Project: ALERT (3rd PITHIA TNA call)

SCINTILLATIONS IN SOUTHERN EUROPE DURING THE GEOMAGNETIC STORM OF JUNE 2015

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IONOSPHERIC SCINTILLATIONS

- Ionospheric scintillations are fluctuations of the GNSS signal's phase and amplitude after passing through regions with anomalously low/high electron density
- A degree of the signal perturbation is measured by the scintillation indices (SI):
  - S4 – the amplitude SI
  - ROTI
  - σ_{φ} – the phase SI

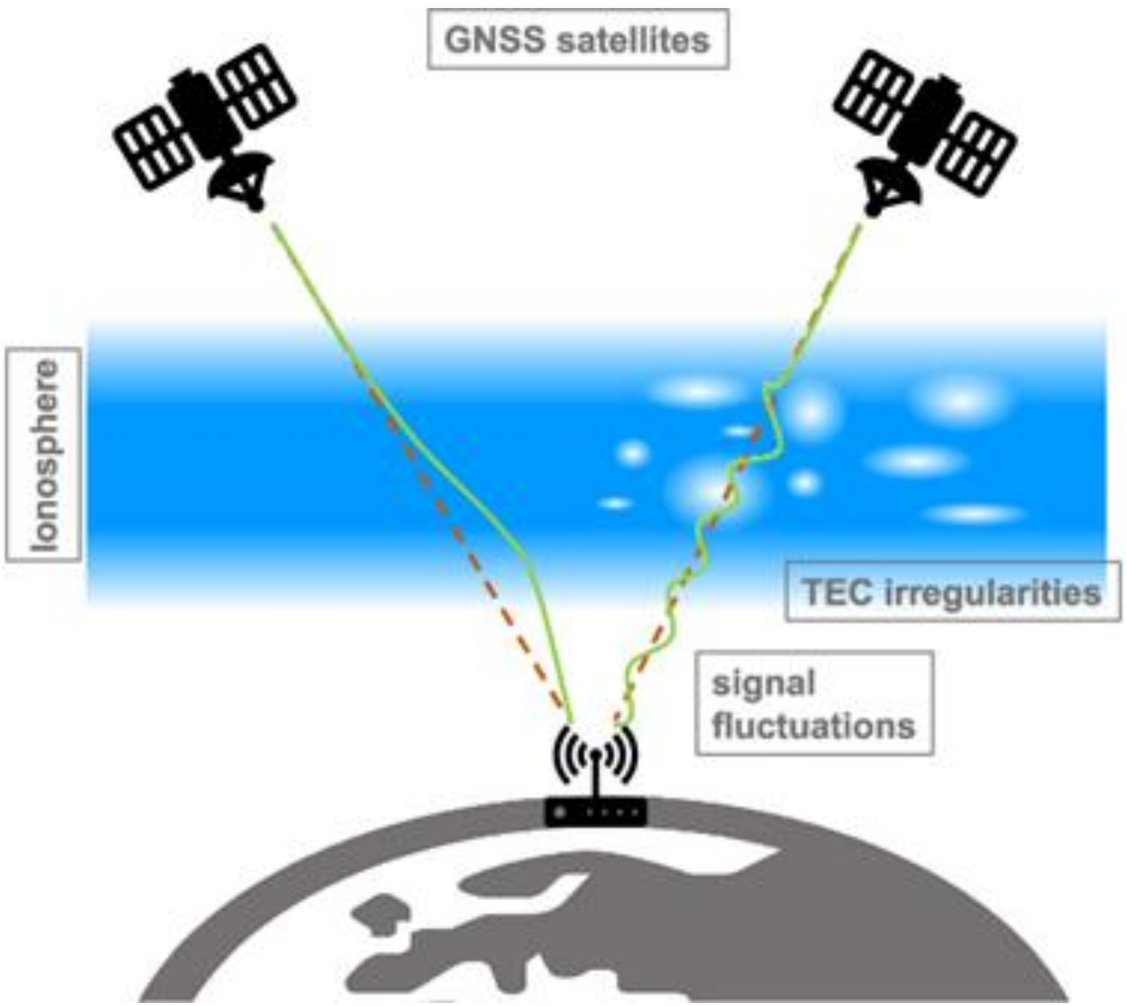
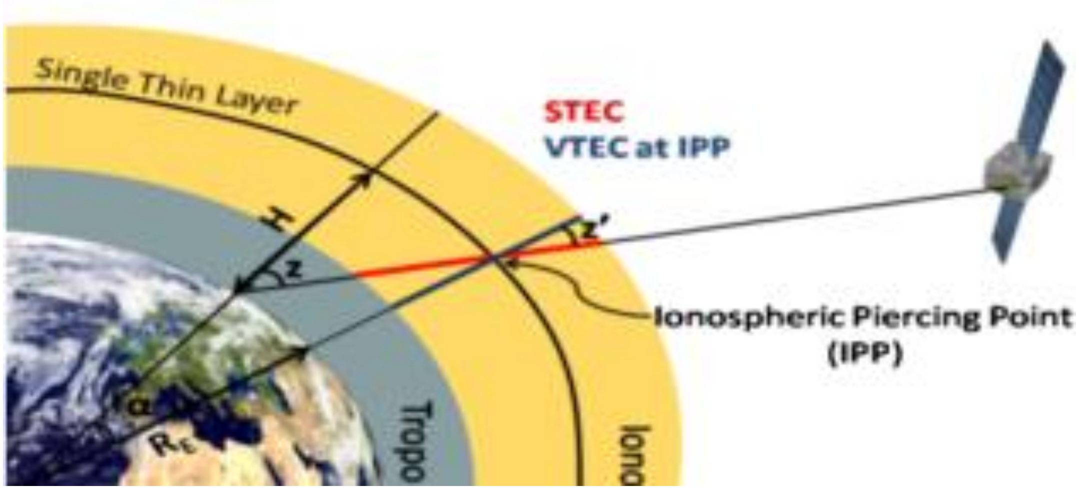
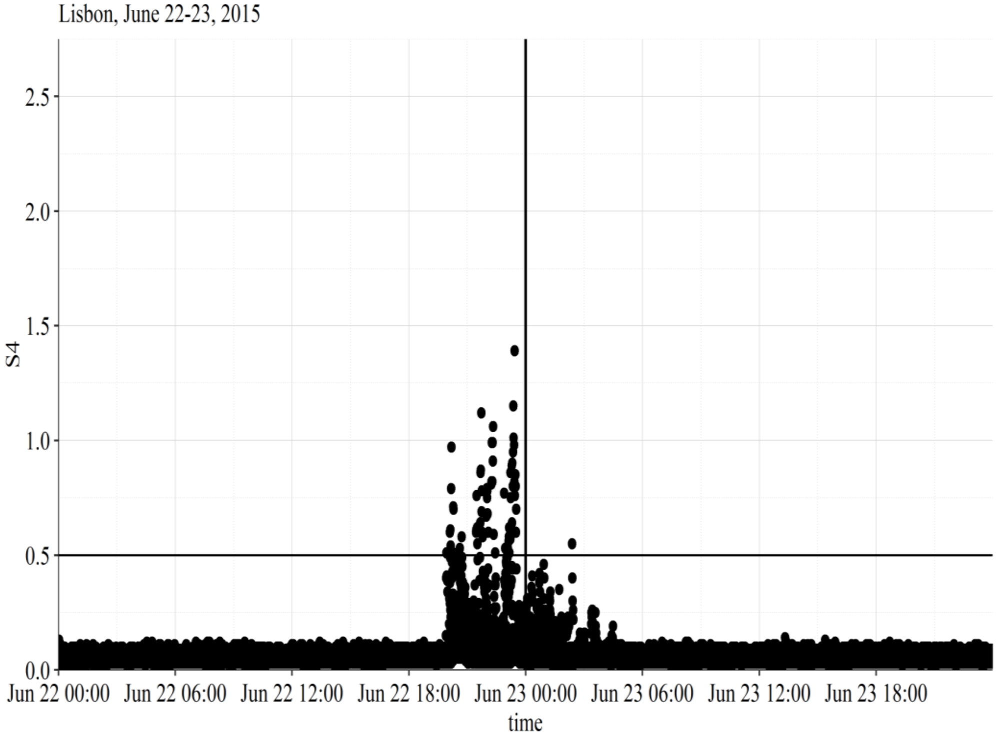


Figure: Scintillation phenomena: the line-of-sight signal path from the GNSS satellites to the receiver on earth (- - -) and continuous signal accounts for propagation distortions (-----) (adapted from Linty et al., 2019)

IONOSPHERIC SCINTILLATIONS

- S4 (amplitude SI) shows the amount of variation in the amplitude of a signal and is calculated as a standard deviation of the GNSS received signal power as seen on the ground
- ROTI (rate of TEC index)
  - TEC = total electron content which is a total number of e- integrated between two points for a tube of 1 m^2 cross section
- S4 and ROTI are calculated for each satellite
  - IPP (ionosphere piercing point)





SOUTHERN EUROPE AND THE EASTERN NORTH ATLANTIC

- **At South European middle latitudes**:
  - Most of the scintillation events take place after a sunset and before a sunrise
  - Mostly seen in the signal from the southward located satellites at low elevation (10-20 º)
- The reason for these behaviours is that the sources of the scintillations seen at the South European middle latitudes are in the equatorial zone or "spilled-over irregularities"

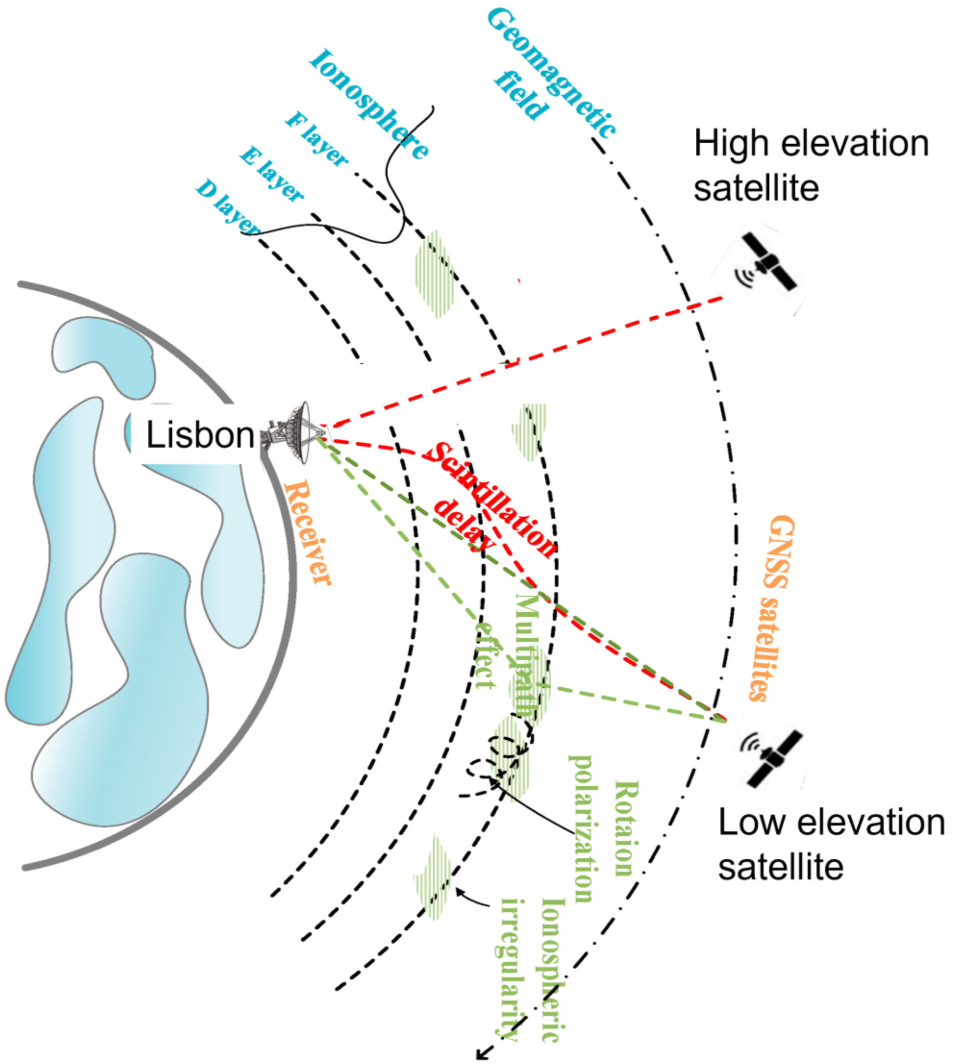
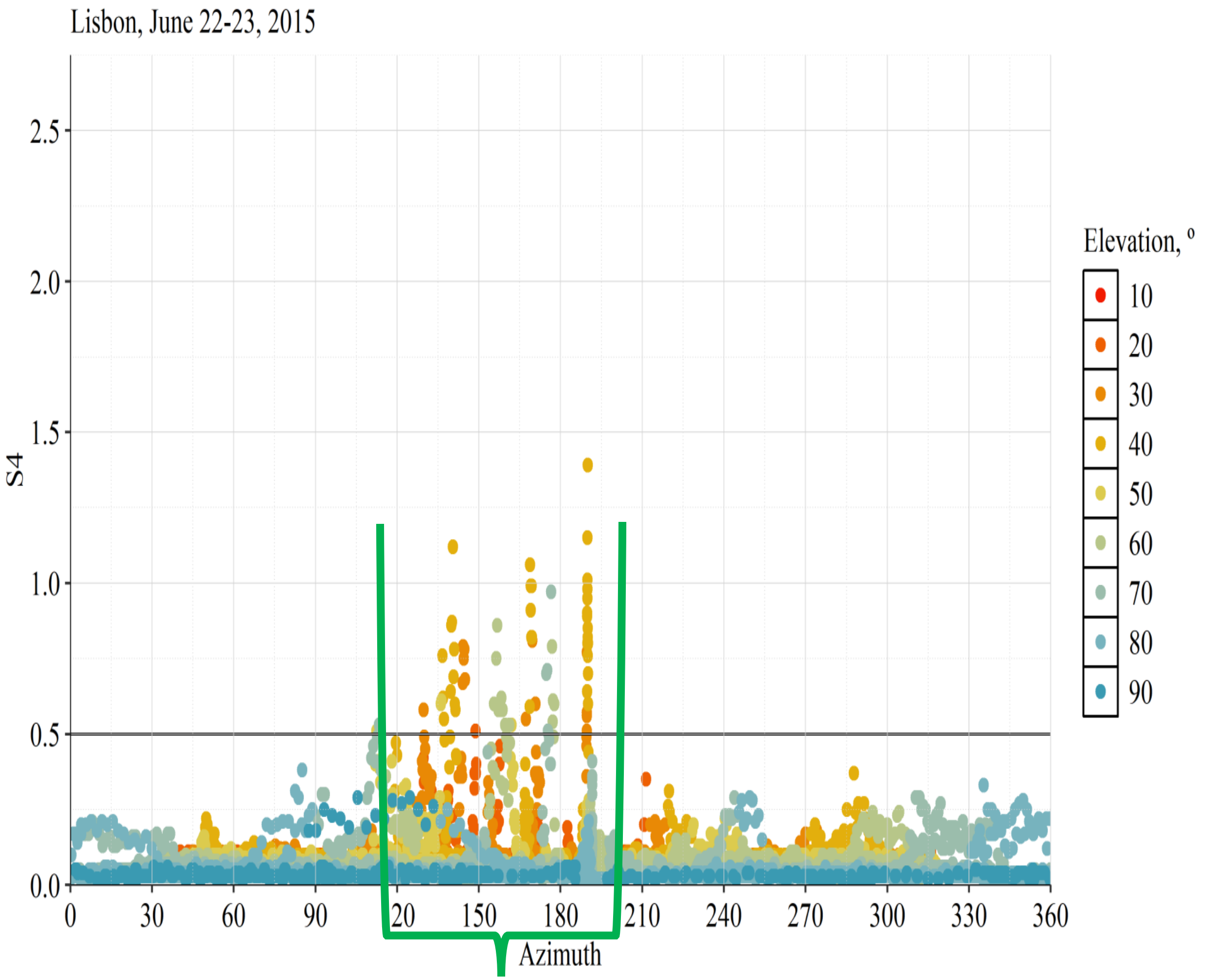


Figure: Adapted from Lin et al., 2021

SOUTHERN EUROPE AND THE EASTERN NORTH ATLANTIC



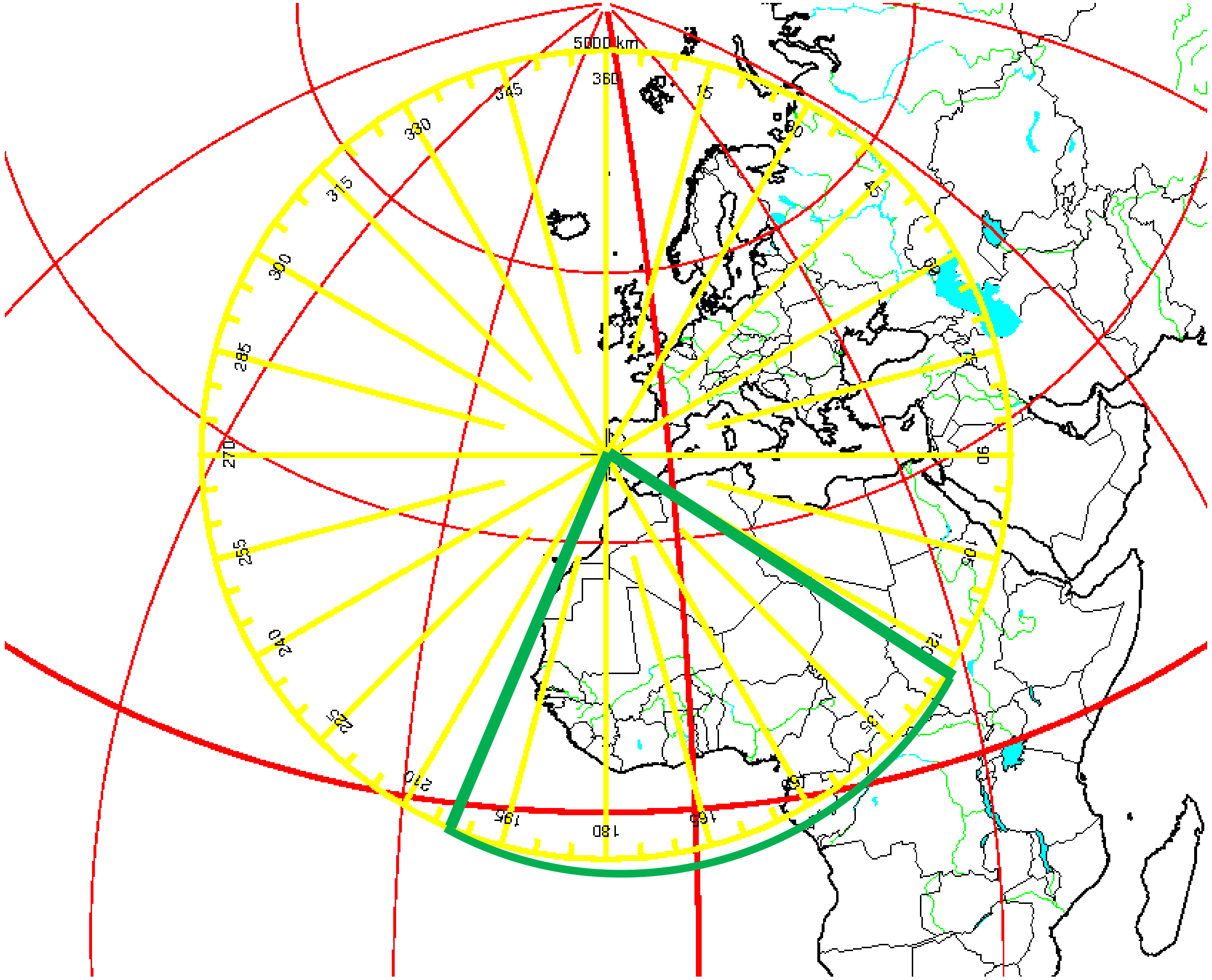


Figure: S4 variations with azimuth and elevation (Lisbon, June 22-23, 2015).

Figure: Azimuthal map for Lisbon

SOUTHERN EUROPE AND THE EASTERN NORTH ATLANTIC

- The reason for these behaviours is that the sources of the scintillations seen at the South European middle latitudes are in the equatorial zone:
  - Equatorial electrojet (an eastward-directed current in the ionosphere, E layer, along the magnetic equator) - EEJ
  - Equatorial plasma bubbles (small areas with lower electron density; may have internal inhomogeneities of the electron density; **±20º lat** band) - **EPB**

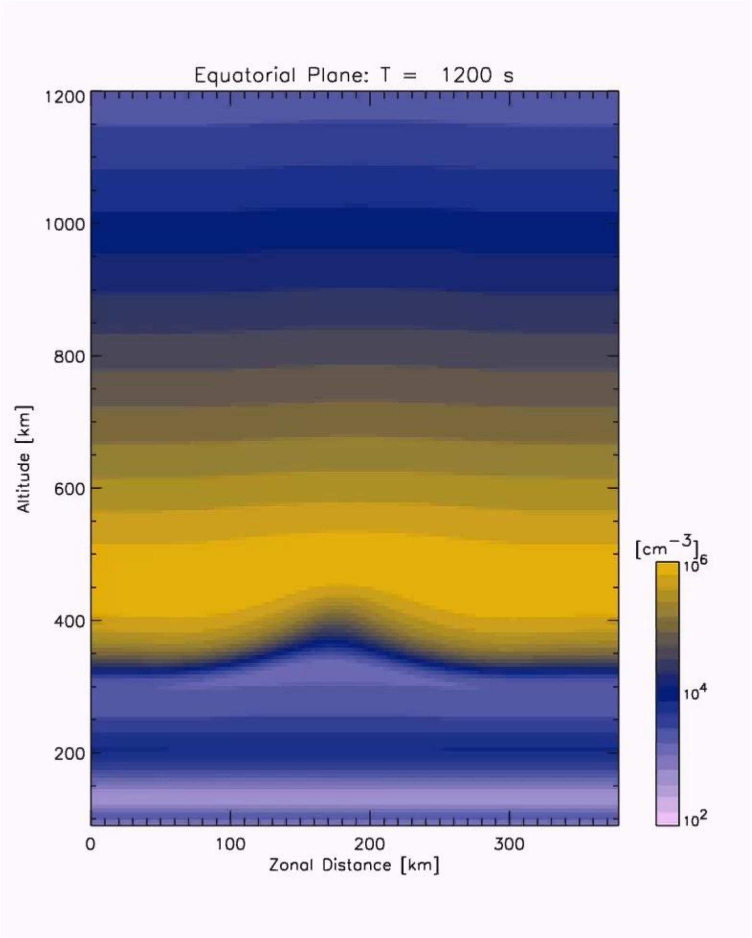


Figure: Simulation of EPB development(Yokoyama et al., 2014)

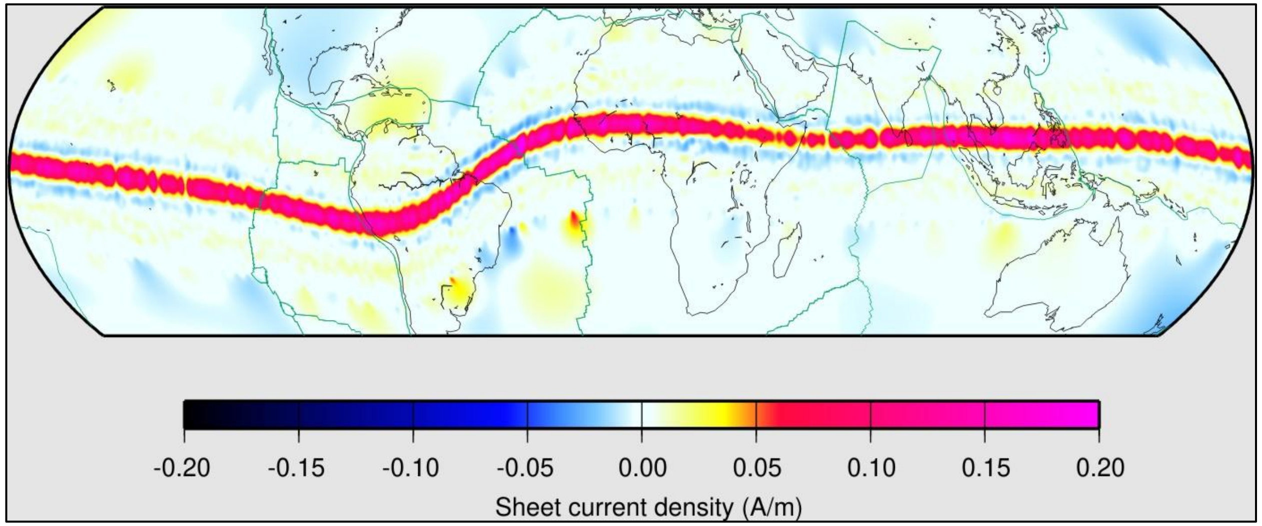
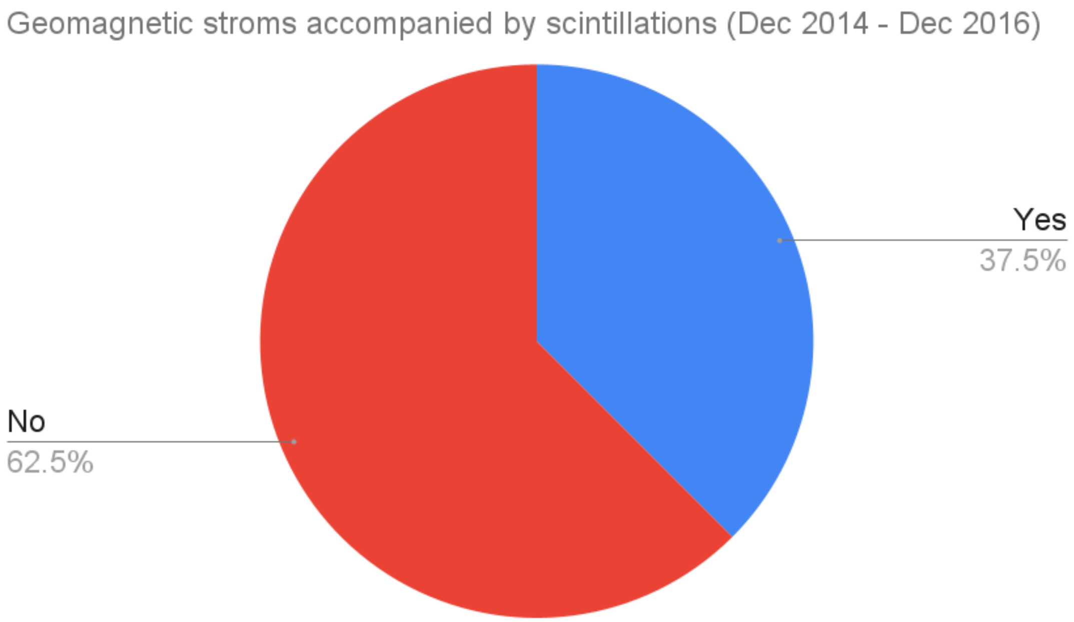
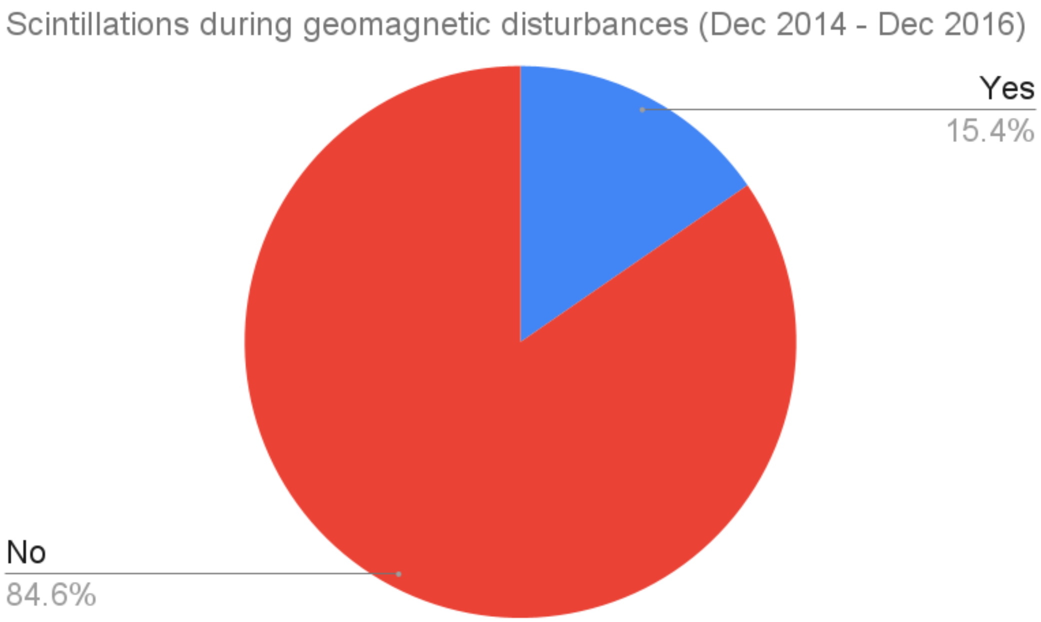


Figure: Electrojet current densities (CHAMP satellite over the magnetic equator between 11:00 and 13:00 L, http://www.geomag.us/info/equatorial_electrojet).

SOUTHERN EUROPE AND THE EASTERN NORTH ATLANTIC

- At middle latitudes there is no strong dependence on the geomagnetic activity level and appearance of scintillation events*:
  - scintillations occur during night hours and are not related to the dynamics of geomagnetic storm
- At middle latitudes scintillations happens more often between February and April than during other months*





** Data from December 2014 to December 2016, measured at Lisbon*

EVENT OF JUNE 2015

- Took place during a **very strong geomagnetic storm** (June 22-23, 2015)
  - the second-strongest geomagnetic storm of the 24th solar cycle
- Took place in **summer**
- Both **low and high elevation** satellites were affected
- Associated with specific electric field variations (Prompt-Penetrating Electric Fields)

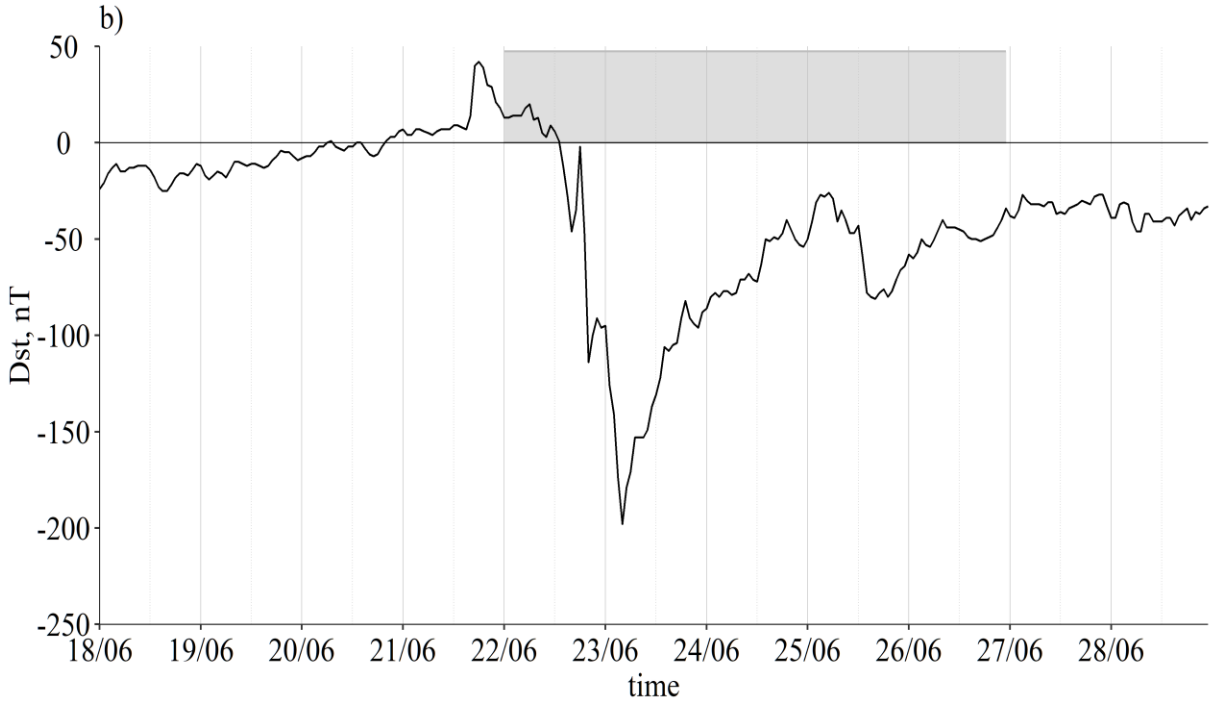


Figure: Variations of the geomagnetic index Dst during the storm of June 2015

EVENT OF JUNE 2015

- The GM storm of 22 June 2015 was associated with specific electric field variations which produce conditions that may be favourable
  - for the development of EPBs during the storm time
  - **EPBs spill-over to the middle latitudes**
- Such a rare phenomenon as an EPB spill-over was observed twice during this storm
  - in the Euro–African longitudinal sector between 20 h UTC on 22 June and 2 h UTC on 23 June
  - in the American longitudinal sector between 4 h UTC and 7 h UTC on 23 June
- The EPB spill-over resulted in strong scintillations of the GNSS signal in the middle latitudes (e.g., Cherniak and Zakharenkova, 2016)
- This event was already studied using ROTI and TEC data
- **We have S4 data! (different spatial scale)**

EVENT OF JUNE 2015 – DATA

- S4 data from GNSS receivers – 3 stations @ Lisbon, Lampedusa & Tenerife
  - Small scale irregularities (~10^2 m)
- ROTI data from GNSS receivers - 10 stations, & ROTI maps (also GNSS-based)
  - Medium scale irregularities (~10^3 m)
- Swarm Ionospheric Plasma Bubble index (IBI)
- Ionospheric spatial gradients (TEC gradients)
  - TEC gradients can show boundaries of areas with higher/lower electron density
  - Medium-to-large scale irregularities (≥10^3 m)

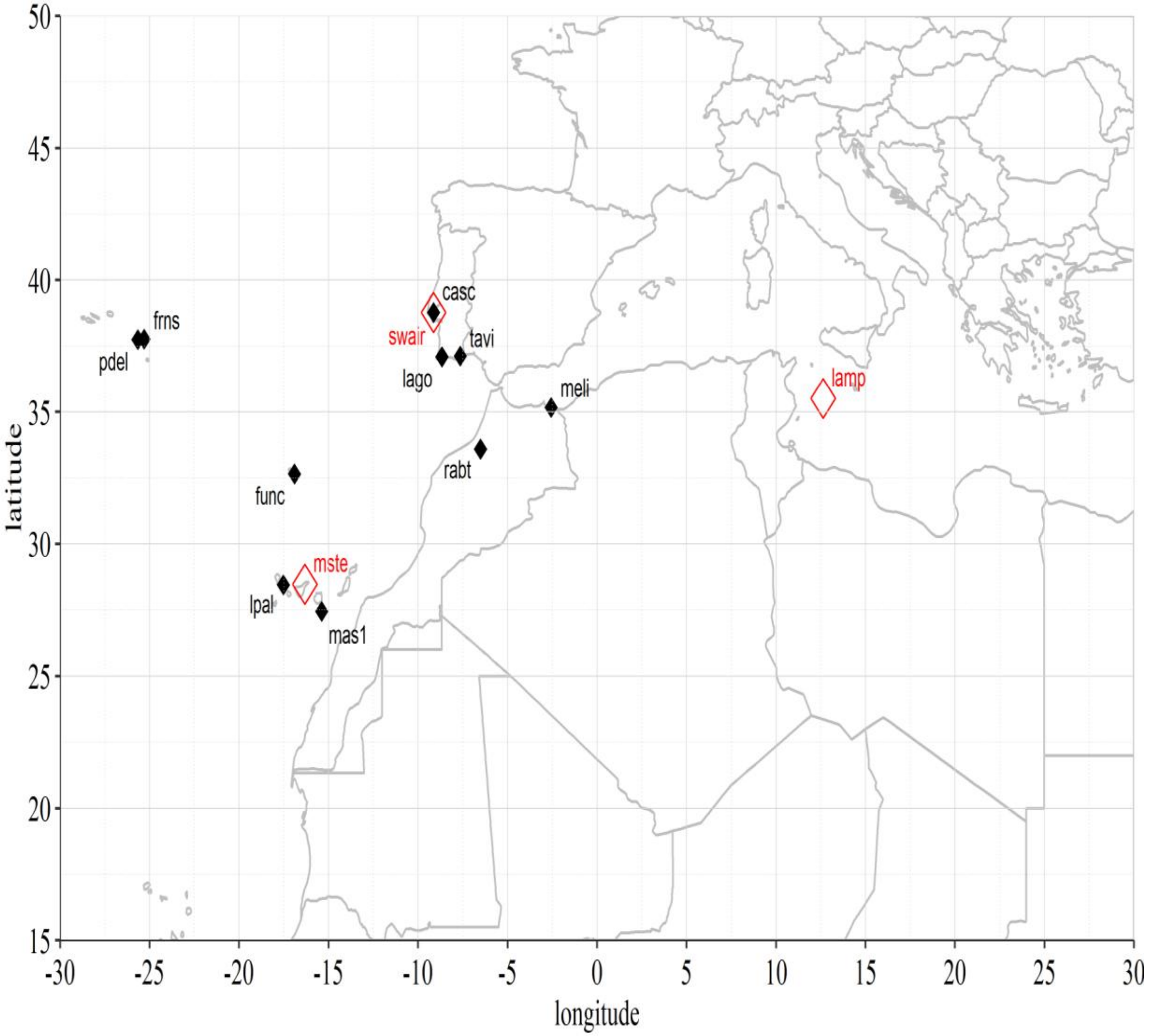


Figure: Locations of GNSS receivers used to calculate S4 (red open diamonds) and ROTI (black diamonds) scintillation indices.

EVENT OF JUNE 2015 – SCINTILLATIONS

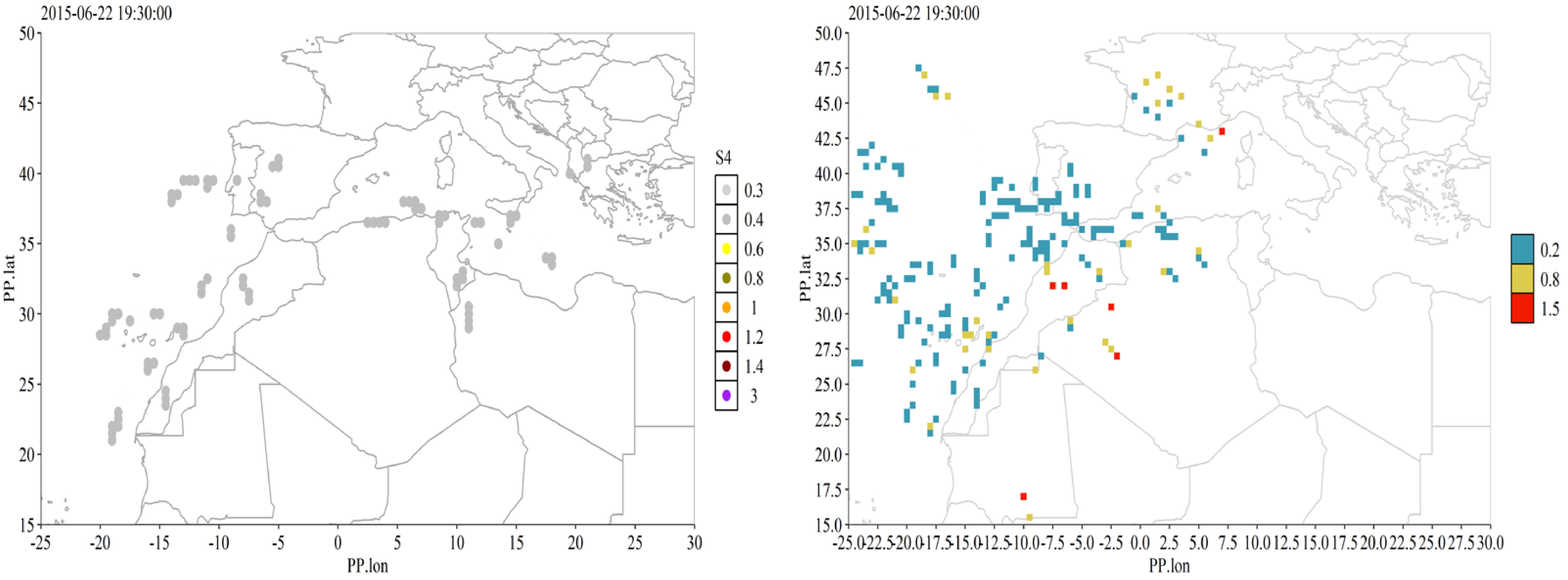


Figure: Variations of S4 (left) and ROTI (right) at IPP between June 22 19:30 UTC and June 23 02:30 UTC (15')

EVENT OF JUNE 2015 – SCINTILLATIONS

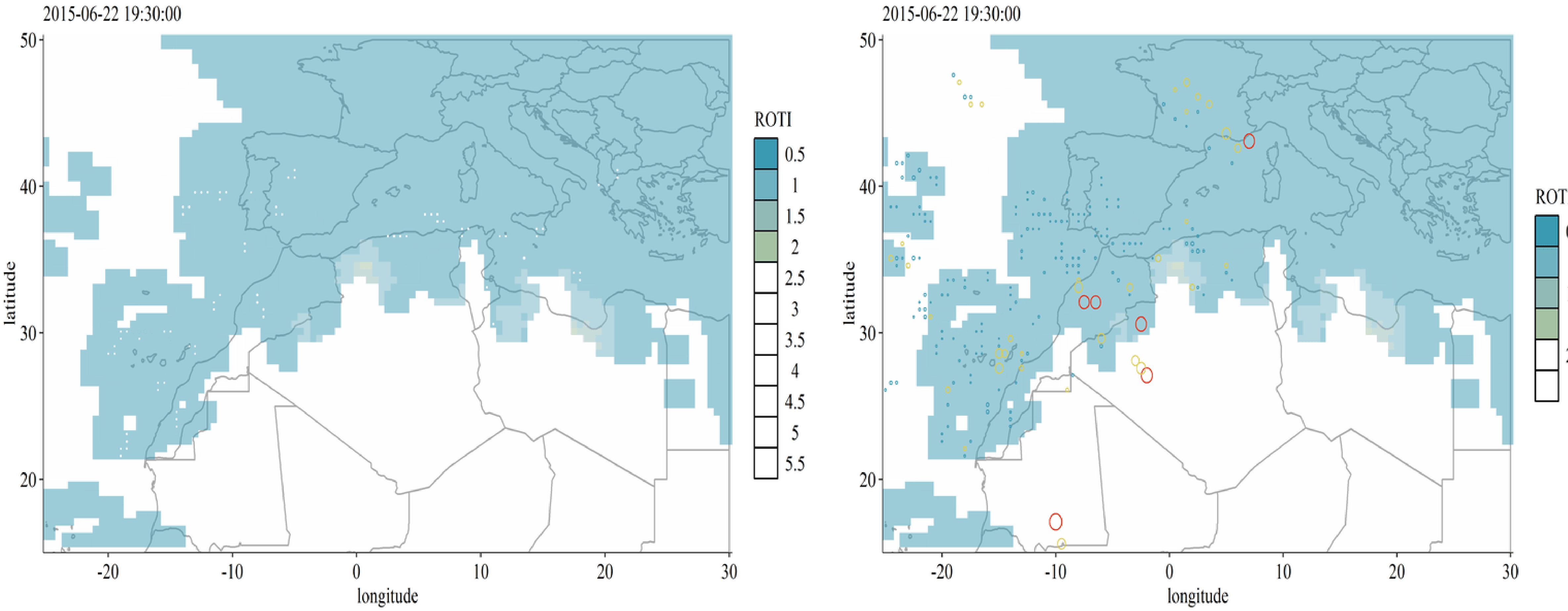


Figure: Variations of S4 (left, black/white circle) and ROTI (right, coloured circles) at IPP between superposed on ROTI maps. Locations of plasma bubbles detected by Swarm are shown as lines of grey dots along meridians

EVENT OF JUNE 2015 – SCINTILLATIONS

- The sources of the scintillations observed in the region were travelling in the area between the Iberian Peninsula and the Canary Islands, moving generally in the NW direction
- IPPs for the high S4 values are mostly located in a region between the Canary Islands and the Iberian Peninsula, above northwestern Africa and the neighboring areas of the Atlantic Ocean
  - Weak scintillations are associated with IPPs over Northern Africa (to the south of Lampedusa)

EVENT OF JUNE 2015 – SCINTILLATIONS

- S4 and ROTI indices can detect the electron density inhomogeneity on different spatial scales
- High S4 values tend to cluster in the regions with higher ROTI values
- The link between ROTI and S4 is more clearly seen during the night hours of 22 June than during the early hours of 23 June
- The comparison of the S4 and ROTI variations allows us to conclude that the scintillation event of 22–23 June 2015 was caused by inhomogeneities in the ionospheric electron density that existed at different spatial scales.

EVENT OF JUNE 2015 – TEC GRADIENTS

- EPBs are inhomogeneities…
  - elongated in the meridional and altitudinal directions
  - containing plasma with electron density much lower than the surrounding ionosphere
  - large EPBs may have complex internal structures
- To identify these structures, we used TEC spatial gradients calculated using TEC map

EVENT OF JUNE 2015 – TEC GRADIENTS

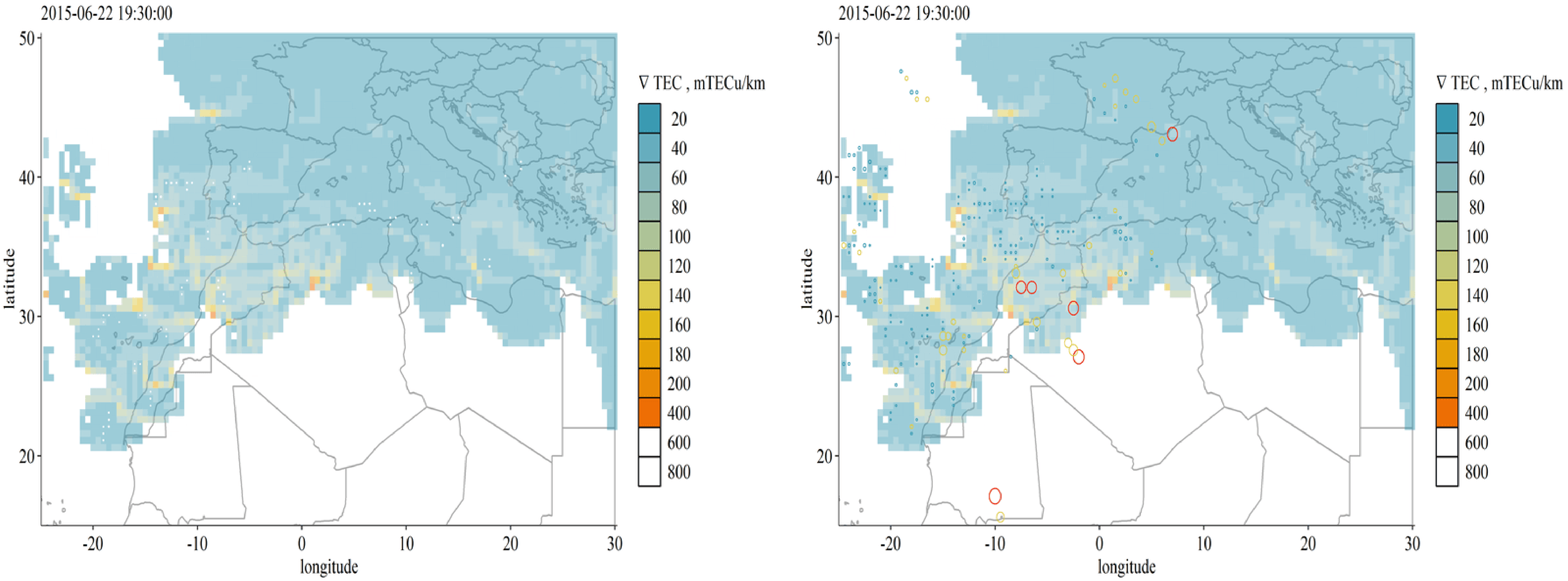


Figure: Variations of S4 (left, black/white circle) and ROTI (right, coloured circles) at IPP between superposed on maps of TEC gradients. Locations of plasma bubbles detected by Swarm are shown as lines of grey dots along meridians

EVENT OF JUNE 2015 – TEC GRADIENTS

- The areas of high ROTI and S4 values coincide with regions of high spatial TEC gradients
- Several structures stretched along the NW–SE direction are seen both in the maps of the spatial gradients and the ROTI and are located between the Canary Islands/Madeira and the Iberian Peninsula
- Most of the IPPs of the signals with high S4 values are located inside these structures
- The high TEC gradients depict boundaries of inhomogeneities in the ionospheric electron density that caused ionospheric scintillations

Figure: Variations of S4 at IPP between June 22 19:30 UTC and June 23 02:30 UTC (15')

CONCLUSIONS

- The dynamics of the ionosphere in the low–middle latitudes of the Euro–African meridional sector during the geomagnetic storm of 22–23 June 2015 was different from what is normally expected for this region
- Large variations in scintillation indices (S4 and ROTI) as well as large spatial TEC gradients were observed there between 19 h UTC on 22 June and 03 h UTC on 23 June. These ionospheric disturbances were caused by a rare event of a spill-over of EPBs from low latitudes triggered by the storm dynamics
- During the studied event, EPBs were seen as elongated (NW–SE) areas of lower electron density travelling NW-ward through the studied region
- High values of S4 and ROTI obtained from individual GNSS receivers were located, as a rule, inside those areas

Figure: Variations of S4 at IPP between June 22 19:30 UTC and June 23 02:30 UTC (15’)

CONCLUSIONS

- The region the include the South-west Europe and the eastern North Atlantic is one of the regions where EPB spill-over event can occur
- This regions is in the south and southwest parts of the area covered by EGNOS, a satellite-based augmentation system developed by the European Space Agency and EUROCONTROL to enhance the reliability and accuracy of the positioning data
- GNSS services and technologies are highly susceptible to disruptions caused by ionospheric irregularities as EPBs
- Continuous monitoring and analysis of ionospheric irregularities in this region are essential to mitigate these risks and ensure the integrity of critical GNSS-dependent technologies

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PITHIA-NRF EXPERIENCE

- Two TNA calls in 2021 (PRIMA project) and 2022 (ALERT project)
- Two 1-week visits to a TNA node (UPC-IonSAT, Barcelona, Spain, and INGV, Rome, Italy)
- The participation in the PITHIA TNAs allowed us to acquire knowledge and obtain software and technical support from the TNA node teams
- Two papers and two book chapters were published based on the results of these projects
- Most valuable aspects: possibility to meet in-person with experts, obtain first-hand experience with data processing, discuss collaborations, do studies together
- Problematic aspects: financial bureaucracy