Ionospheric Irregulates Response to the April 2023 Major Geomagnetic Storm: A European Perspective

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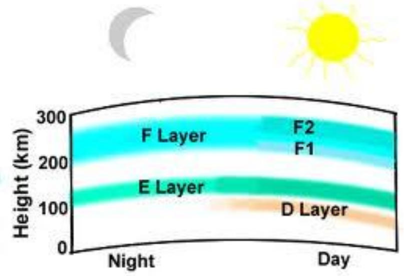
Outline

Introduction



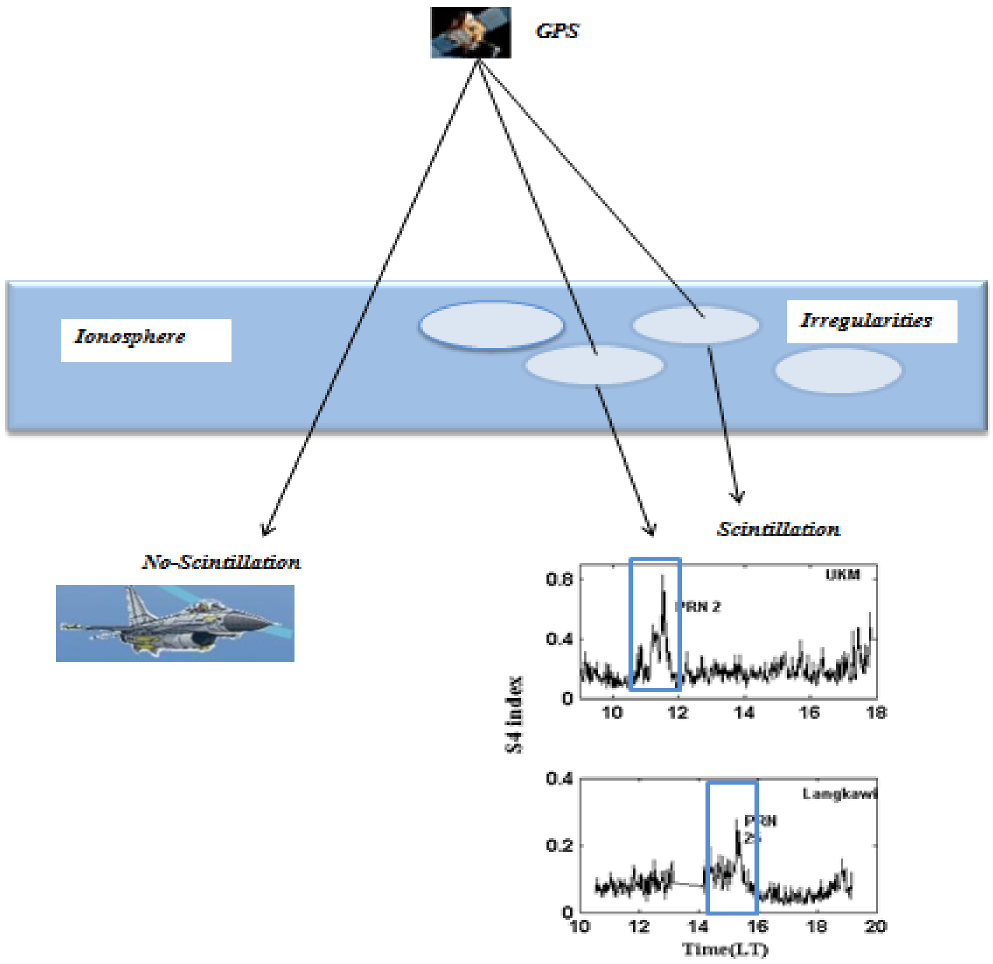


Figure 1. Sketch of Ionospheric Scintillation.

- **Ionospheric scintillation**: Rapid variations of amplitude and phase in radio signals caused by small scale irregularities of electron density known as scintillation.

- **Amplitude scintillation(S4 index)**:
- **Phase scintillation (Sigmaphi)**:

Scintillation is stronger at polar, auroral , and **equatorial** latitudes.

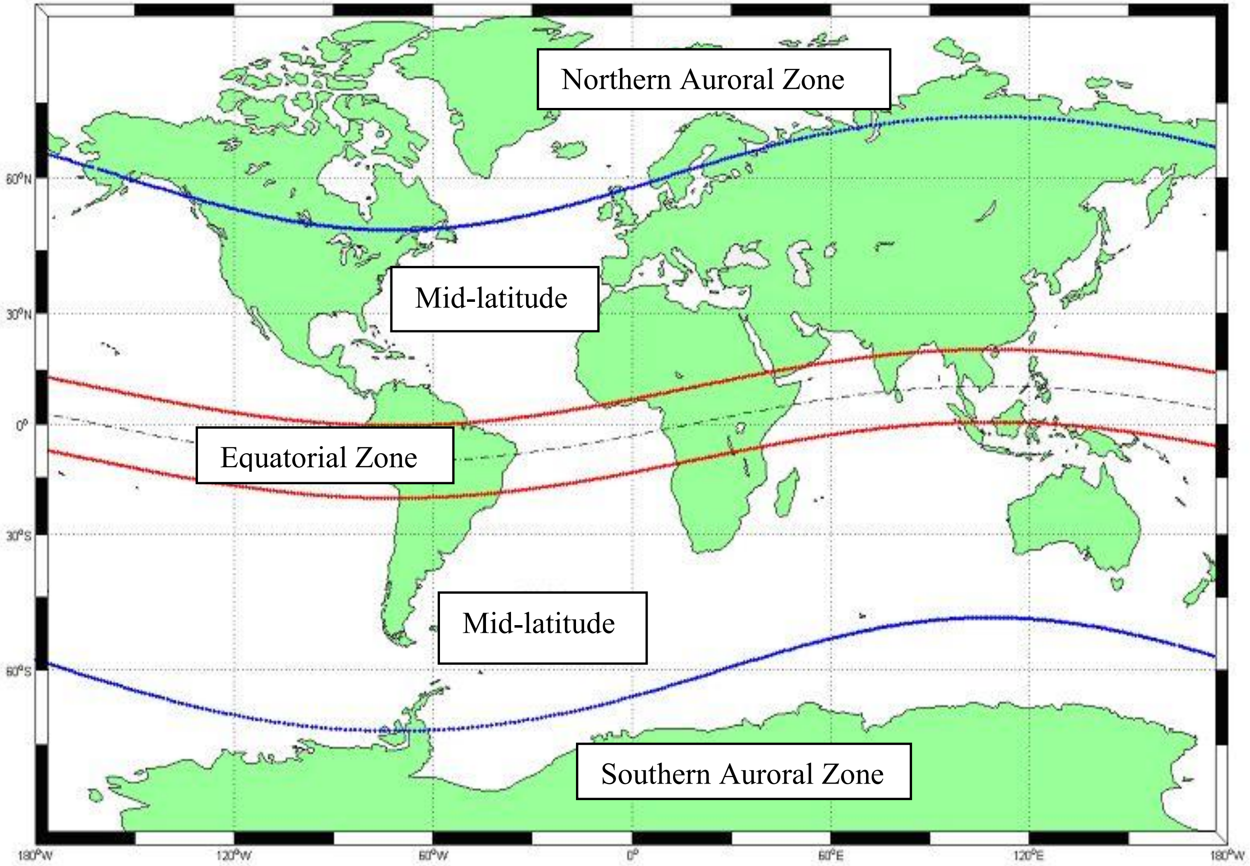
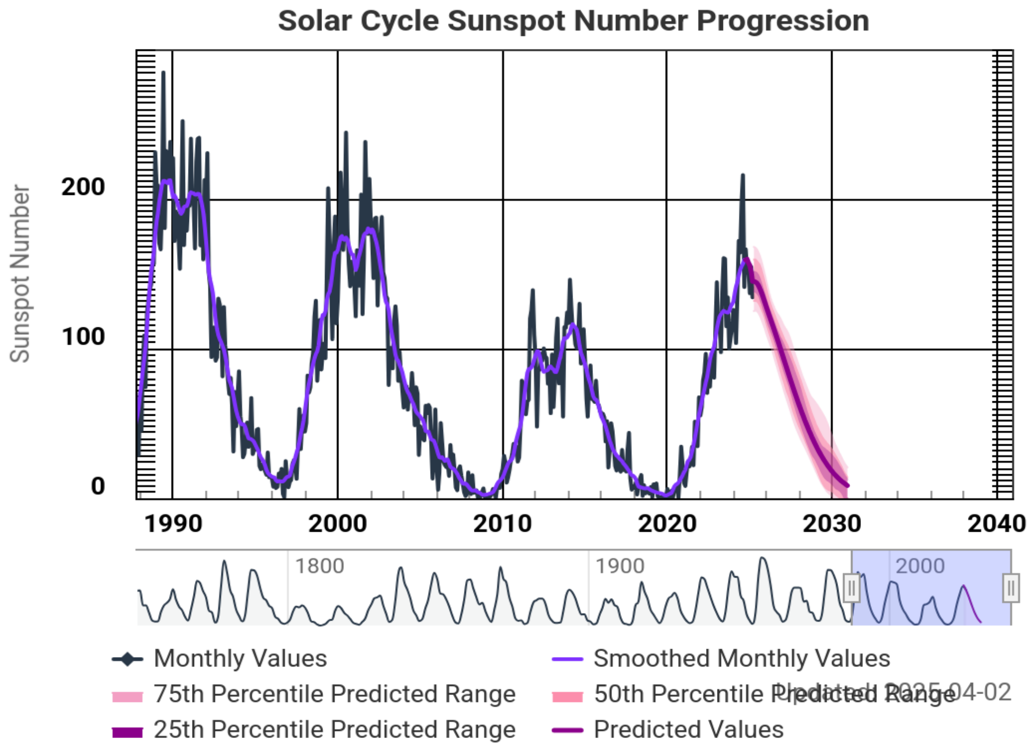


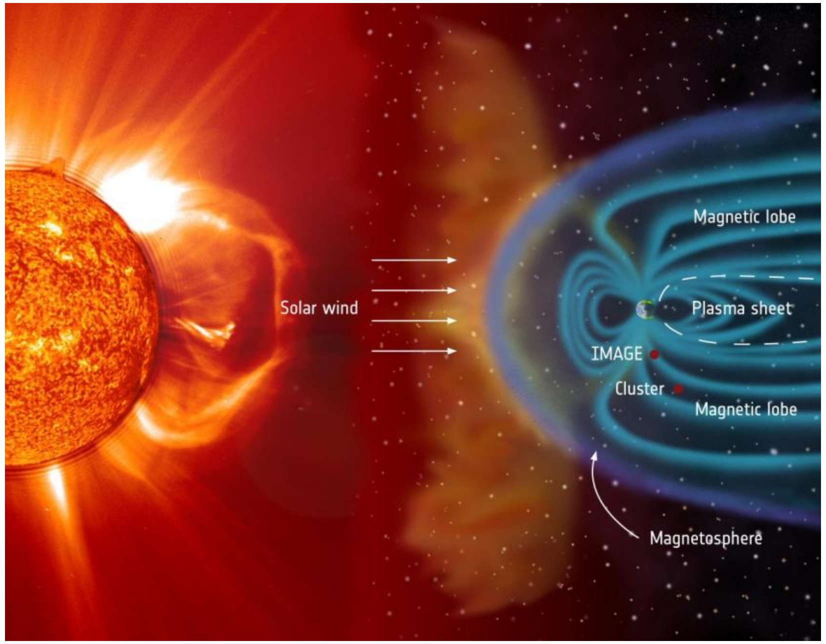
Figure 2. Regions of the ionosphere.

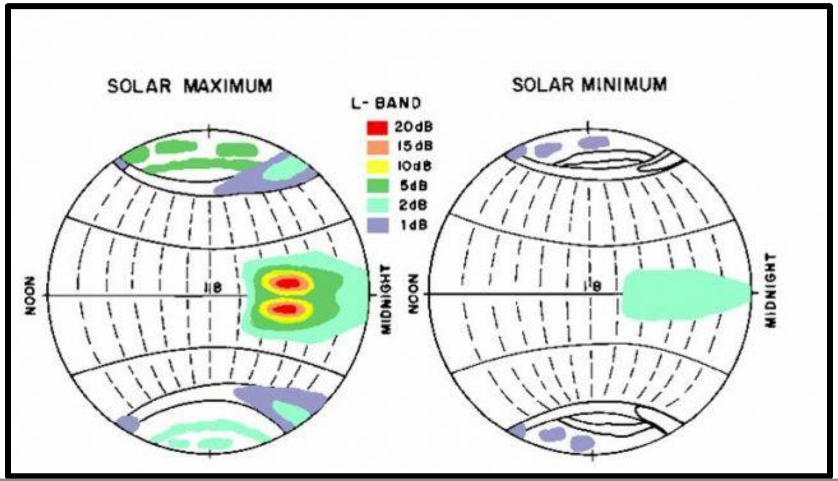
Source: Willis 2008

At midlatitudes (roughly between ~30°–60° geomagnetic latitude), scintillation is **much less frequent** compared to the equatorial or polar regions. But when it does happen, it's often linked to **geomagnetic storms** or strong space weather events, not regular day-night patterns.

Solar Cycle







Basu, S. et al., J. Atmos. Terr. Phys, 2002

Solar cycle influences the general behavior of the phenomenon
https://www.swpc.noaa.gov/products/solar-cycle-progression

Problem Statement

- Investigate the temporal and spatial variability of ionospheric irregularities—specifically scintillation, Total Electron Content (TEC), and Rate of TEC Index (ROTI)—during the geomagnetic storm of 23–25 April 2023 over Europe, using multi-source data from LOFAR, UPC, and DLR, in order to improve understanding of space weather impacts on GNSS systems and support the development of mitigation strategies.

Methodology

- **LOFAR Data:** The Low-Frequency Array (LOFAR) provides high-resolution radio observations in the megahertz range. This dataset is used to analyze ionospheric scintillation by measuring amplitude and phase fluctuations, helping to characterize small-scale irregularities.

- **UPC ROTI Data:** The Universitat Politècnica de Catalunya (UPC-IonSAT) supplies Rate of TEC Index (ROTI) worldwide data, which is derived from 30-seconds real-time GNSS observations. ROTI is used to quantify rapid TEC variations and assess large-scale ionospheric disturbances.

- **DLR VTEC and ROTI Data:** The German Aerospace Center (DLR) provides Vertical TEC (VTEC) and ROTI datasets for 29 LOFAR stations. These data allow us to examine large-scale ionospheric irregularities and their temporal evolution during the storm.

LOFAR Stations

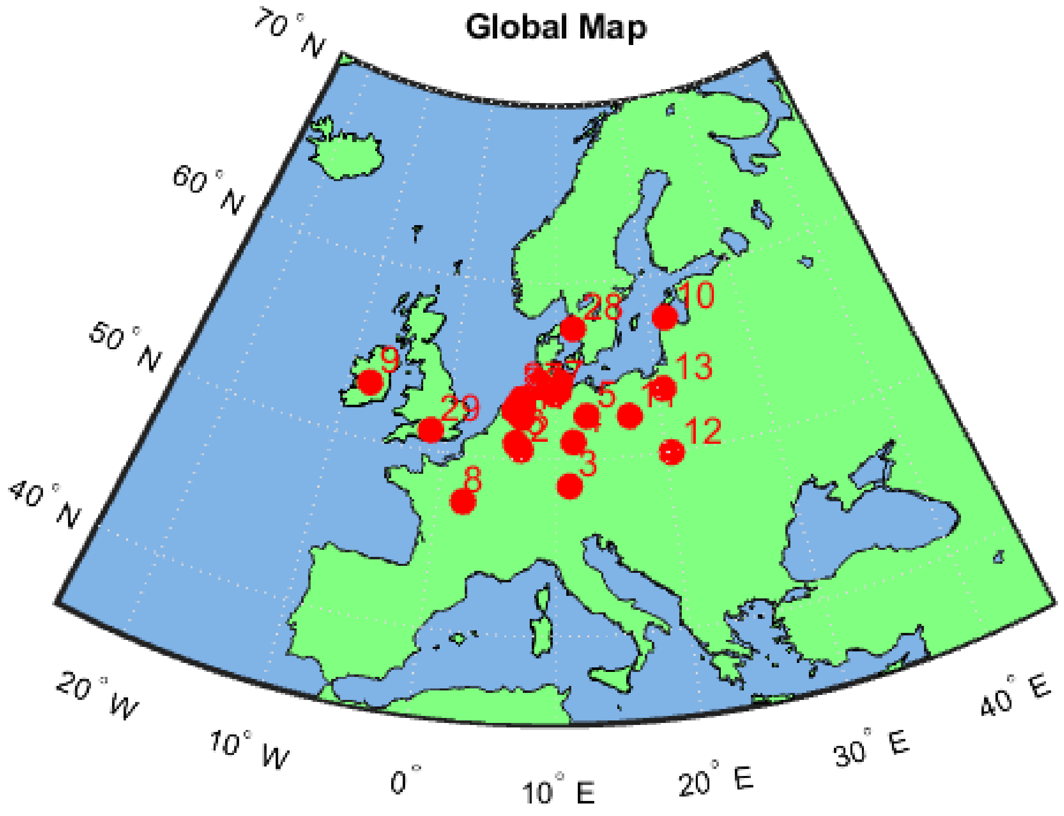


Figure 3. The locations of the 29 LOFAR stations used in this analysis.

Station Number	Name of Stations	Longitude	Latitude
Station1	CS002LBA	6.8698	52.9151
Station2	DE601LBA	6.884	50.5233
Station3	DE602LBA	11.2881	48.5011
Station4	DE603LBA	11.7113	50.9793
Station5	DE604LBA	13.0163	52.4385
Station6	DE605LBA	6.4234	50.8973
Station7	DE609LBA	9.9698	53.6985
Station8	FR606LBA	2.1934	47.3759
Station9	IE613LBA	-7.9222	53.0953
Station10	LV614LBA	21.8549	57.5569
Station11	PL610LBA	17.0733	52.2761
Station12	PL611LBA	20.4901	49.9646
Station13	PL612LBA	20.5889	53.5938
Station14	RS106LBA	6.9851	52.874
Station15	RS205LBA	6.8968	52.8575
Station16	RS208LBA	6.919	52.6693
Station17	RS210LBA	6.8736	52.3309
Station18	RS305LBA	6.7739	52.8995
Station19	RS306LBA	6.7433	52.8901
Station20	RS307LBA	6.6809	52.8032
Station21	RS310LBA	6.1386	52.7644
Station22	RS406LBA	6.7504	53.0179
Station23	RS407LBA	6.7843	53.0926
Station24	RS409LBA	6.358	52.9807
Station25	RS503LBA	6.8509	52.945
Station26	RS508LBA	6.9532	53.24
Station27	RS509LBA	6.7853	53.4089
Station28	SE607LBA	11.9297	57.3988
Station29	UK608LBA	-1.4335	51.1438

DST, Kp, and Ap

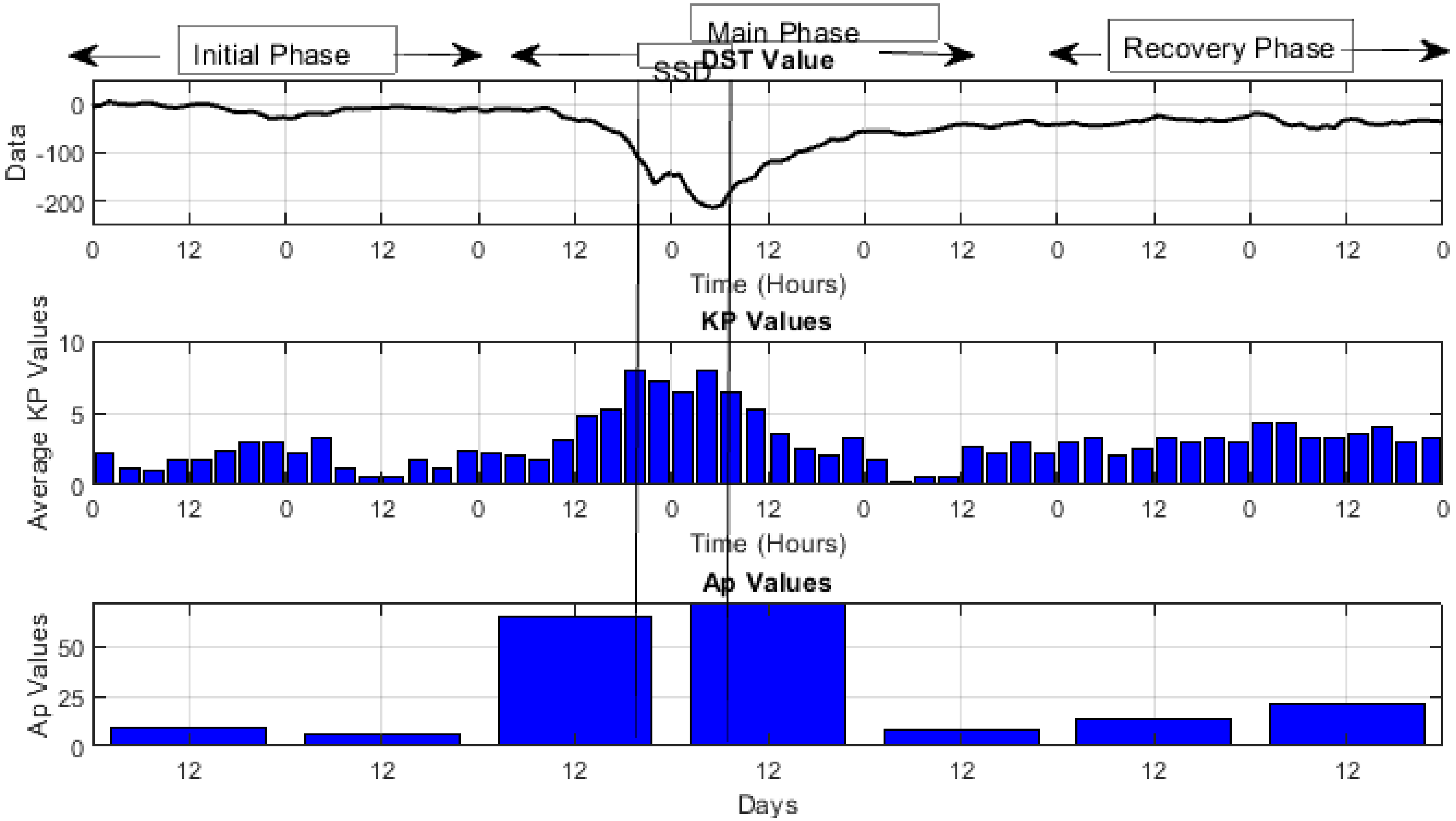


Figure 4. Dst, Kp, Ap indices during 21-27 April 2023.

3.1 Geomagnetic Storm Characterization

The disturbances of the Earth magnetic field lead to geomagnetic storm. In addition, transferring the energy from the solar winds through the magnetosphere will cause a geomagnetic storm.

A classical storm divided into three phase: the initial phase, main phase, and recovery phase. The initial phase indicates the beginning of the storm, with abrupt sudden storm commencement (SSC) occurrence and last for a few hours. The main phase is the interval from the SSC to the end of recovery phase. The recovery is the time interval that a storm takes to return to its normal conditions and this takes a few days.

Table 1 summarizes the World Data Center (WDC) classification of geomagnetic storm for these three phases.

Storm	**Kp**	**Ap**	**DST (nT)**
Major	≥ 7	≥ 50	Dst ≥ -200 nT
Minor to major	5 ≤ Kp ≤ 7	40-49	-100 nT≤ Dst ≤ -200nT
Minor	4	30-39	-50 nT ≤ Dst ≤ -100 nT

DST, Kp, and Ap

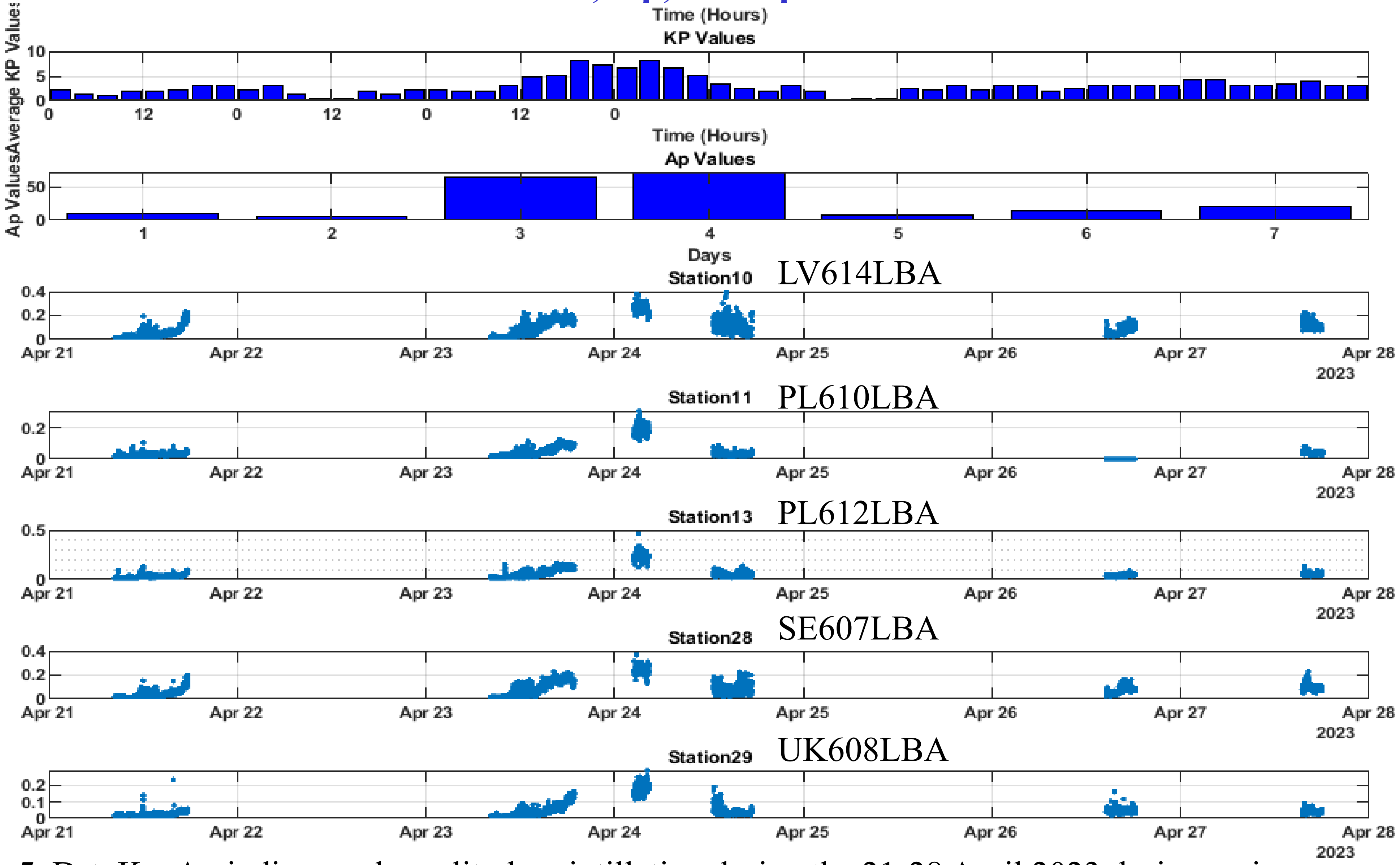
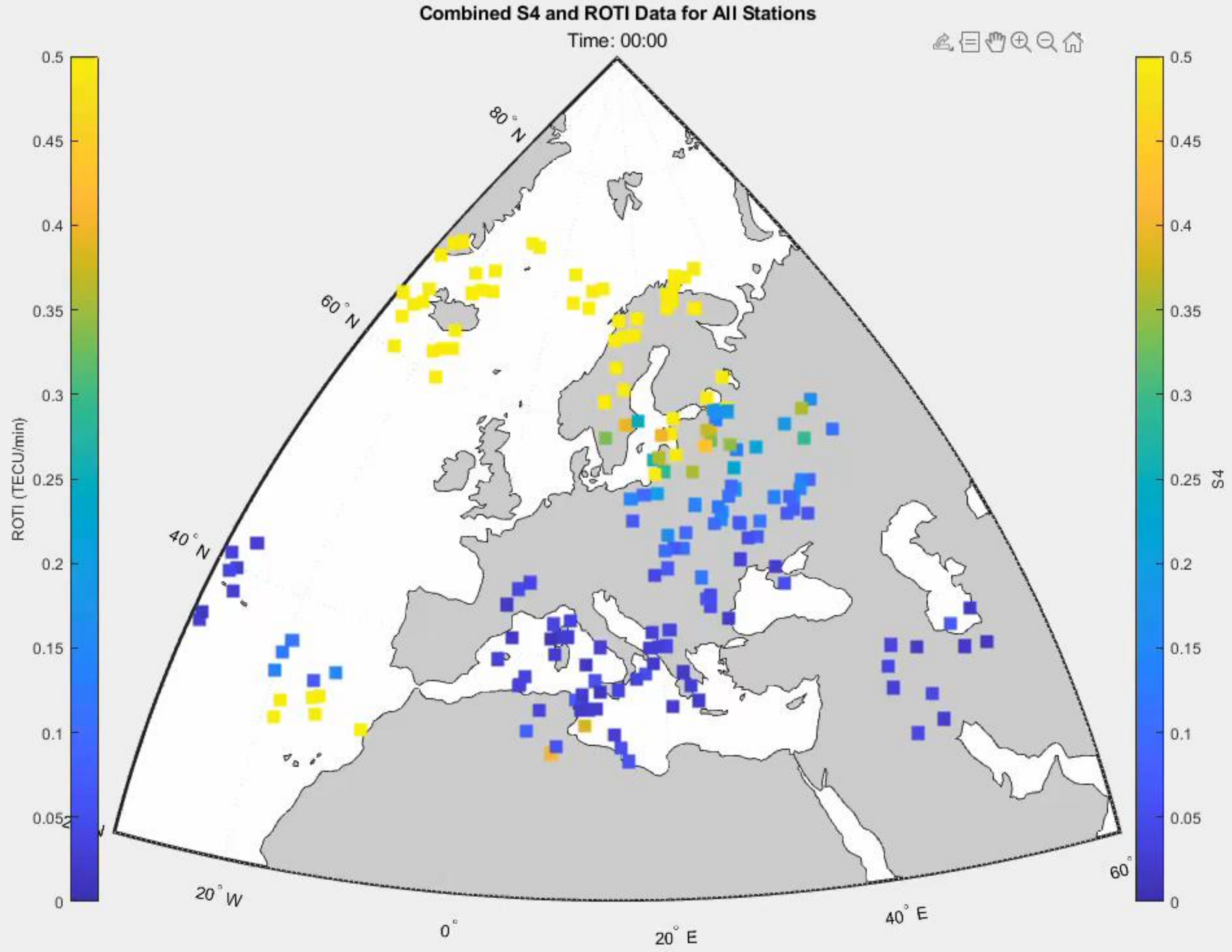
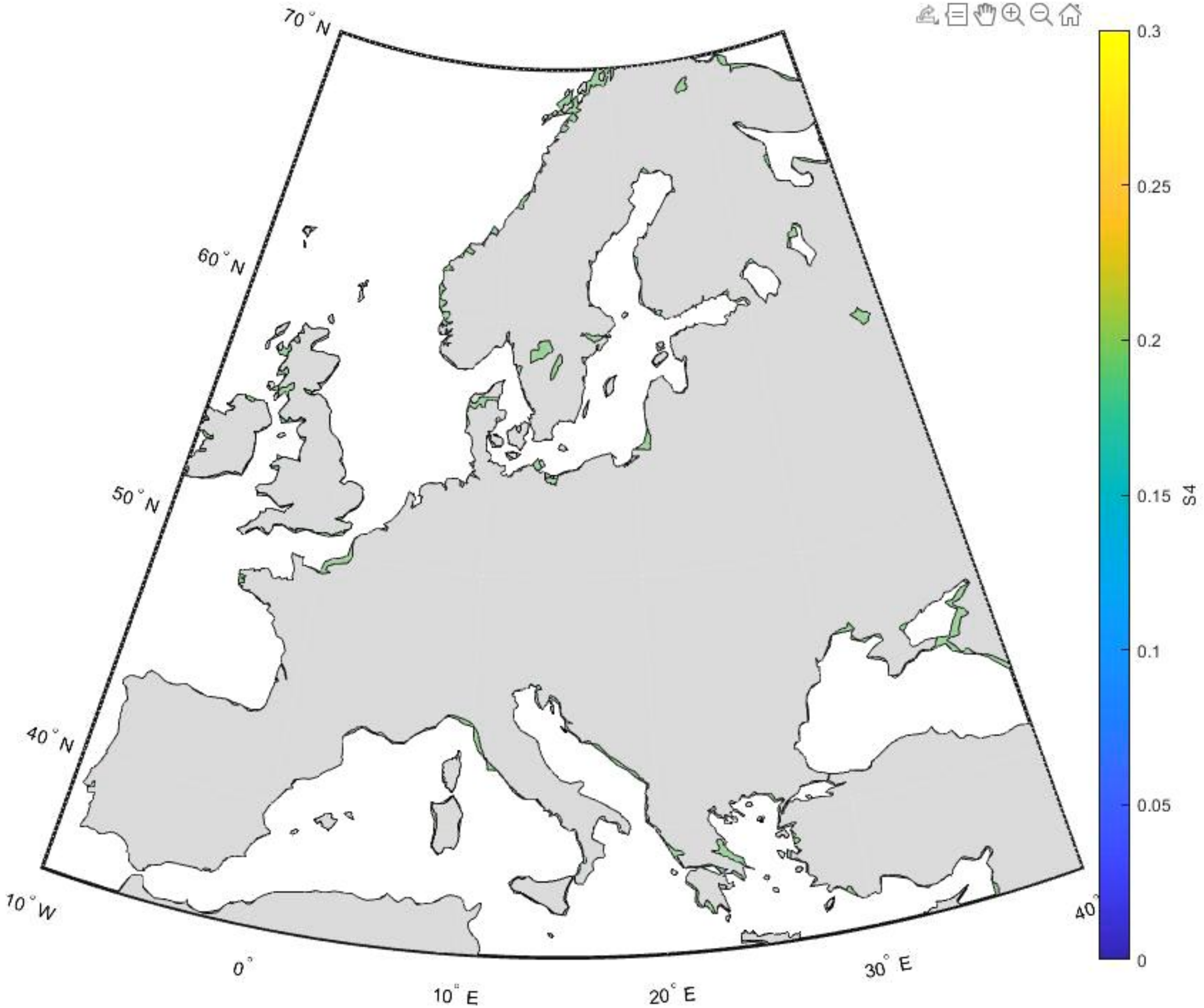


Figure 5. Dst, Kp, Ap indices and amplitude scintillation during the 21-28 April 2023 during major geomagnetic storm.

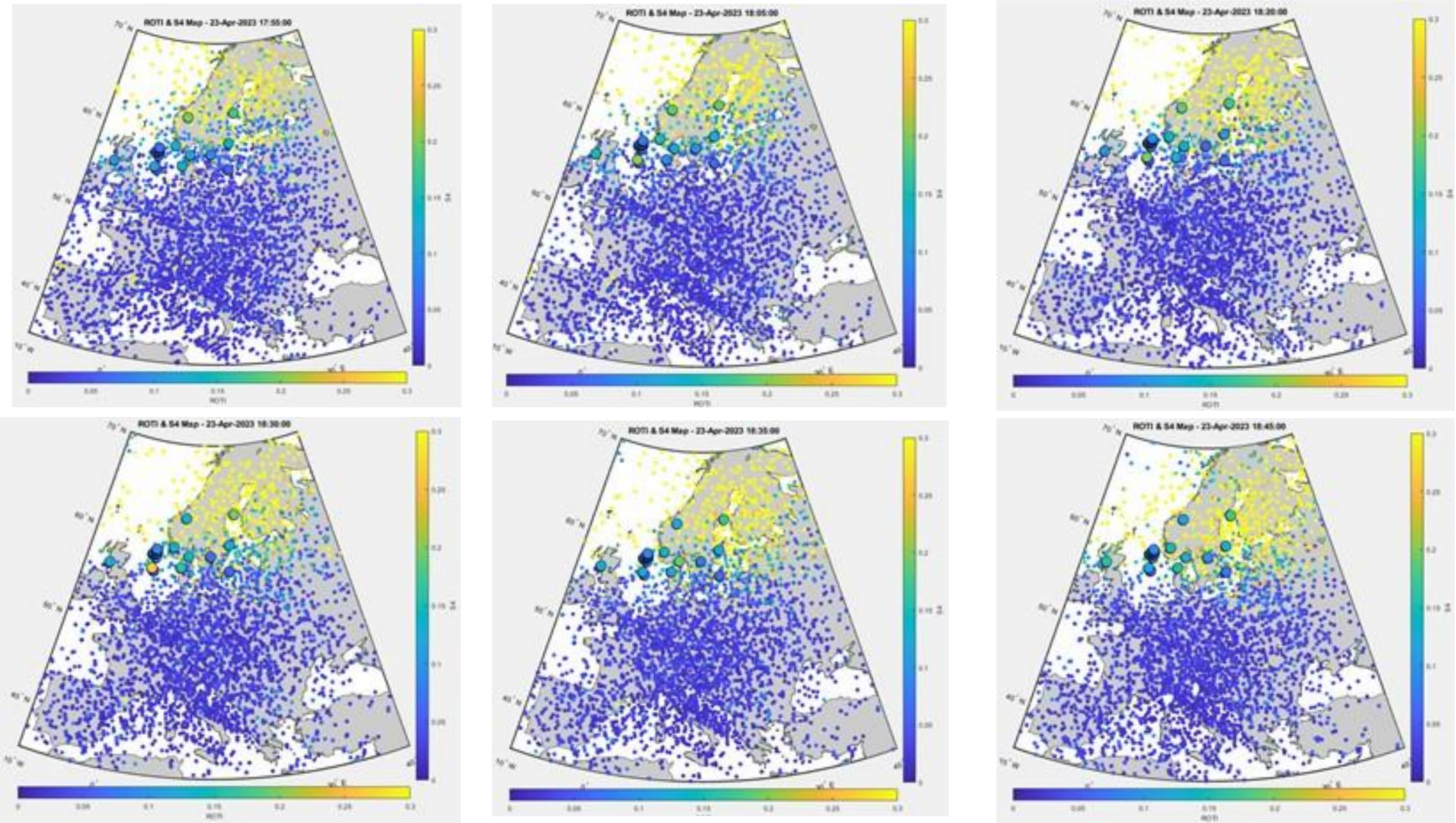


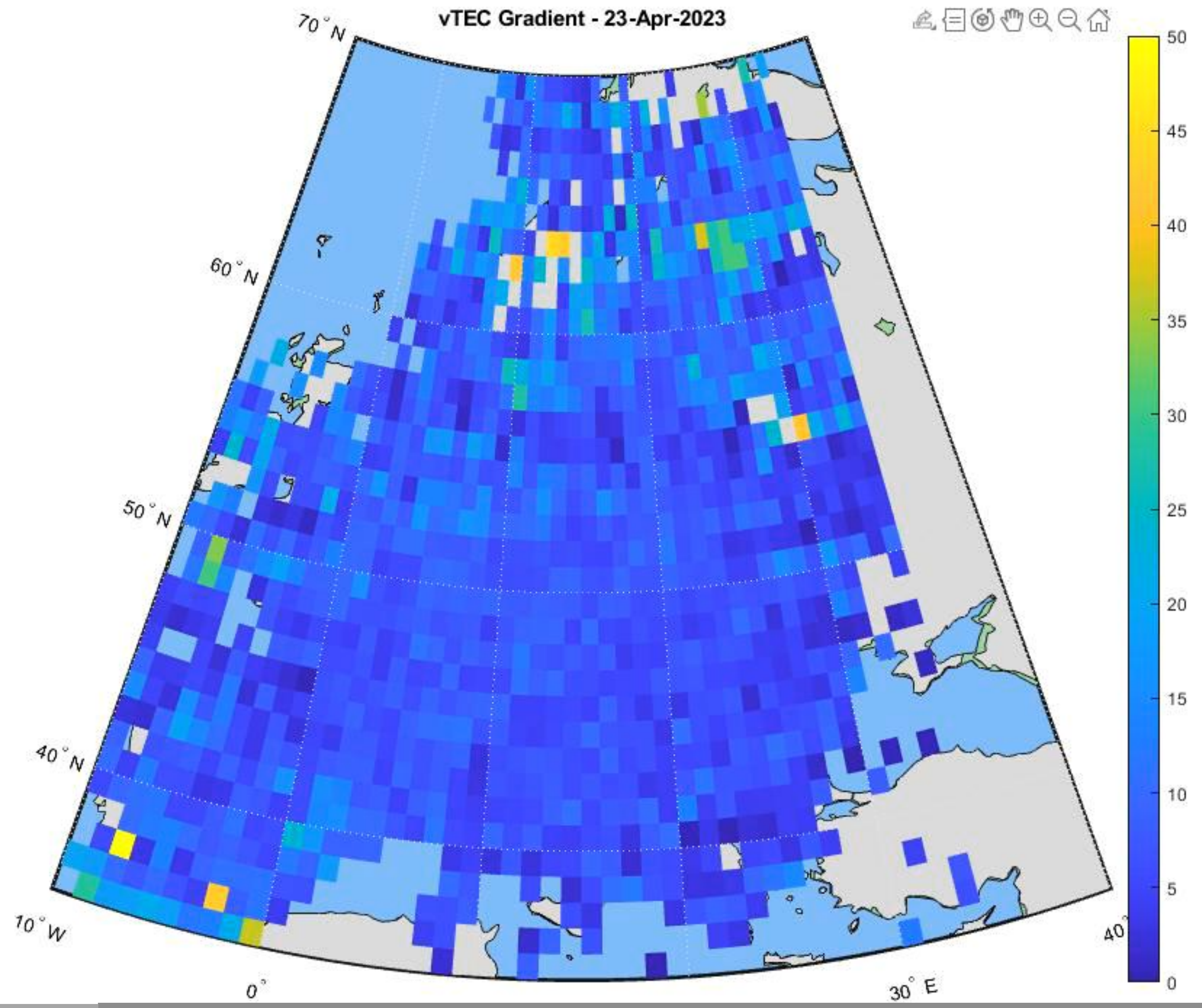
Combined S4 and ROTI Data for All Stations
Time: 00:00
ROTI (TECU/min)
S4
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
80° N
60° N
40° N
20° W
0°
20° E
40° E
60°



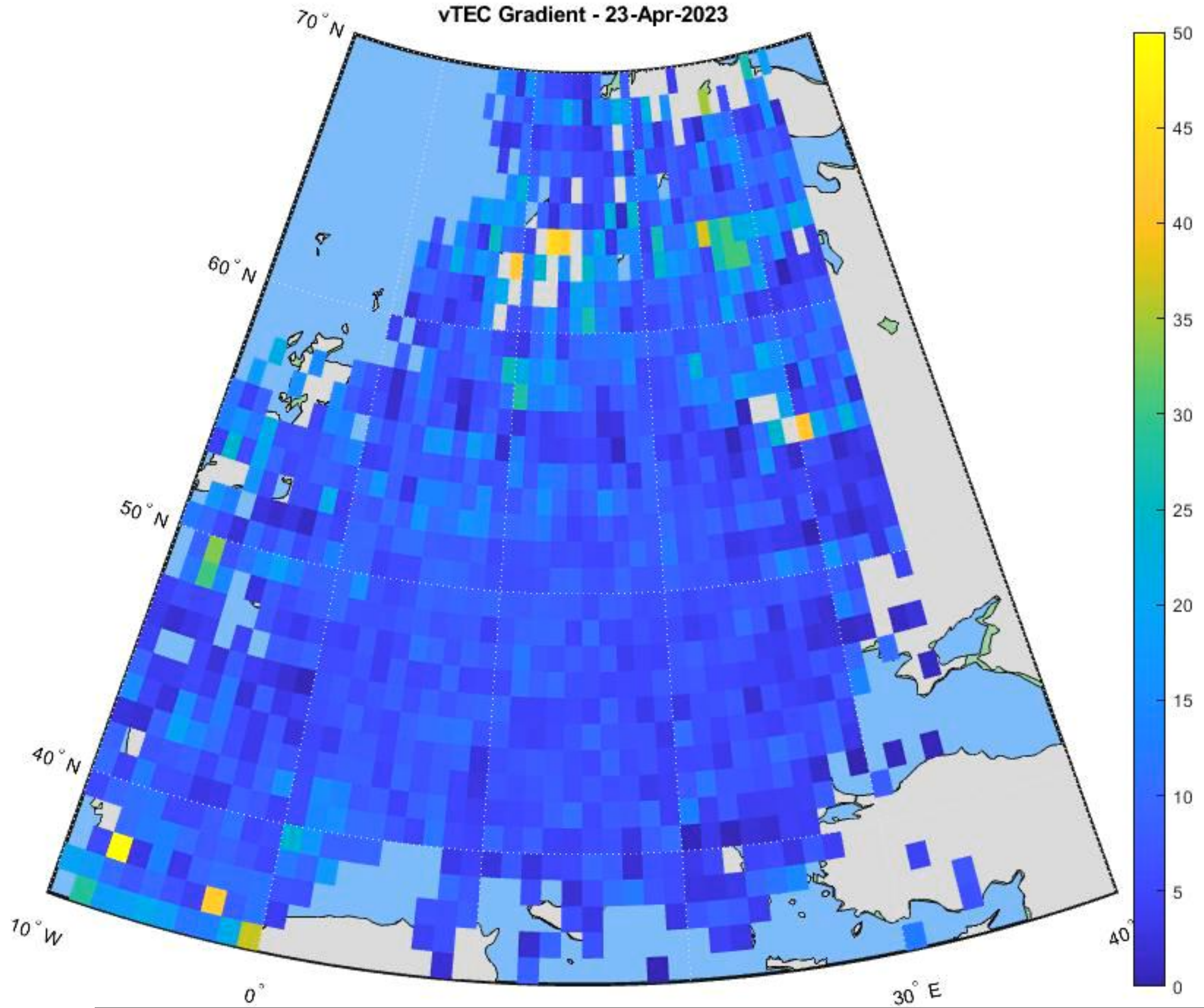
70° N
60° N
50° N
40° N
10° W
0°
10° E
20° E
30° E
40°
0.3
0.25
0.2
0.15
0.1
0.05
0
S4

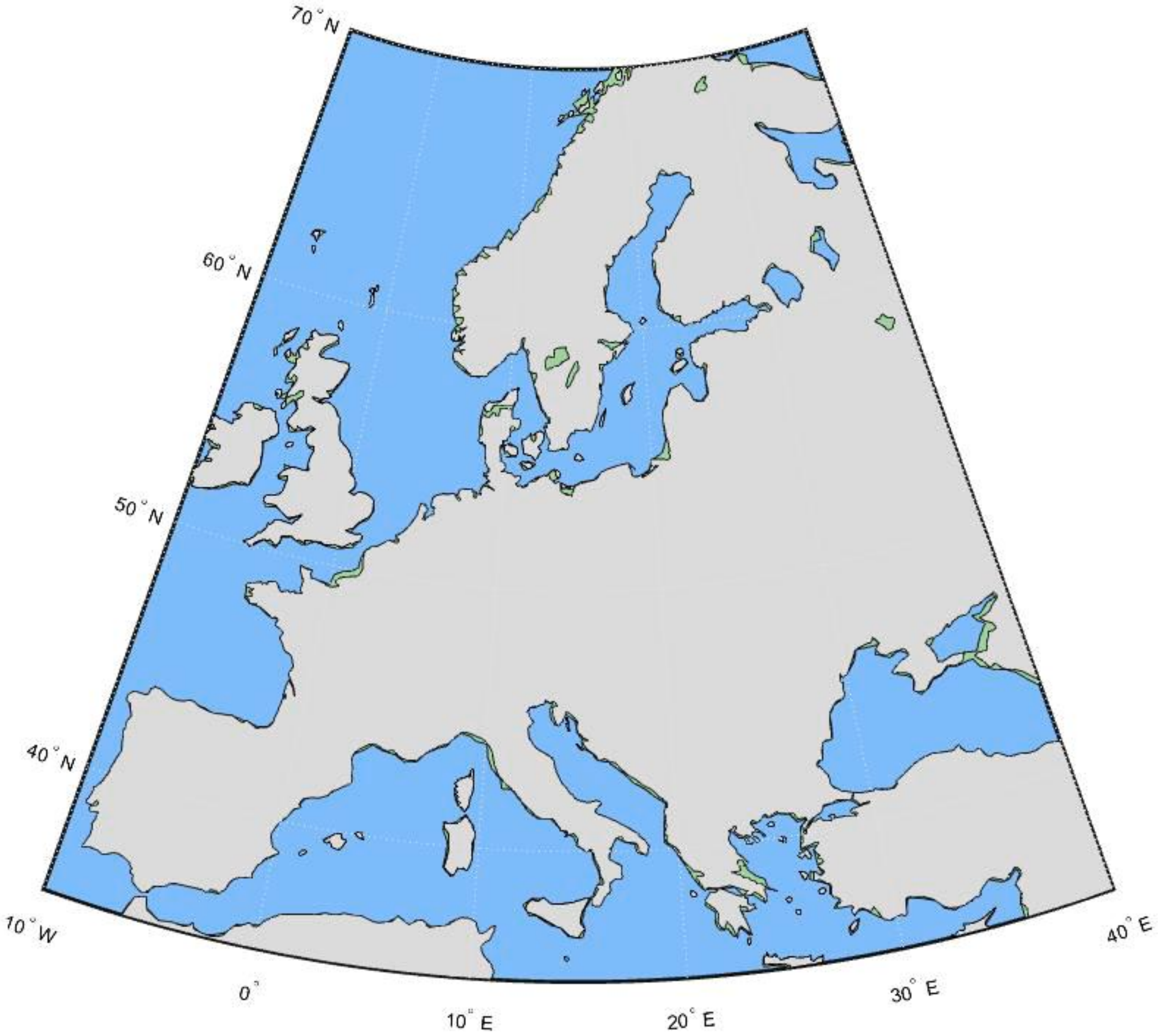
ROTI and Scintillation occurred on 23 April 2023 at 17:55 to 18:45





vTEC Gradient - 23-Apr-2023
70° N
60° N
50° N
40° N
10° W
0°
30° E
40°
50
45
40
35
30
25
20
15
10
5
0


vTEC Gradient - 23-Apr-2023
70° N
60° N
50° N
40° N
10° W
0°
30° E
40°
50
45
40
35
30
25
20
15
10
5
0


70° N
60° N
50° N
40° N
10° W
0°
10° E
20° E
30° E
40° E

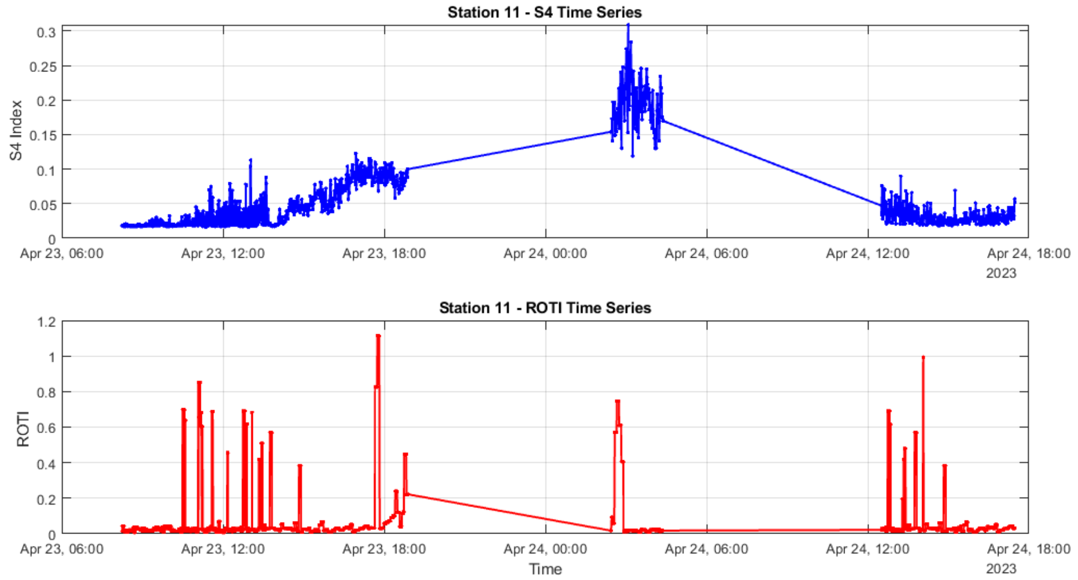
The top panel presents the S4 index, which indicates the presence of amplitude scintillation fluctuations in GNSS signals caused by ionospheric irregularities. The S4 values remain consistently low (< 0.05) during the early hours (08:00–10:30), reflecting quiet ionospheric conditions. However, beginning around 11:00 LT, the S4 index exhibits a gradual rise, with intermittent spikes reaching values up to 0.2. From approximately 13:00 to 19:00 LT, the S4 values remain elevated, suggesting persistent moderate amplitude scintillation activity likely linked to the development of ionospheric irregularities in the daytime E- or F-region.

The bottom panel displays the corresponding ROTI values, reflecting phase fluctuations due to spatial and temporal variations in total electron content (TEC). Similar to the S4 index, ROTI remains negligible during the early hours but begins to show sporadic increases around 10:00 LT. Short-duration bursts of enhanced ROTI continue through midday, with a sharp and sustained increase observed after 17:00 LT, peaking near 2.0 shortly before 19:00 LT. This abrupt rise may indicate the presence of intense large-scale irregularities.

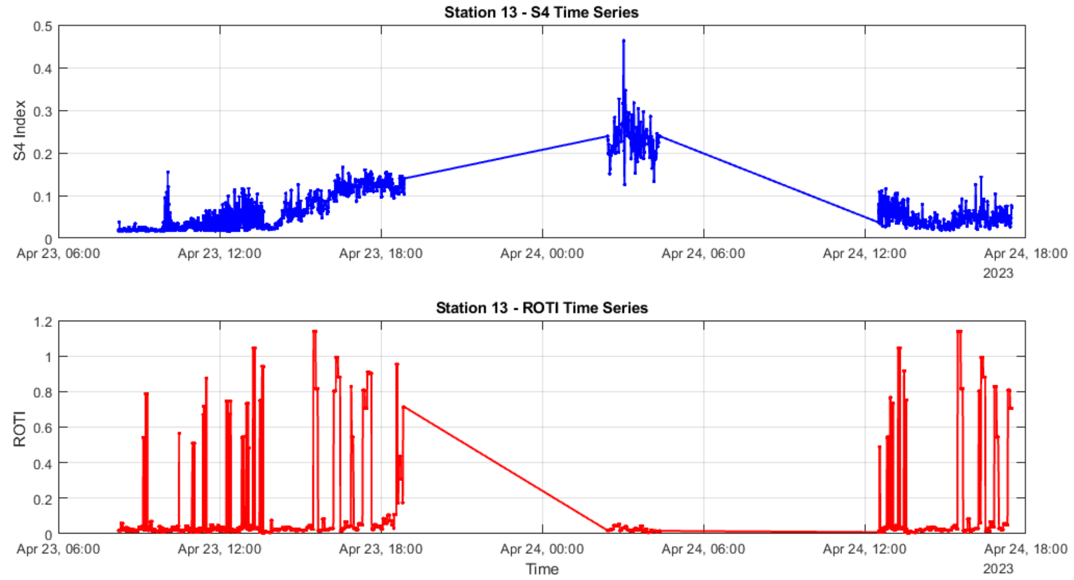
The observed temporal correlation between the elevated S4 and ROTI values suggests the co-existence of amplitude and phase scintillations, implying multi-scale irregularities in the ionosphere. This behavior is consistent with the signatures of sporadic E (Es) layers or post-sunset equatorial irregularities, which are known to degrade GNSS signal quality.

These findings support the need for continued joint analysis using complementary datasets such as LOFAR's high-frequency radio observations, UPC's GNSS TEC/scintillation maps, and DLR's model outputs to enhance the understanding and forecasting of ionospheric space weather impacts.

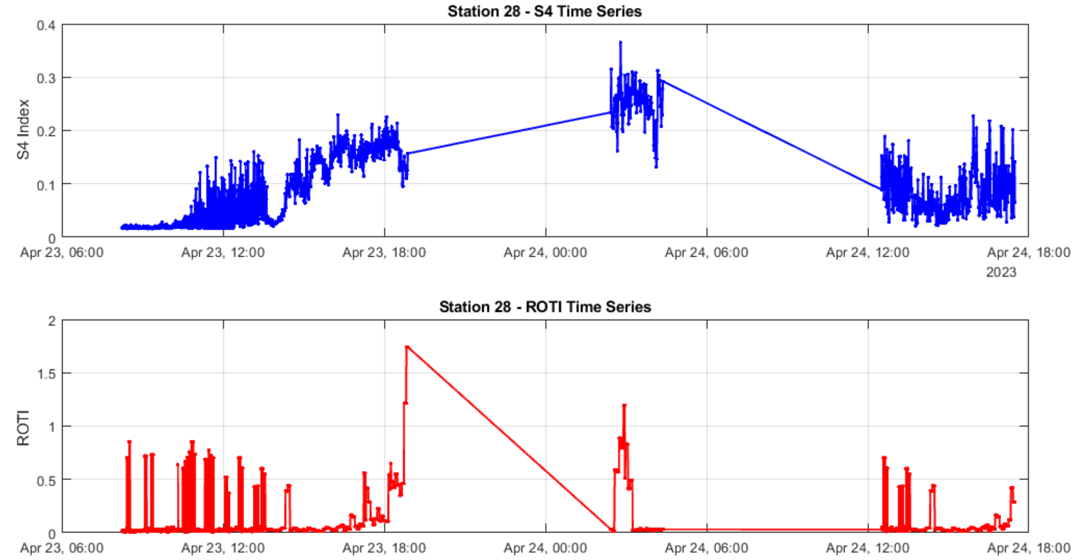
PL610LBA



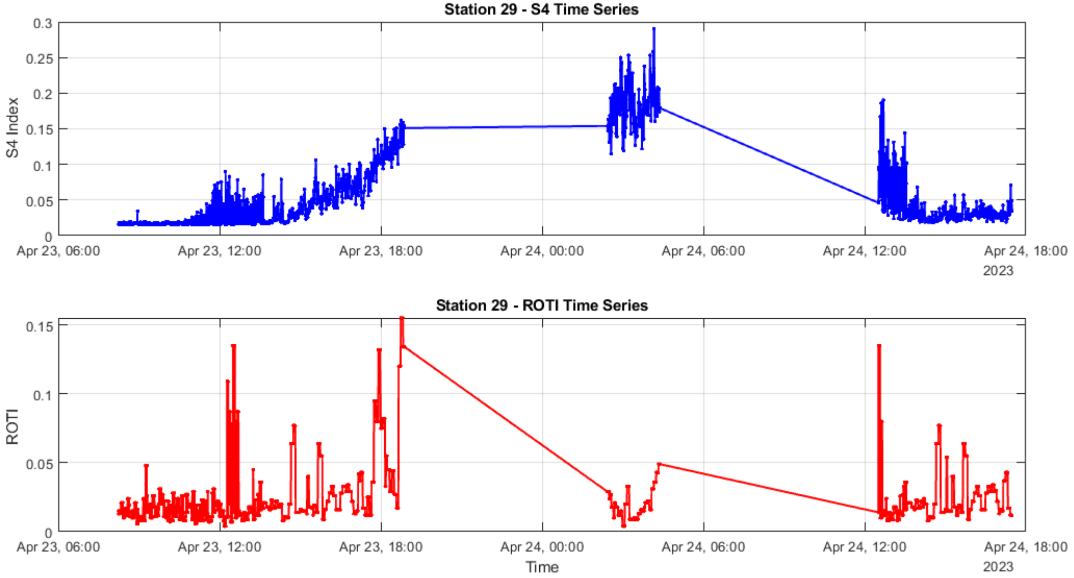
PL612LBA



SE607LBA

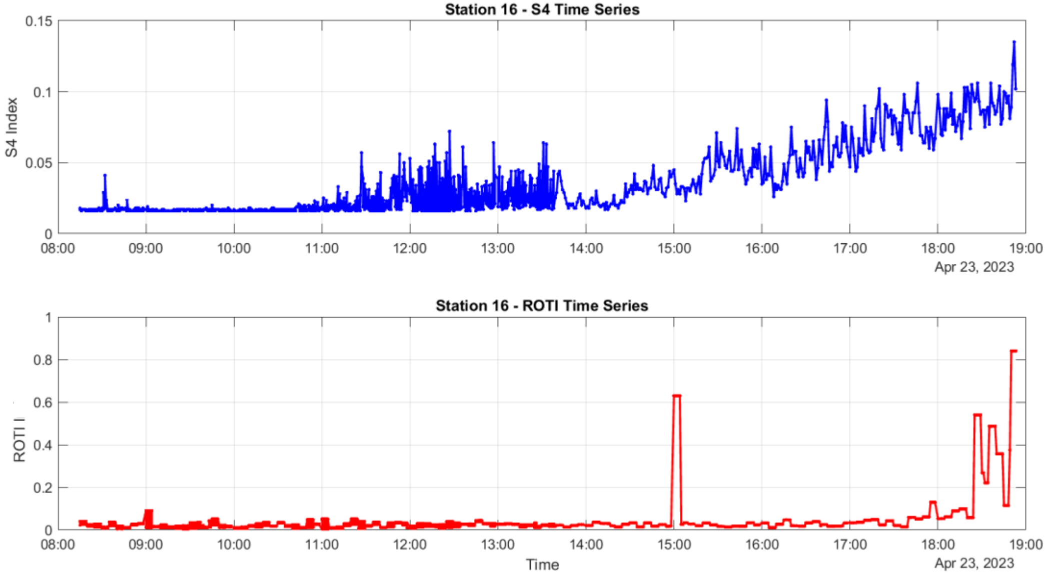


UK608LBA

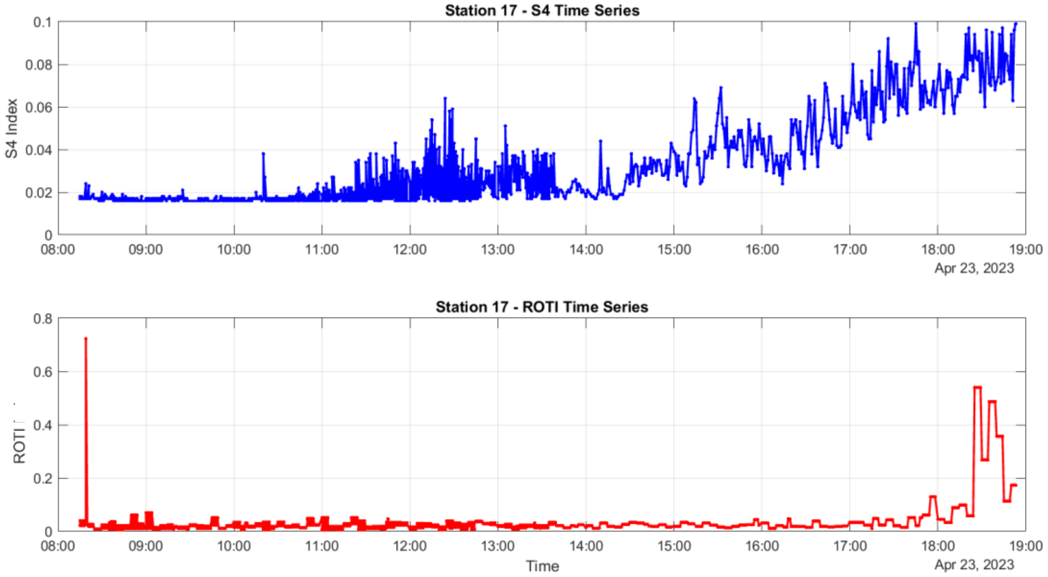


Without correlation

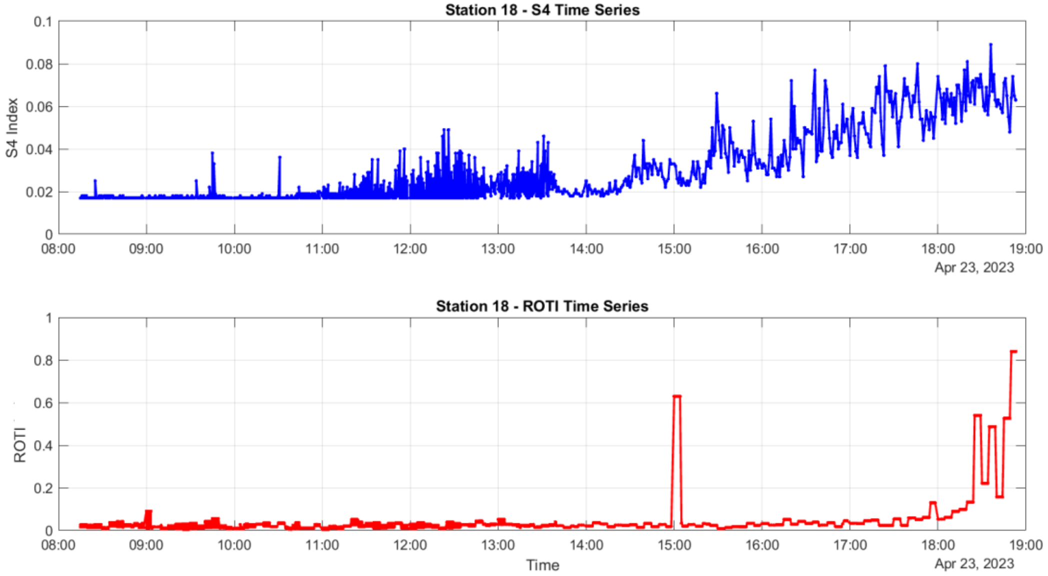
RS208LBA



RS210LBA



RS305LBA



Summary

This study investigates how disturbances in the Earth's ionosphere affect the signals used by satellite navigation systems like GPS. During strong space weather events, such as geomagnetic storms, irregularities in the ionosphere can disrupt these signals, leading to navigation errors or even loss of signal. To understand this better, we examined data from the LOFAR radio telescope network in Europe, alongside measurements from GNSS receivers (ROTI and TEC data provided by UPC and DLR), during the large geomagnetic storm on 23–25 April 2023. We focused on comparing two key indicators: the S4 index, which reflects rapid signal fluctuations (scintillation), and ROTI, which shows how much the total electron content in the ionosphere is changing over time. Our analysis revealed that in Europe's mid- and high-latitude regions, the S4 and ROTI signals do not always rise together, suggesting that small-scale and large-scale ionospheric disturbances can occur independently. This is an important finding because it highlights the need for using multiple kinds of measurements to accurately monitor and predict ionospheric conditions. The PITHIA-NRF infrastructure played a critical role by providing access to diverse datasets and enabling integrated analysis across instruments and observation networks. These results contribute to advancing Europe's capacity for space weather monitoring and the development of mitigation strategies to protect GNSS-dependent services.

Role of PITHIA-NRF in My Project

- During my TNA-supported research, I analyzed ionospheric irregularities and scintillation using GNSS radio occultation data and LOFAR/UPC datasets.

❑ How PITHIA-NRF Helped:

- Provided access to high-quality datasets (GNSS TEC/scintillation, RO measurements) essential for studying ionospheric disturbances over Europe.
- Enabled collaboration with expert staff at hosting institutions, facilitating tailored guidance on data selection and interpretation.
- Access to the e-Science Centre (esc.pithia.eu) simplified the process of discovering and downloading key data.

❑ Most Valuable Aspects of the TNA Programe:

- Technical support from local scientists during my work helped overcome data preprocessing challenges.
- Exposure to state-of-the-art instrumentation and best practices in space weather data analysis.

- Challenges Encountered:

- Initial difficulty navigating the metadata and search tools in the e-Science Centre; clearer tutorials or walkthroughs would be helpful.

- Suggestions for Future Development:

- Integration of cross-dataset visual dashboards for TEC, scintillation, and ROTI events.
- More training modules on platform usage and data interpretation.

Final Note: PITHIA-NRF has played a critical role in enabling my research on ionospheric irregularities, and I look forward to contributing to future developments of this valuable infrastructure.

Thank You!