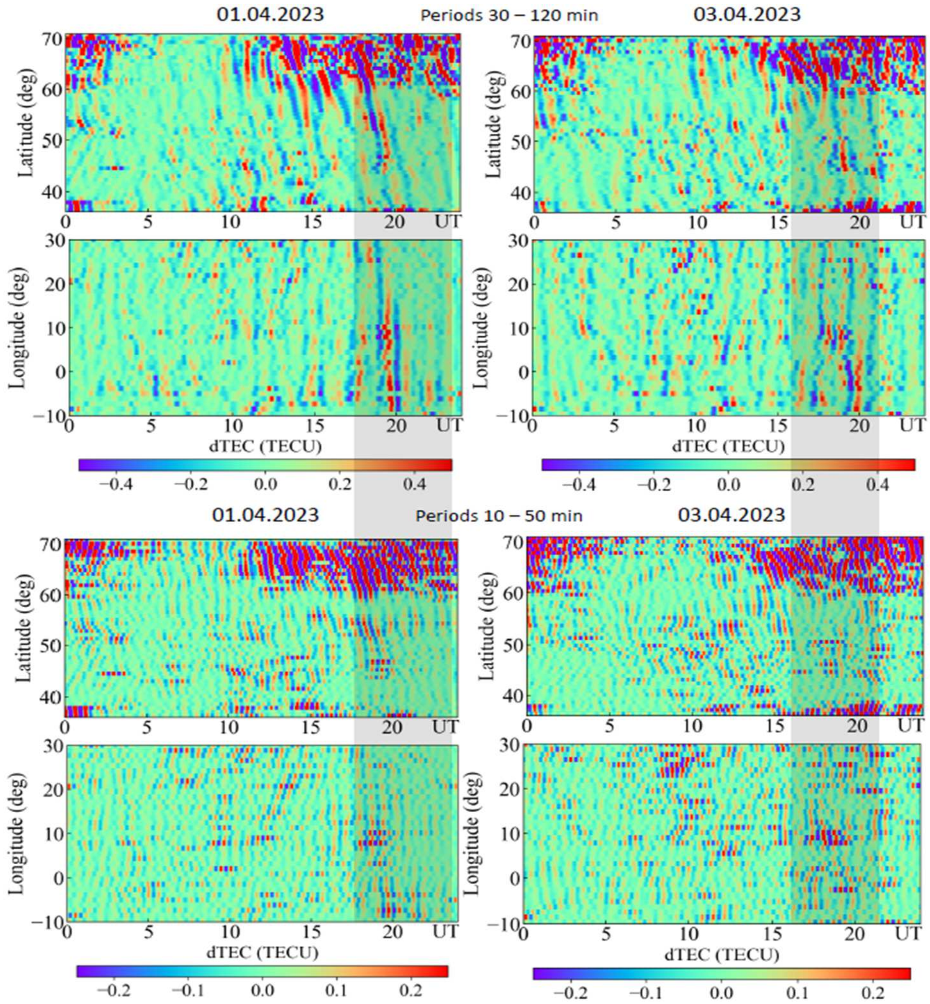


Figure 6. TID propagation on April 1 (a) and April 3 (b), 2023. Grey strips indicate the time intervals during which TIDs induced by the magnetic storm under investigation were confidently observed using both ionosonde and GNSS techniques.

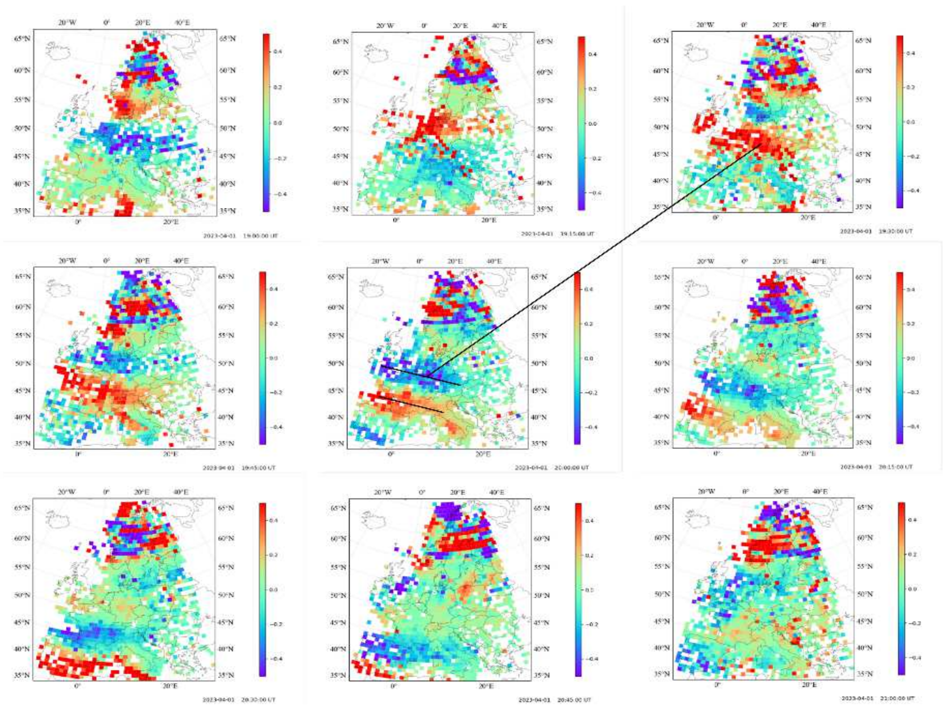
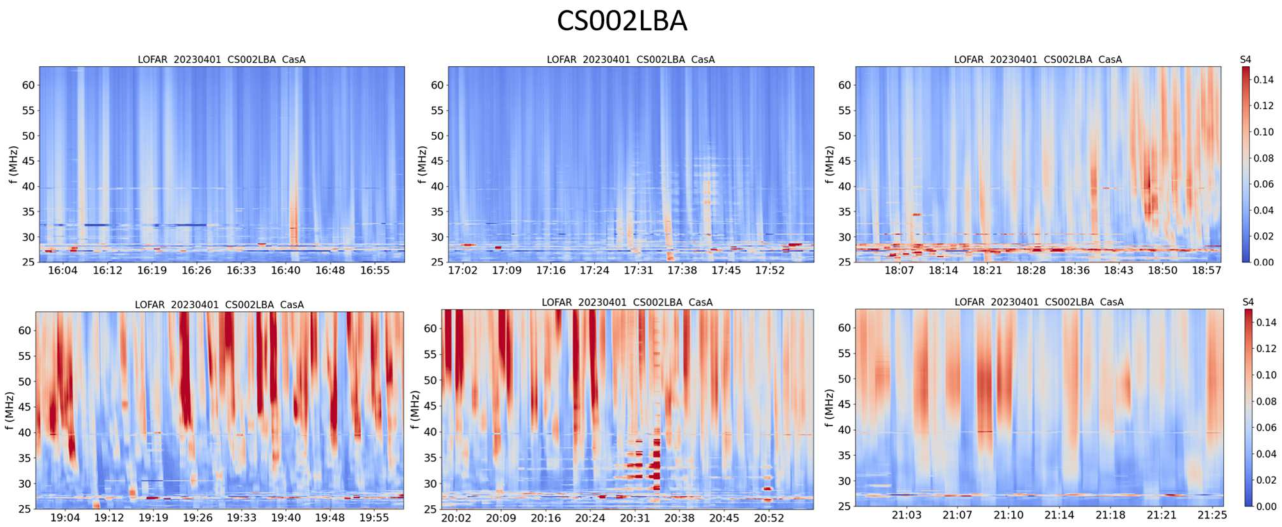


Figure 7. Maps showing large scale TID southward propagation during 19 – 21 UT on Apr. 1, 2023.

LOFAR observations. Fig. 8 shows an enhancement in the S4 scintillation index beginning around 17:30 – 18:00 UT on April 1, 2023, observed over both LOFAR stations. This increase in scintillation activity may be attributed to two potential sources: the passage of the solar terminator and intensified auroral activity. A more detailed future analysis is required to separate the influence of these two drivers and to identify potential TID signatures in the LOFAR data.

As an initial step, we conducted a preliminary visual analysis of the S4 scintillation patterns recorded at two LOFAR stations located at different latitudes (Fig. 9). This figure reveals similarities in certain features observed at both stations, with a noticeable time delay at the more southerly station (DE601LBA). For example, similar structures appear near 18:21 UT and 18:50 UT with a delay at DE601LBA. This temporal offset may indicate the southward propagation of small-scale ionospheric irregularities, possibly linked to TID activity.

To further investigate, we plan to apply established methodologies for drift velocity estimation developed at ASTRON and the CBK/PAS Node. These analyses will help determine whether the observed structures represent TID manifestations in the LOFAR data. Also, raw dynamic spectra will be used to conduct a more precise and detailed evaluation.



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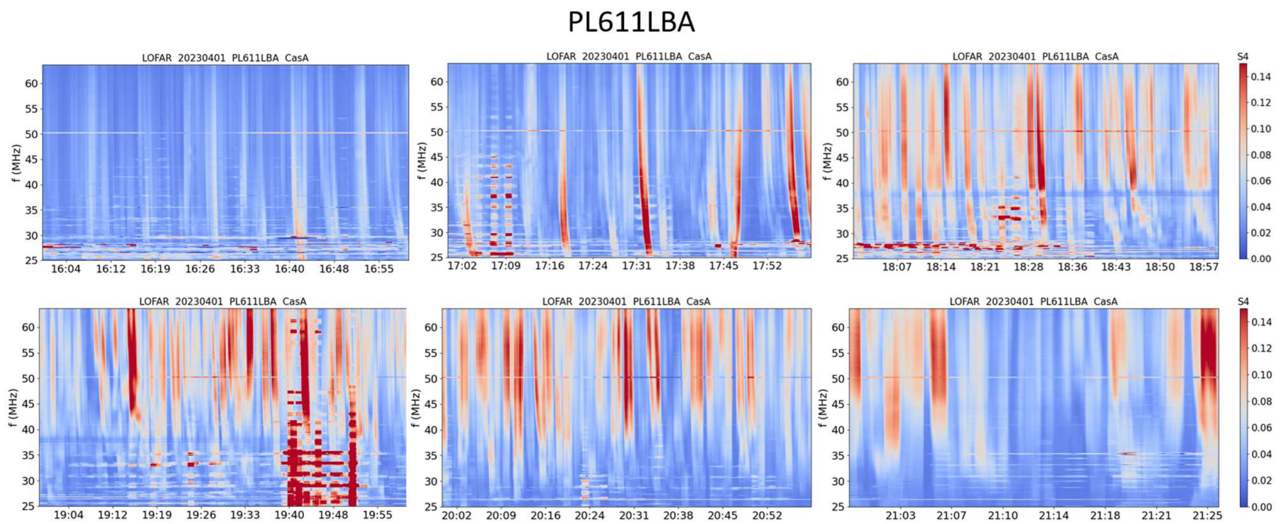

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Figure 8. LOFAR derived S4 scintillations on April 1, 2023 obtained by core CS002LBA station (Netherlands) (a) and PL611LBA station (Poland) (b) Time is in UT.

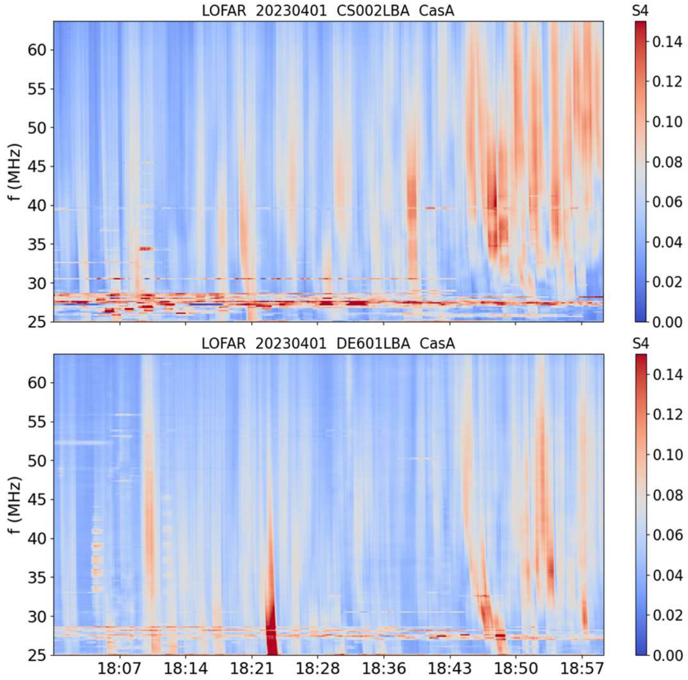

Figure 9. Comparison of S4 scintillations over two LOFAR stations having close longitudes but different latitudes. Time is in UT.

6. The added value gained from the TNA

The added value provided by the TNA program included expert consultations and several joint in-person and online seminars attended by scientists from the Institute of Atmospheric Physics and the CBK/PAS Node. Thanks to these fruitful discussions and collaborative efforts, a number of new results were achieved and validated. Additionally, the TNA facilitated access to LOFAR data and analysis scripts, as well as the LOFAR facility itself, enabling in-depth investigations of TIDs over Europe triggered by CIR/HSS-driven storm events. This collaboration offers long-term benefits for both institutions and significantly contributes to a deeper understanding of complex atmospheric and ionospheric dynamics during periods of enhanced auroral activity.

7. Summary

CIR / HSS-driven magnetic storms typically exhibit lower peak intensity but last longer in duration (Borovsky and Denton, 2006), and they can recur roughly every 27 days if the associated coronal hole remains stable. Several studies have indicated that storms caused by HSSs and CIRs are often more efficient in depositing energy from the solar wind into the magnetosphere (Turner et al., 2009). Moreover, the effects of these storms can extend for several days after their main phase ends (Burns et al., 2012), supporting prolonged and effective generation of atmospheric gravity waves (AGWs) and TIDs. Observational evidence of TIDs originating at high latitudes and propagating equatorward during CIR / HSS-driven storms has been documented (e.g., Panasenko et al., 2023). However, a comprehensive statistical investigation is still lacking to determine which type of storm driver is more prone to initiating atmospheric wave activity across various temporal and spatial scales.

In the framework of PITHIA NRF TNA “SUNDIAL” project, we thoroughly investigated the TIDs, originated by the HSS/CIR driven storm on Mar. 30 – Apr. 6, 2023. The data from dense GNSS receiver, LOFAR and ionosonde European networks were employed for joint analysis. We detected the several time intervals with TIDs propagated from the high latitudes towards the equator associated with an enhancement in auroral activity. The main results can be summarized as follows.

1. The unified methodology was improved and extended and the software was updated for joint analysis of ionosonde, GNSS and LOFAR data to retrieve TID characteristics.

2. We detected several time intervals with intensification of both types of TIDs propagating from the high latitudes towards the equator and associated with an increase in auroral activity.

3. Ionosonde and GNSS based results show the consistency in estimation of characteristics of TIDs, which have the dominant periods of 30 – 80 min, horizontal phase velocities of 200 – 600 m/s and horizontal wavelengths of 400 – 3500 km.

4. The obtained results showed the significant increase in TID occurrence rate and the prevalence in their southward propagation during the observed magnetic storm.

5. The LOFAR S4 scintillation index exhibited increased intensity during the period when TID activity was detected using other observational techniques. The observed time delay in S4 index signatures between two LOFAR stations with latitudinal separation suggests the southward propagation of small-scale ionospheric irregularities, potentially associated with TID activity.

6. Based on this case study, we spotted that the TIDs at midlatitudes were usually observed several (1 – 4) hours after the increase in the auroral activity characterized by IMAGE IE indices. We continue to analyse other CIR / HSS driven events to establish the validity of such a relationship.

The results of the PITHIA-NRF TNA "SUNDIAL" project were presented at the EGU 2025 General Assembly (Panasenko et al., 2025). A manuscript is also being prepared for submission to a high-impact scientific journal.

References

Borovsky, J. E., & Denton, M. H. (2006). Differences between CME-driven storms and CIR-driven storms. Journal of Geophysical Research: Space Physics, 111(A7), https://doi.org/10.1029/2005JA011447.

Burns, A. G., Solomon, S. C., Qian, L., Wang, W., Emery, B. A., Wiltberger, M., & Weimer, D. R. (2012). The effects of corotating interaction region/high speed stream storms on the thermosphere and ionosphere during the last solar minimum. Journal of Atmospheric and Solar-Terrestrial Physics, 83, 79 – 87, https://doi.org/10.1016/j.jastp.2012.02.006.

Panasenko, S. V., Aksonova, K. D., Burešová, D., Bogomaz, O. V., Zhivolup, T. G., & Koloskov, O. V. (2023). Large-scale traveling ionospheric disturbances over central and eastern Europe during moderate magnetic storm period on 22 – 24 September 2020. Advances in Space Research, 72(10), 4364 – 4378, https://doi.org/10.1016/j.asr.2023.09.035.

Panasenko, S. V., Burešova, D., Skipa, V., and Urbář, J.: Traveling ionospheric disturbances over midlatitude Europe during CIR/HSS driven magnetic storm on March 30 – April 6, 2023, EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025, EGU25-6512, https://doi.org/10.5194/egusphere-egu25-6512.

Turner, N. E., Cramer, W. D., Earles, S. K., & Emery, B. A. (2009). Geoefficiency and energy partitioning in CIR-driven and CME-driven storms. Journal of Atmospheric and Solar-Terrestrial Physics, 71(10 – 11), 1023 – 1031, https://doi.org/10.1016/j.jastp.2009.02.005.

Acknowledgement

We acknowledge the research infrastructure(s) and the access provider CBK / PAS Node of the PITHIA-NRF project (https://www.pithia-nrf.eu/). The PITHIA-NRF project has received funding from European Union's Horizon 2020 research and innovation programme under grant agreement No 101007599. The open source GeospaceLAB Python framework (https://github com/JouleCai/geospacelab) was utilized to fetch data from various open access databases and to build some figures.