Frederick University
Ionospheric remote sensing techniques and their complementary strengths

Website: http://cyirg.frederick.ac.cy/

Haris Haralambous

Assoc. Professor Frederick University
Dep of Electrical Engineering, Computer Engineering and Informatics
Cyprus

Cyprus Ionospheric Research group (CyIRG) research scope

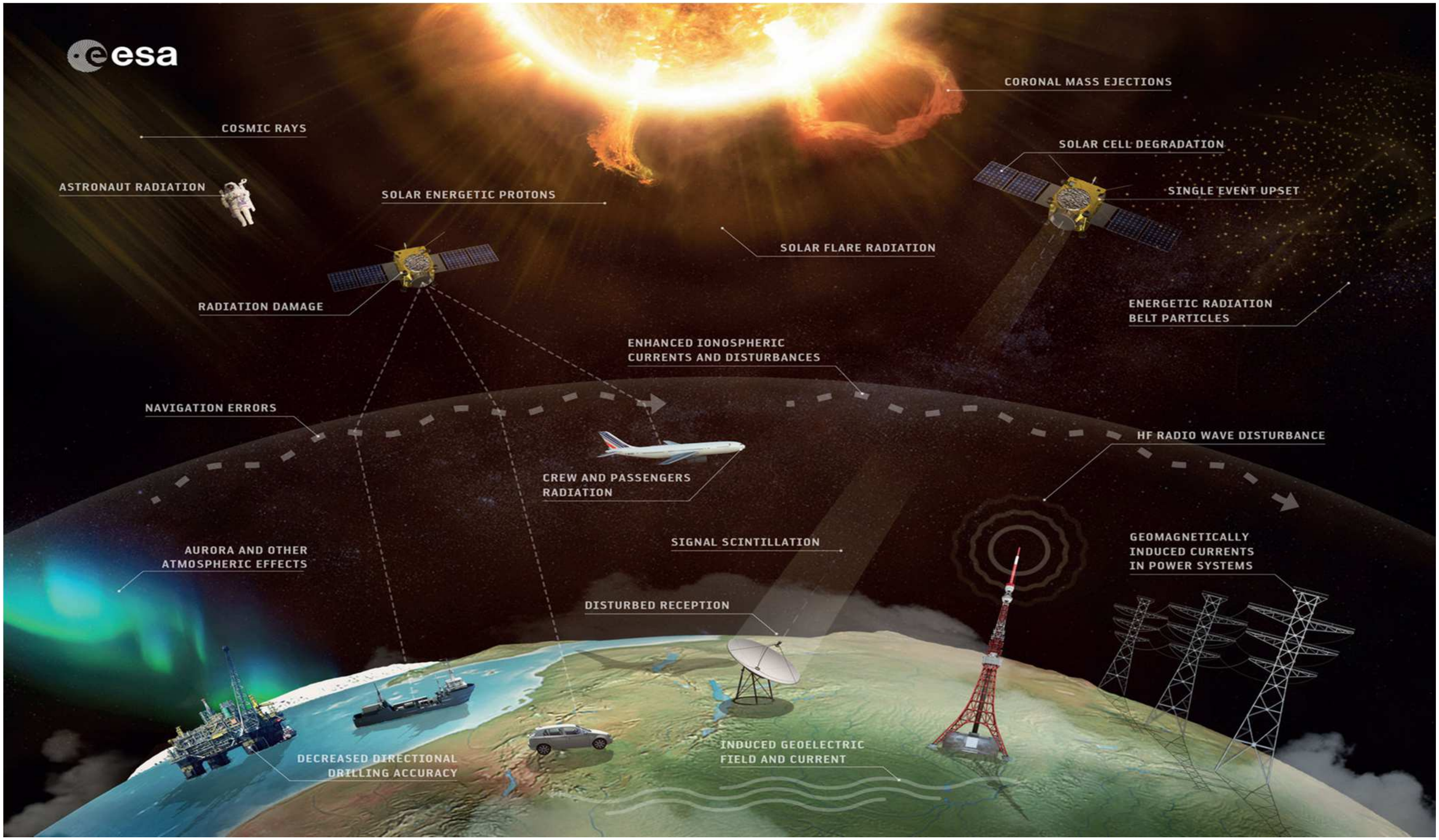
- The research activity of the Cyprus Ionospheric Research group lies in the context of the study and mitigation of ionospheric effects on radio systems.

- It is in the position to pursue this aim by means of its infrastructure that facilitates continuous remote sensing of the state of the ionosphere, within various parts of the electromagnetic spectrum.

- Detrimental ionospheric effects on radio systems usually have their origin on the disturbed state or natural variability of the Sun and therefore the group has a genuine research interest on Space Weather and its subsequent impact on the Upper Atmosphere.

http://cyirg.frederick.ac.cy/

Cyprus Ionospheric Research group (CyIRG) research scope

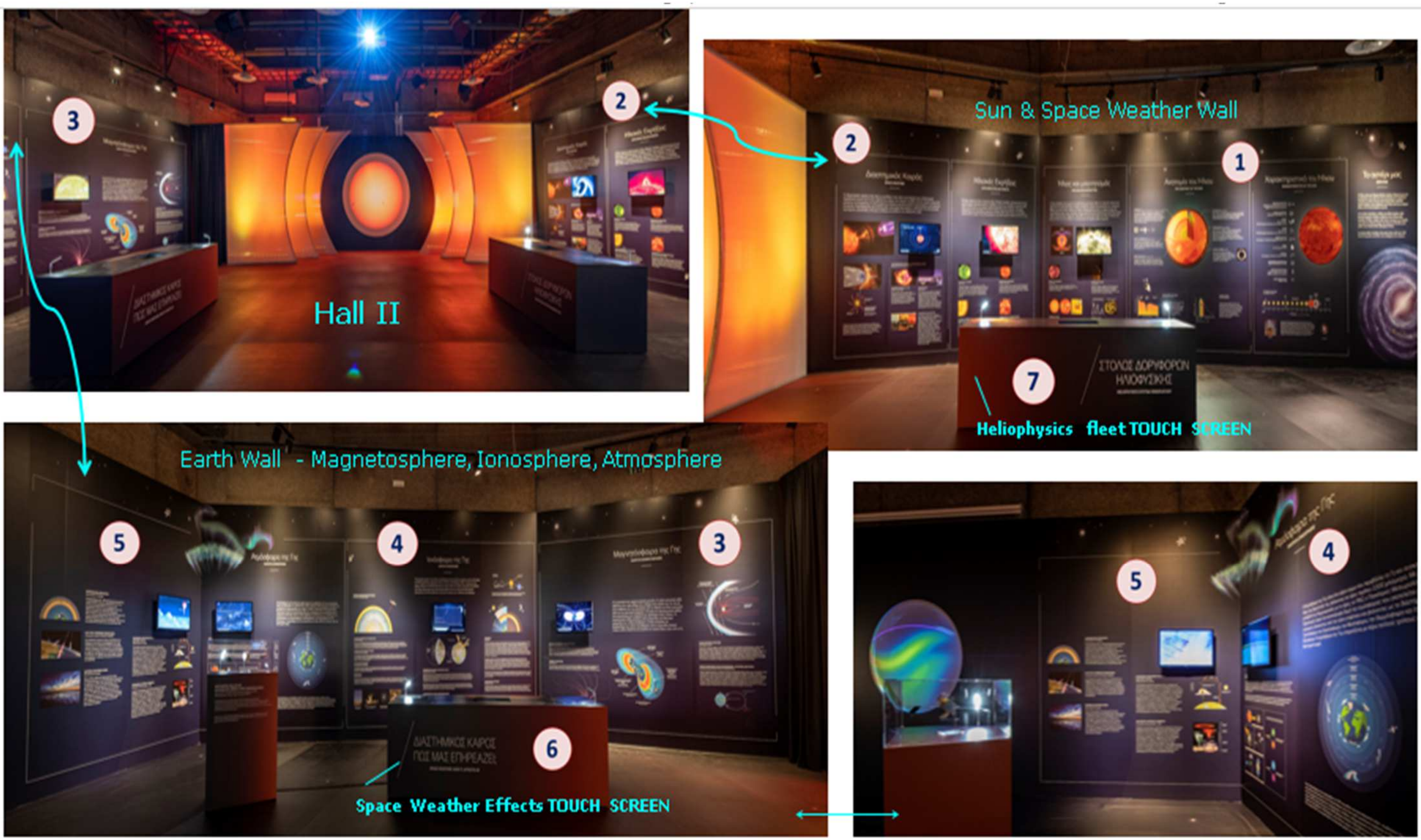


Sun and Us exhibition

Sun and Us exhibition

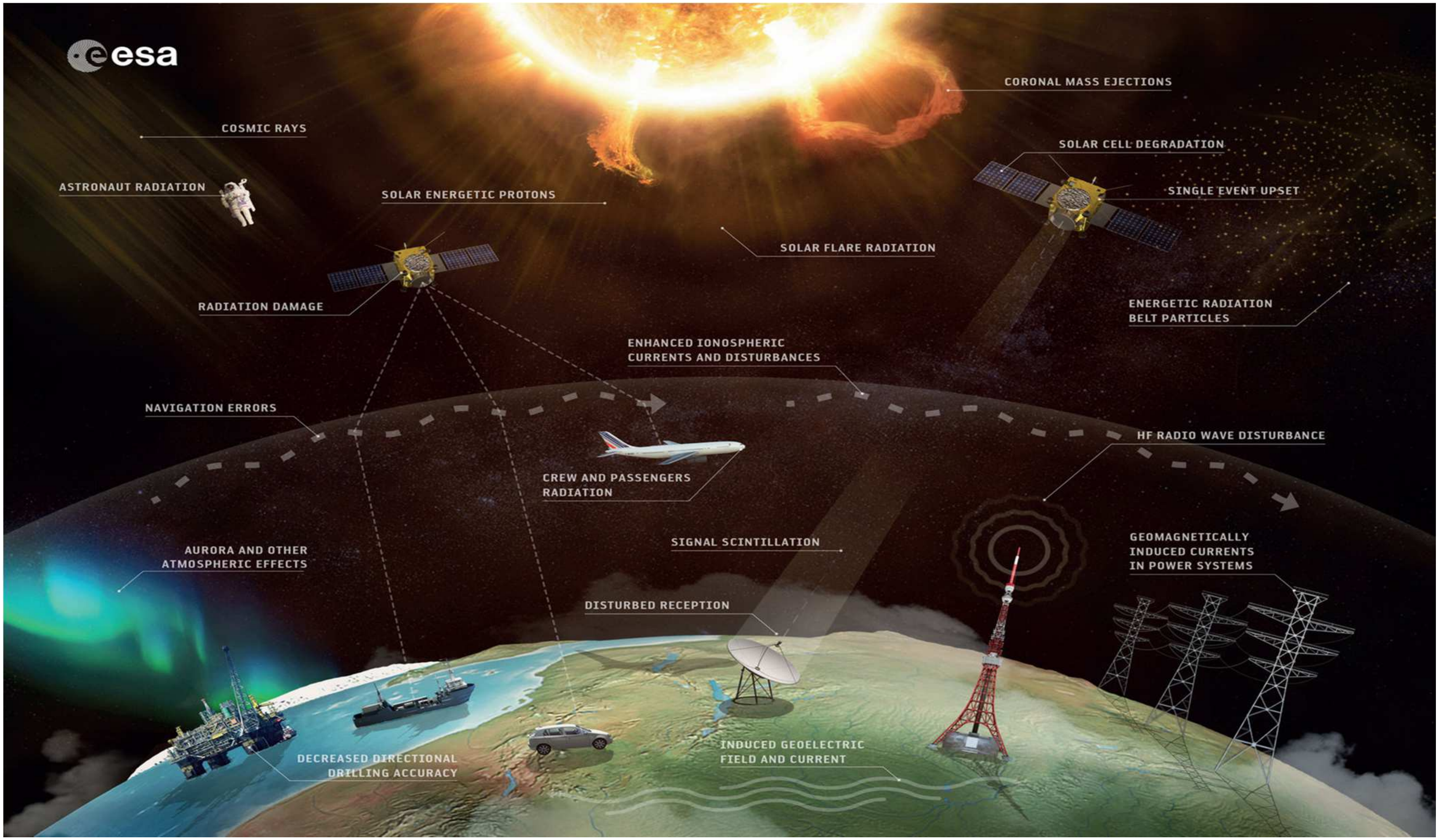
Sun and Us exhibition

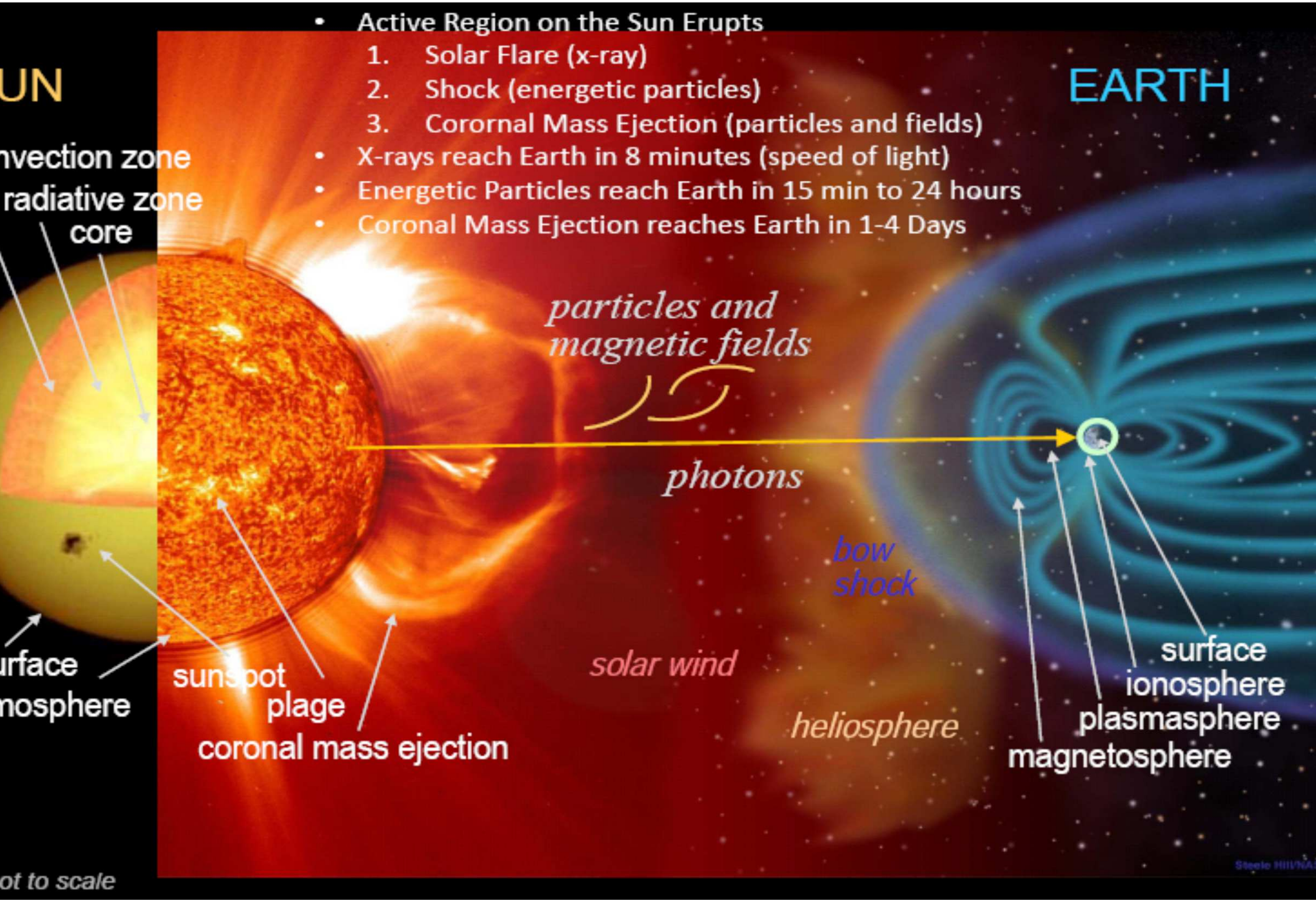
Sun and Us exhibition



Sun and Us exhibition

Cyprus Ionospheric Research group (CyIRG) research scope

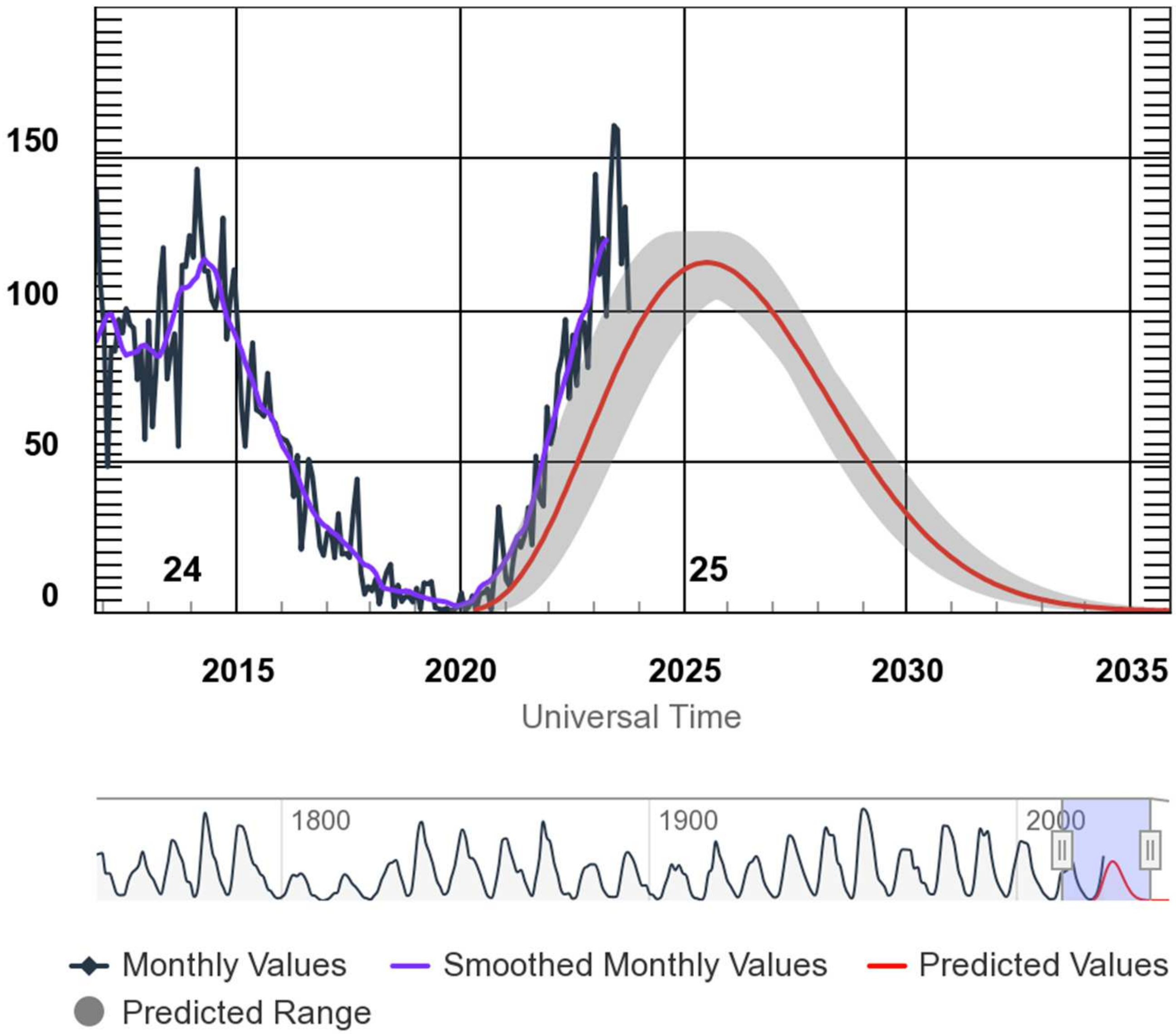


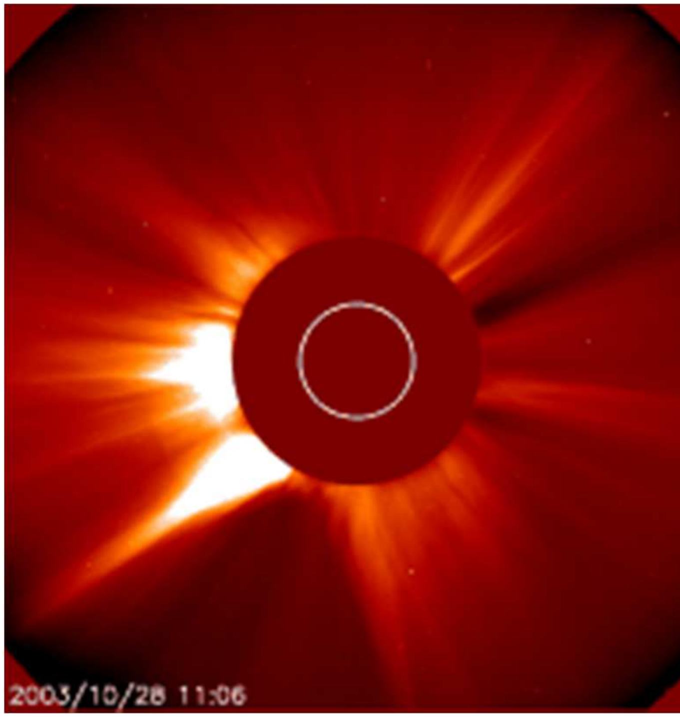


- Active Region on the Sun Erupts
  1. Solar Flare (x-ray)
  2. Shock (energetic particles)
  3. Corornal Mass Ejection (particles and fields)
- X-rays reach Earth in 8 minutes (speed of light)
- Energetic Particles reach Earth in 15 min to 24 hours
- Coronal Mass Ejection reaches Earth in 1-4 Days

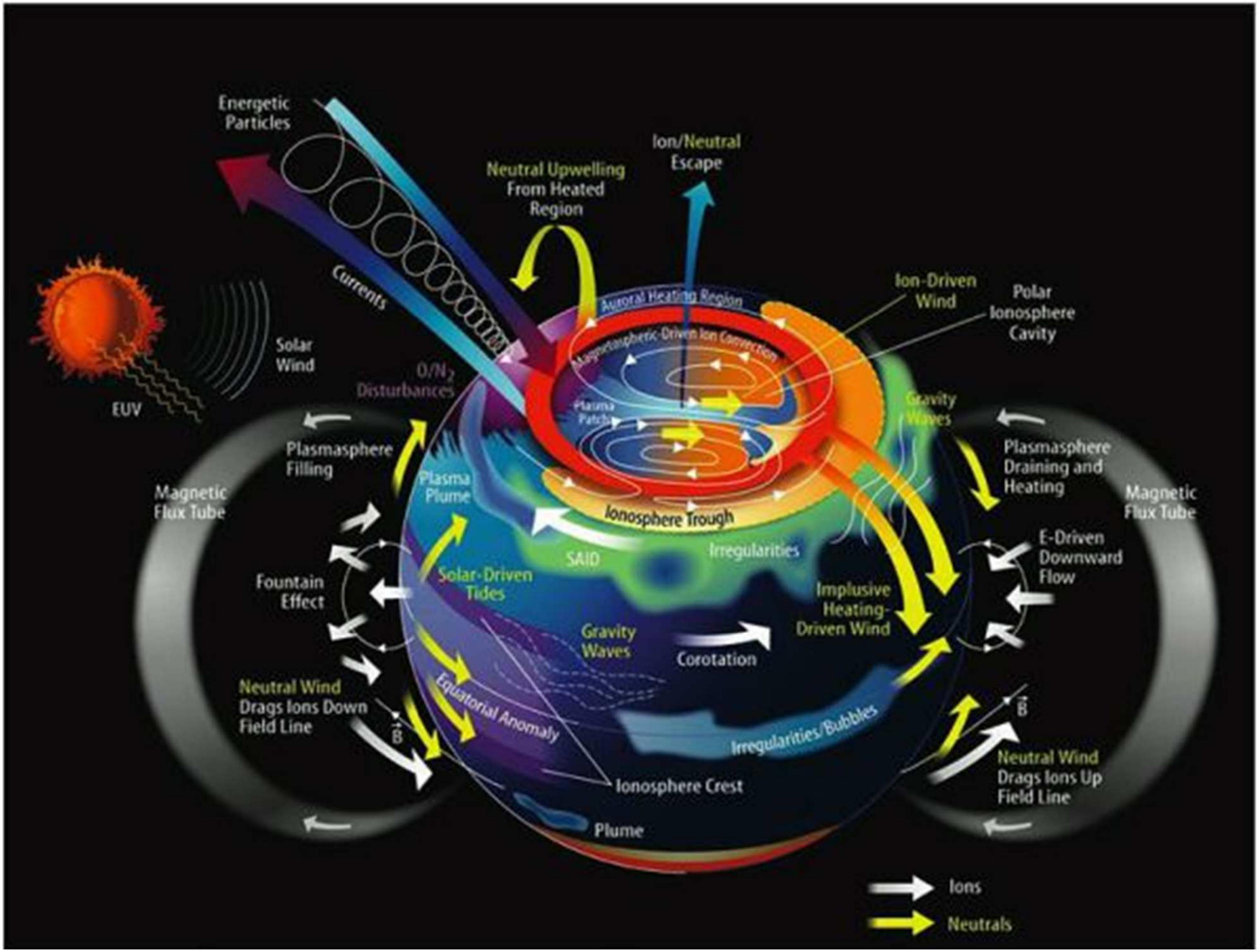
UN
nvection zone
radiative zone
core
urface
nosphere
sunspot
plage
coronal mass ejection
ot to scale
particles and magnetic fields
photons
solar wind
bow shock
heliosphere
EARTH
surface
ionosphere
plasmasphere
magnetosphere

Cyprus Ionospheric Research group (CyIRG) research scope





Ionosphere-Thermosphere processes

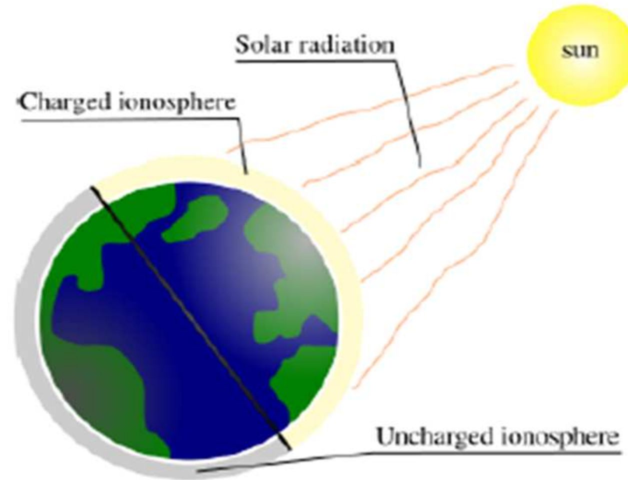


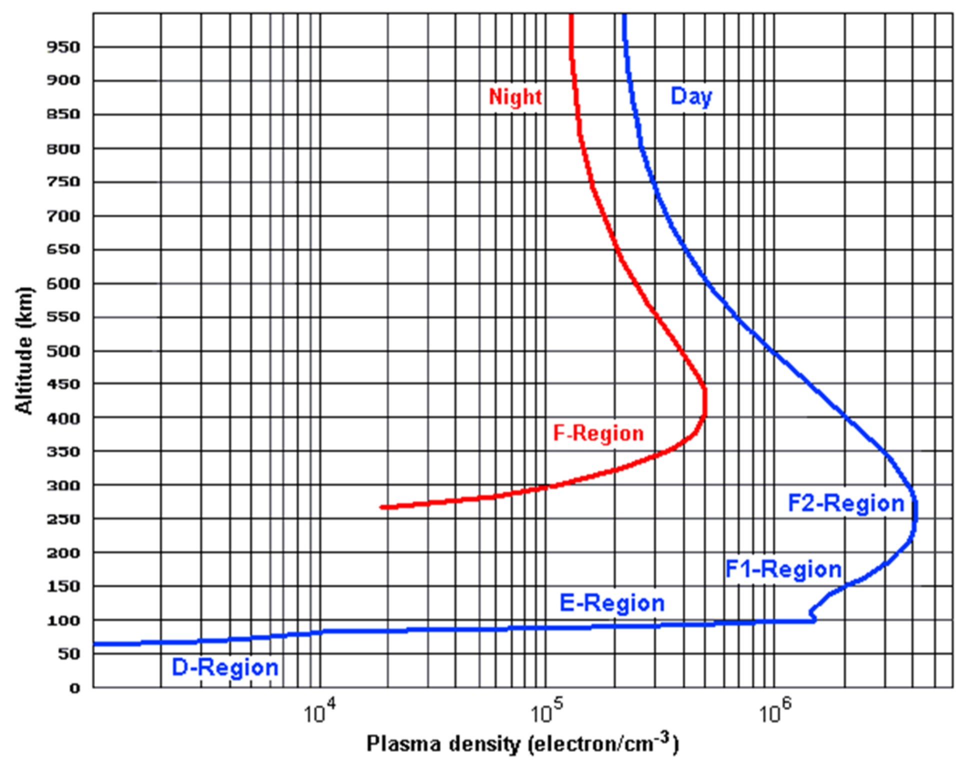
IONOSPHERE The Ionosphere

The **ionosphere is the uppermost part of the atmosphere** and is ionized by solar radiation.

Ionization is the **conversion of atoms or molecules into an ion by light** (heating up or charging) from the sun on the upper atmosphere.

Ionization also **creates a horizontal set of stratum (layer)** where each has a peak density and a definable width or profile that influences radio propagation.





Cyprus Ionospheric Research group (CyIRG) infrastructure

CYPRUS DIGITAL IONOSONDE - DIGISONDE DPS-4D

SCINTILLATION RECEIVER & ANTENNA

GNSS REFERENCE STATION & METEOROLOGICAL STATION – KLIR

HF SPECTRAL MONITORING SYSTEM

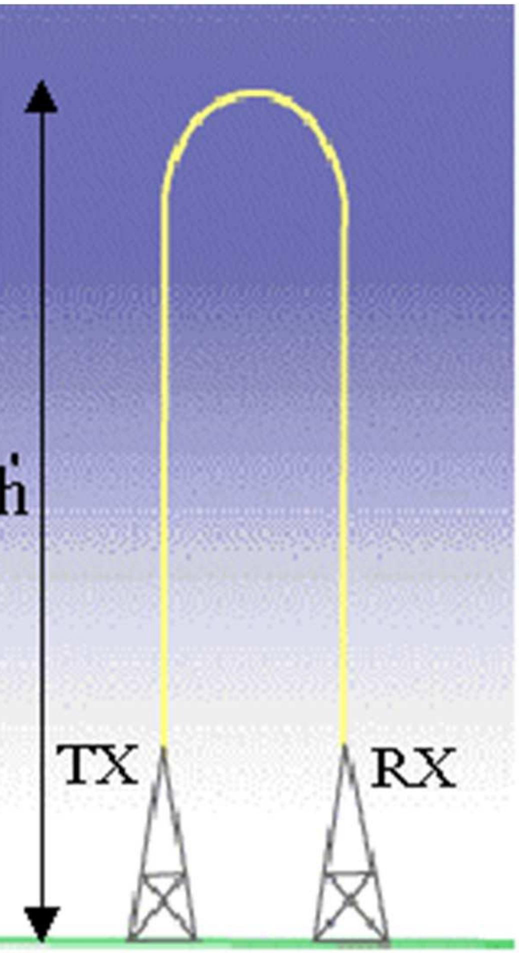
VLF RECEIVER

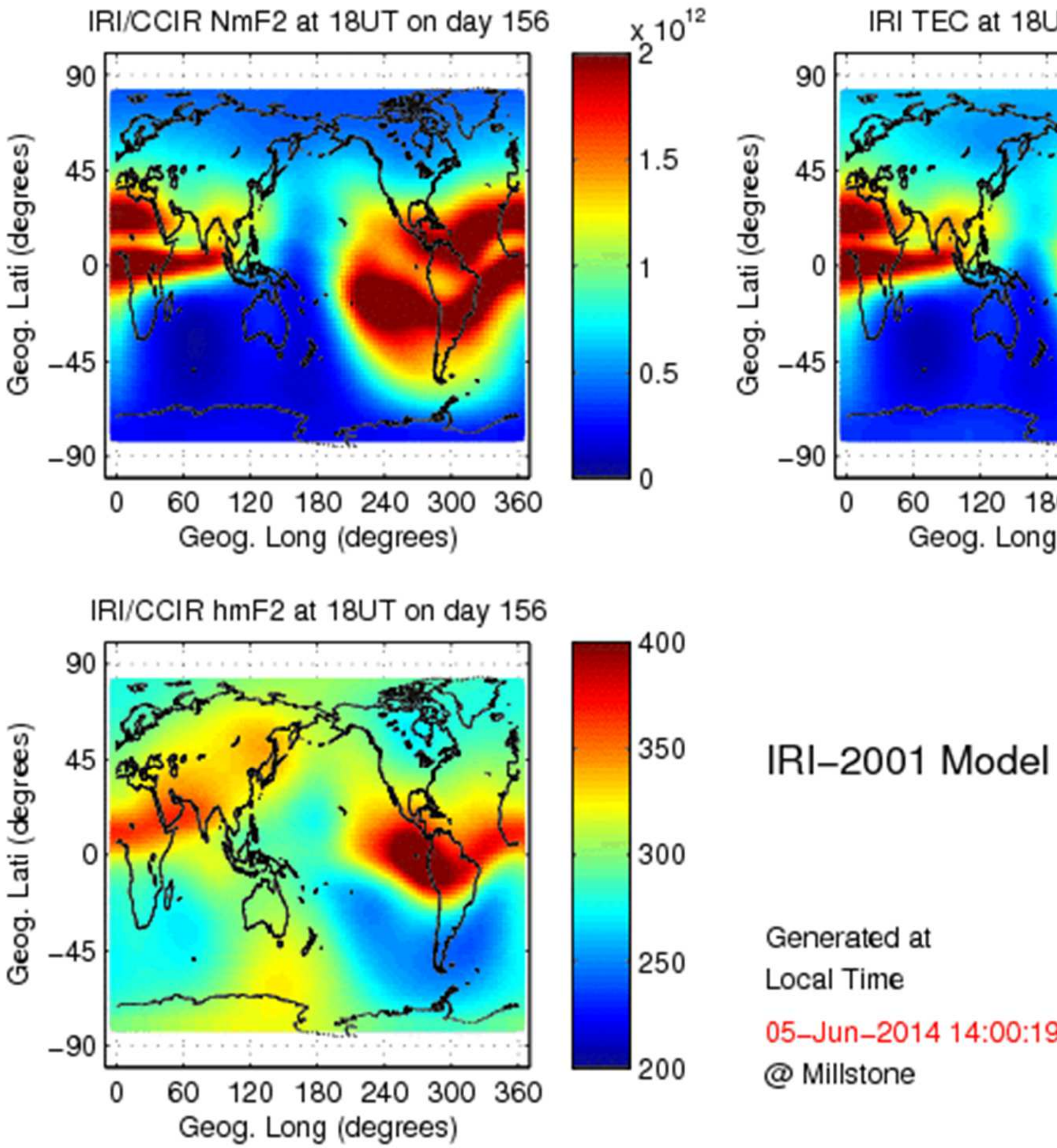
CYPRUS DIGITAL IONOSONDE

More than 15 ground-based ionosondes are currently available covering European ionosphere. The recently started Nicosia DPS-4D ionosonde station is expected to introduce new opportunities for real-time ground based ionospheric operations in the Mediterranean area.

Global Digisonde network

CYPRUS DIGITAL IONOSONDE CONTRIBUTION TO GLOBAL MODELING

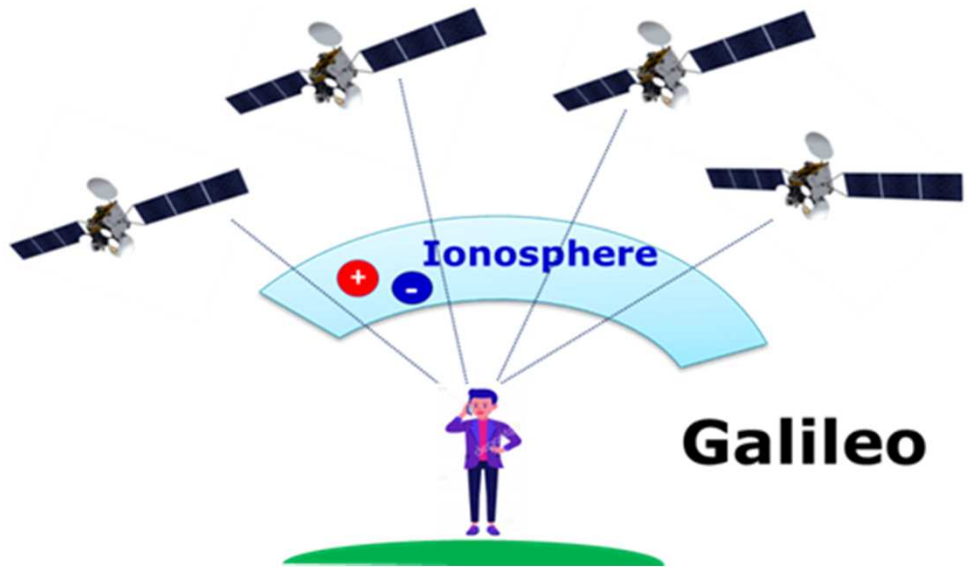




International
Reference
Ionosphere

NeQuick ionospheric model

- Semi-empirical climatological model that describes spatial and temporal variations of the ionospheric electron density at a given time and location



- NeQuick model was adopted as the basis of the real-time ionospheric correction algorithm (NeQuick–G) used for Galileo single-frequency positioning ionospheric correction

CCIR in NeQuick-G

The most significant contribution to TEC comes from the F layer the key parameters to describe the electron density profile specification of NeQuick–G are foF2 and M(3000)F2, the critical frequency at the F2 layer and the propagation factor, respectively. These are calculated from International Radio Consultative Committee (CCIR) maps that are based on the monthly median values of foF2 and M(3000)F_2 from all available ionosondes (about 150 stations) during the years 1954 to 1958, corresponding to an approximate 10,000 station-months of data

Representation of Diurnal and Geographic Variations of Ionospheric Data by Numerical Methods*

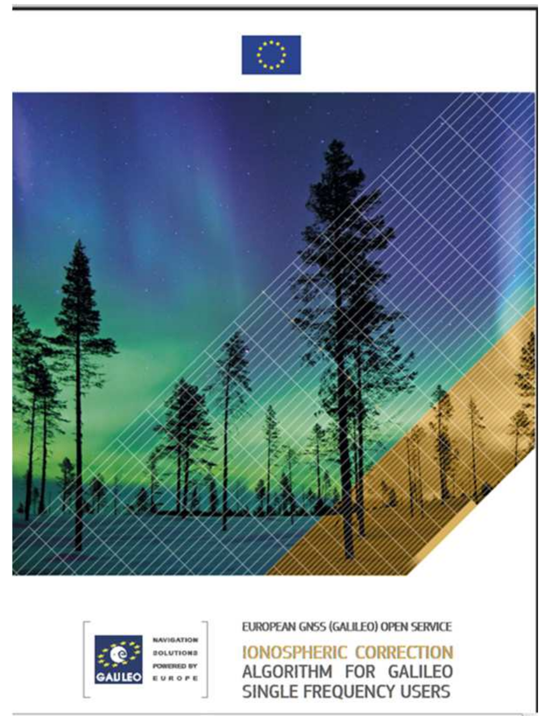
William B. Jones and Roger M. Gallet

For i=1,..,76 calculate the Fourier time series for *foF2*:

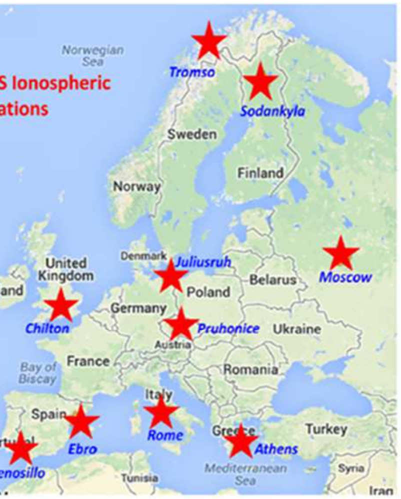
$$cf2_i = af2_{i,1} + \sum_{k=1}^{6}\left[af2_{i,2k}\sin(kT) + af2_{i,2k+1}\cos(kT)\right]$$

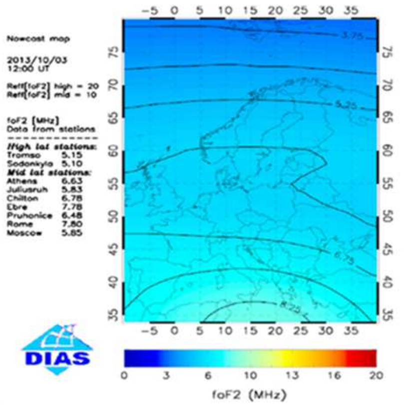
For i=1,..,49 calculate the Fourier time series for *M(3000)F2*:

$$cm3_i = am3_{i,1} + \sum_{k=1}^{4}\left[am3_{i,2k}\sin(kT) + am3_{i,2k+1}\cos(kT)\right]$$

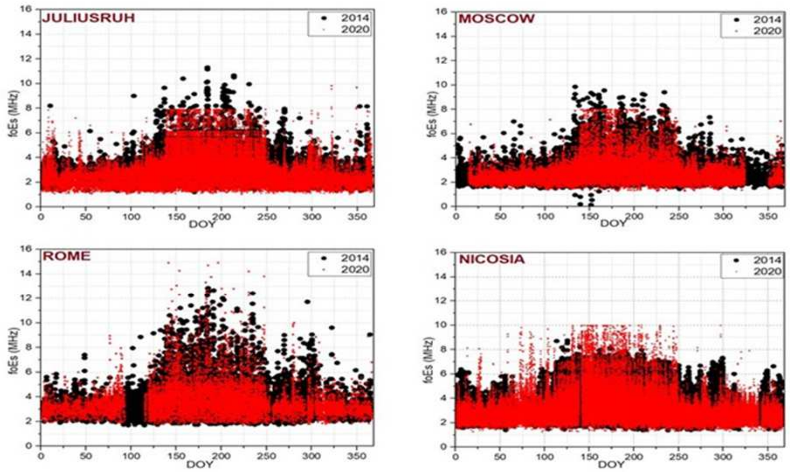


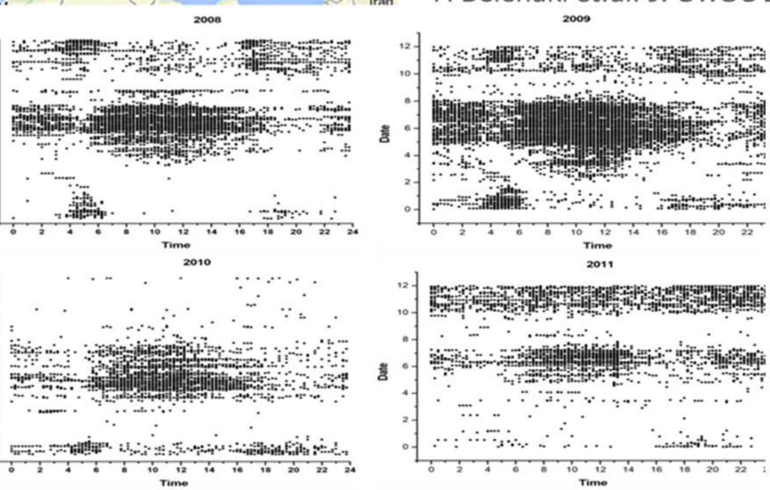
Effect of sporadic E layers (Es) monitoring over Europe

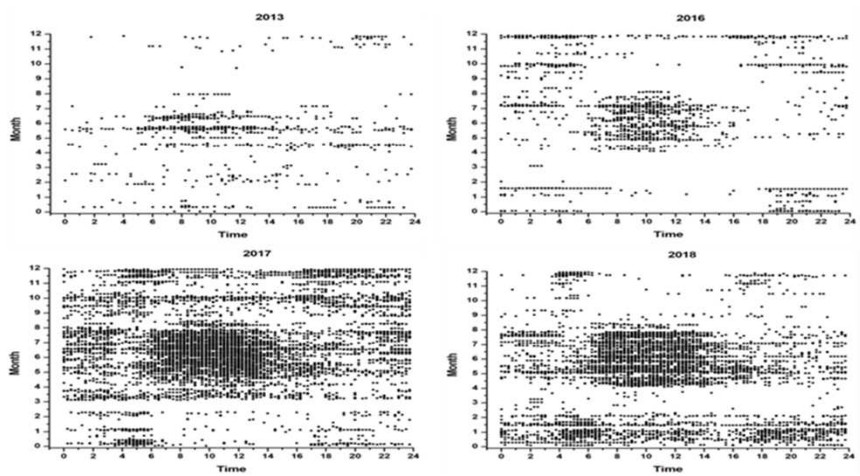




A Belehaki *et.al. J. SWSC 2015*

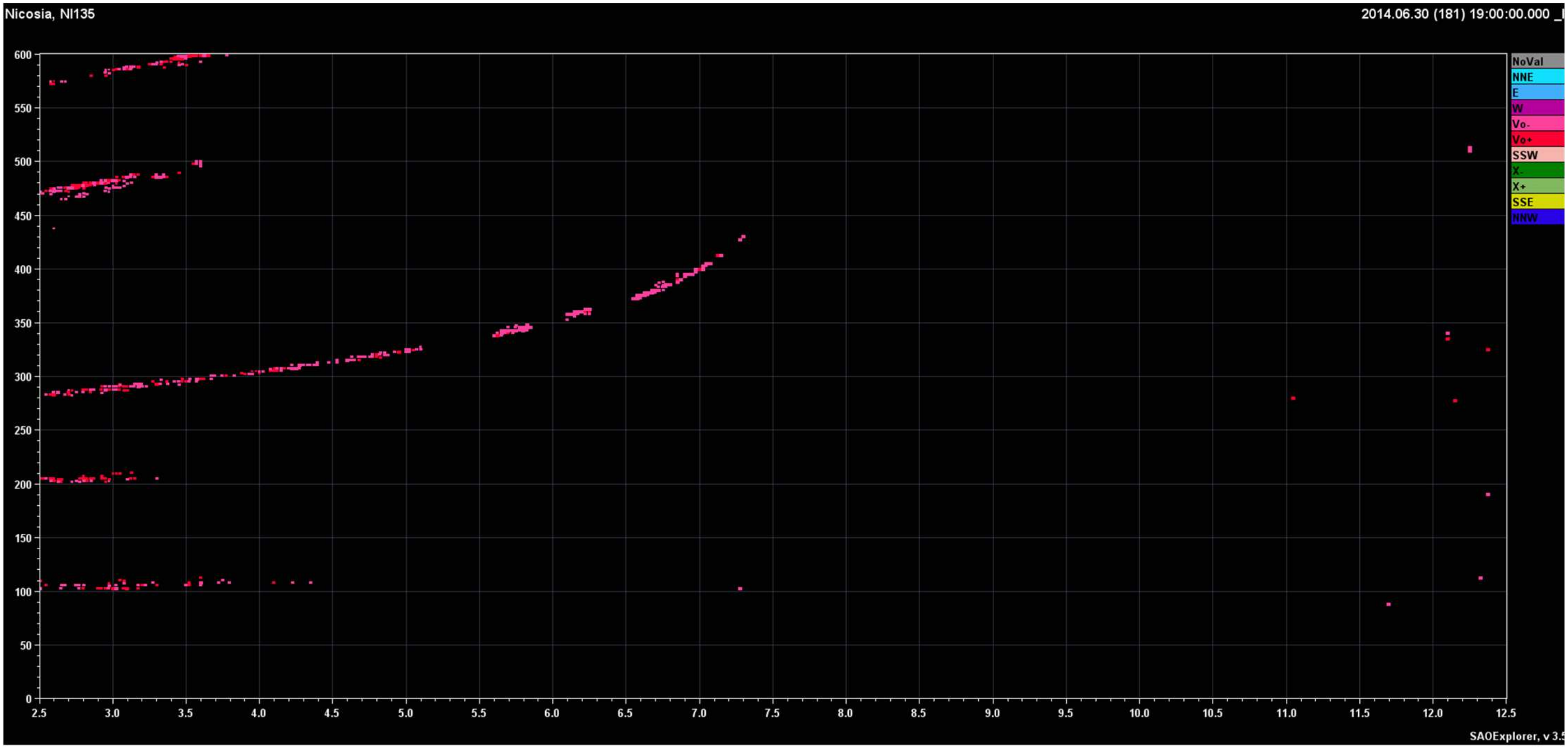




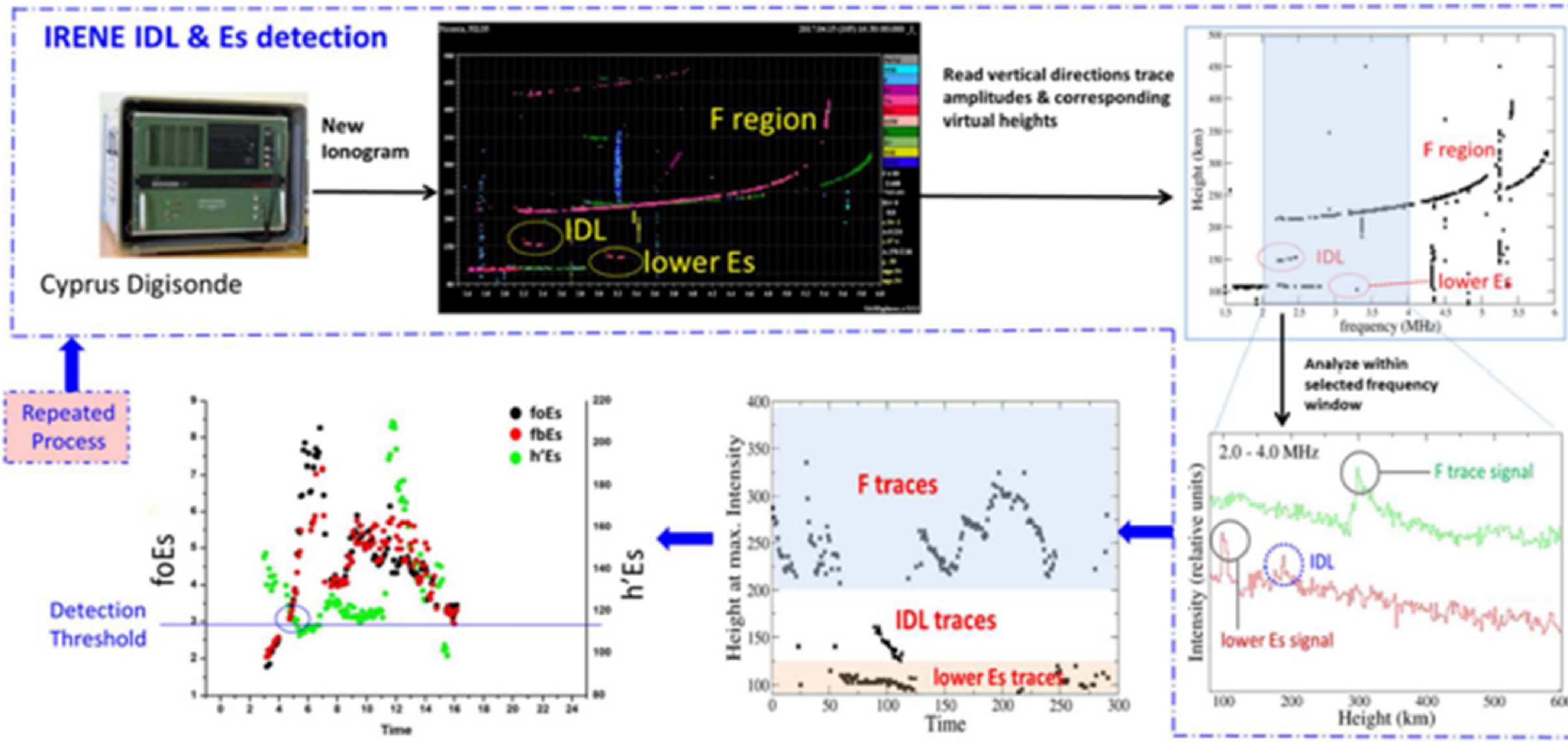


Sporadic E layers deprive the foF2 mapping algorithm of an adequate number of foF2 measurements to generate a reliable foF2 map over European latitudes

Effect of Es over Cyprus

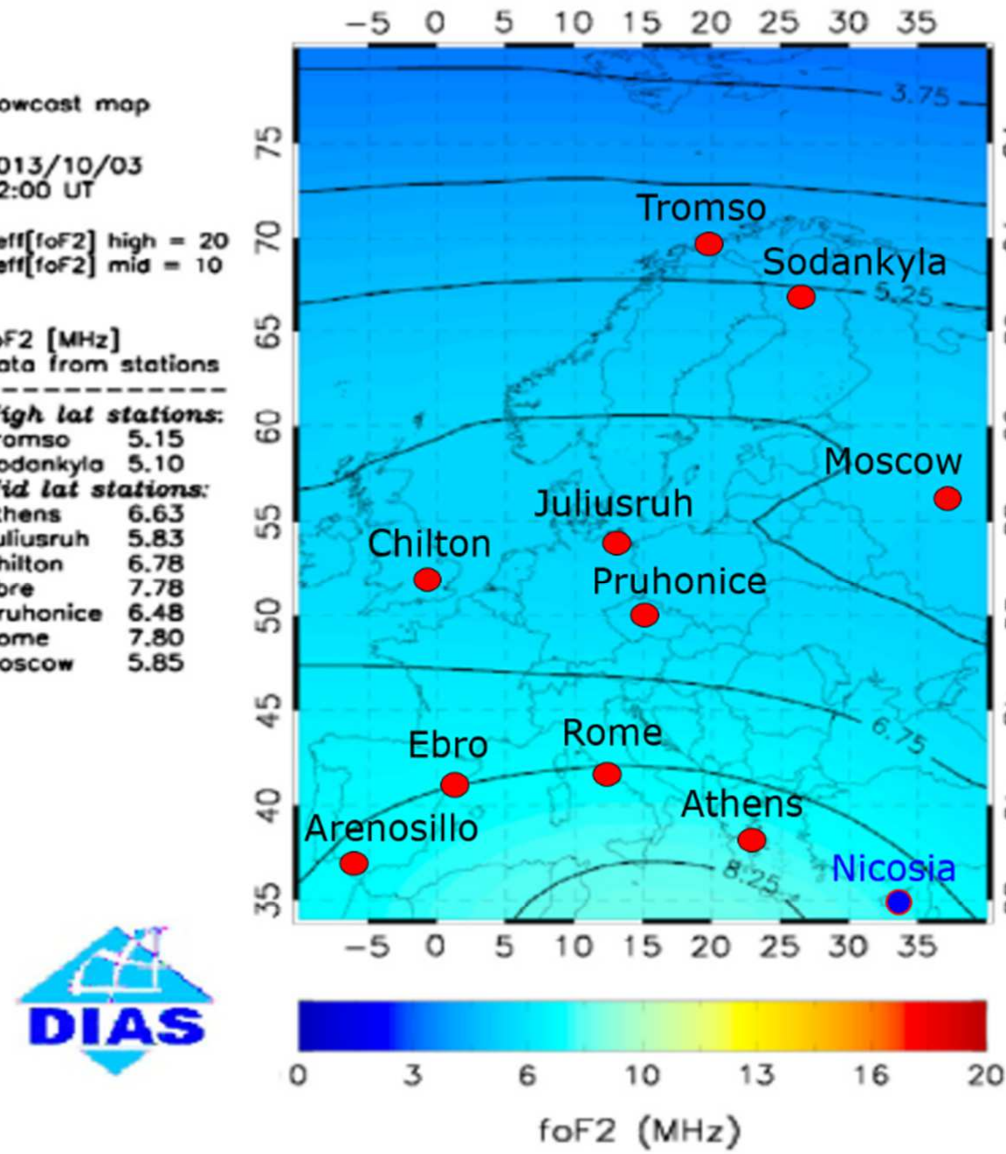


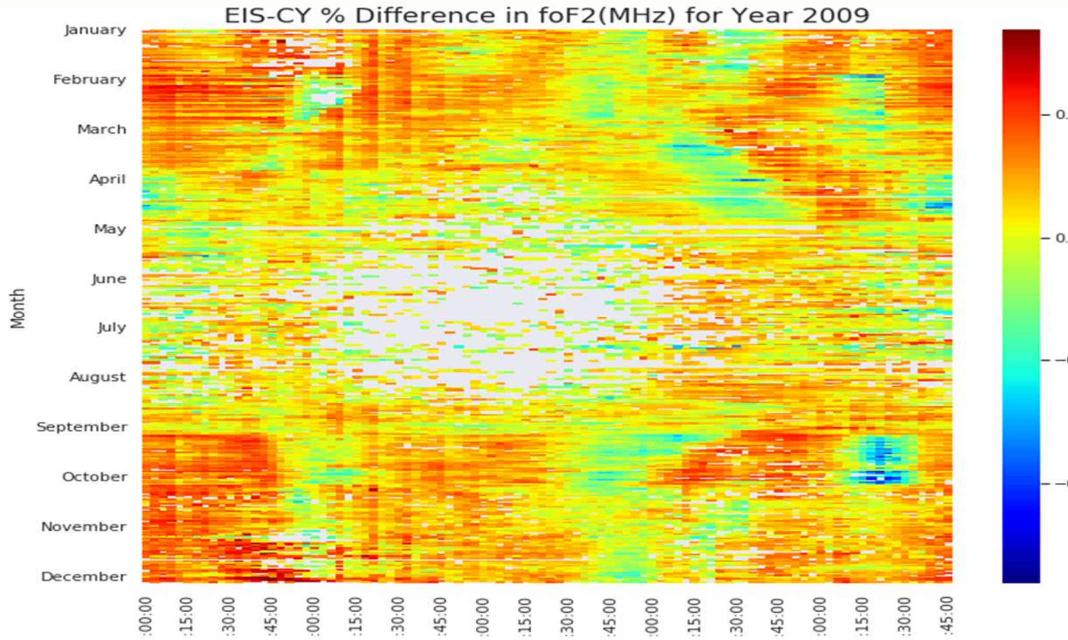
Ionospheric Representation Enhancement in Near-real timE (IRENE)

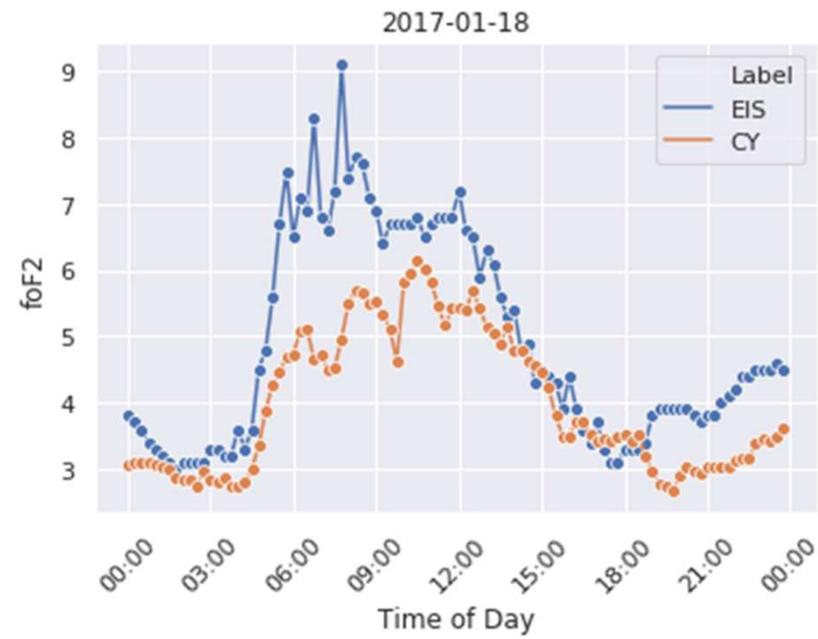


Baseline design of bottomside IRENE aspect.

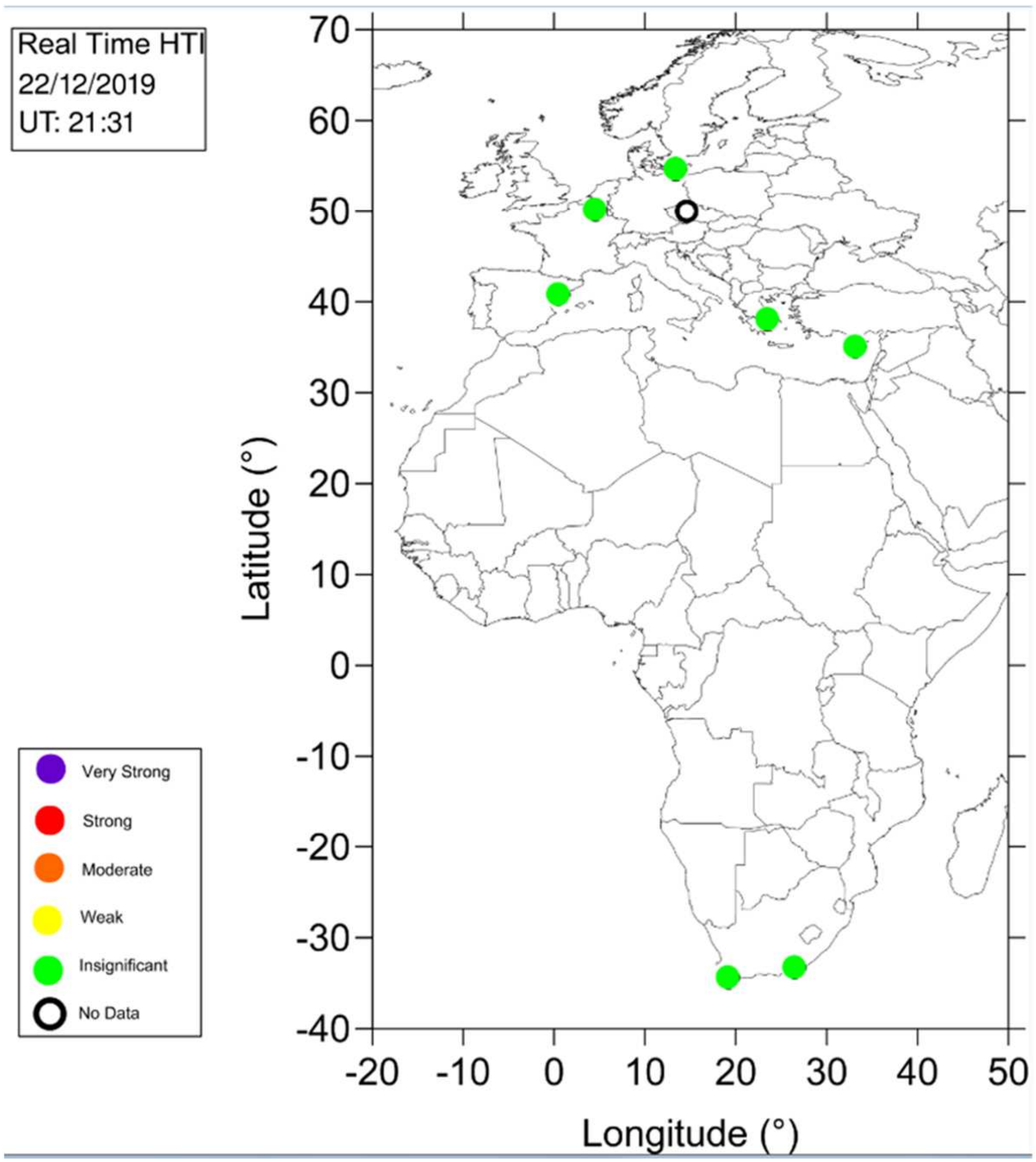
Interpolation of ionospheric maps over Cyprus

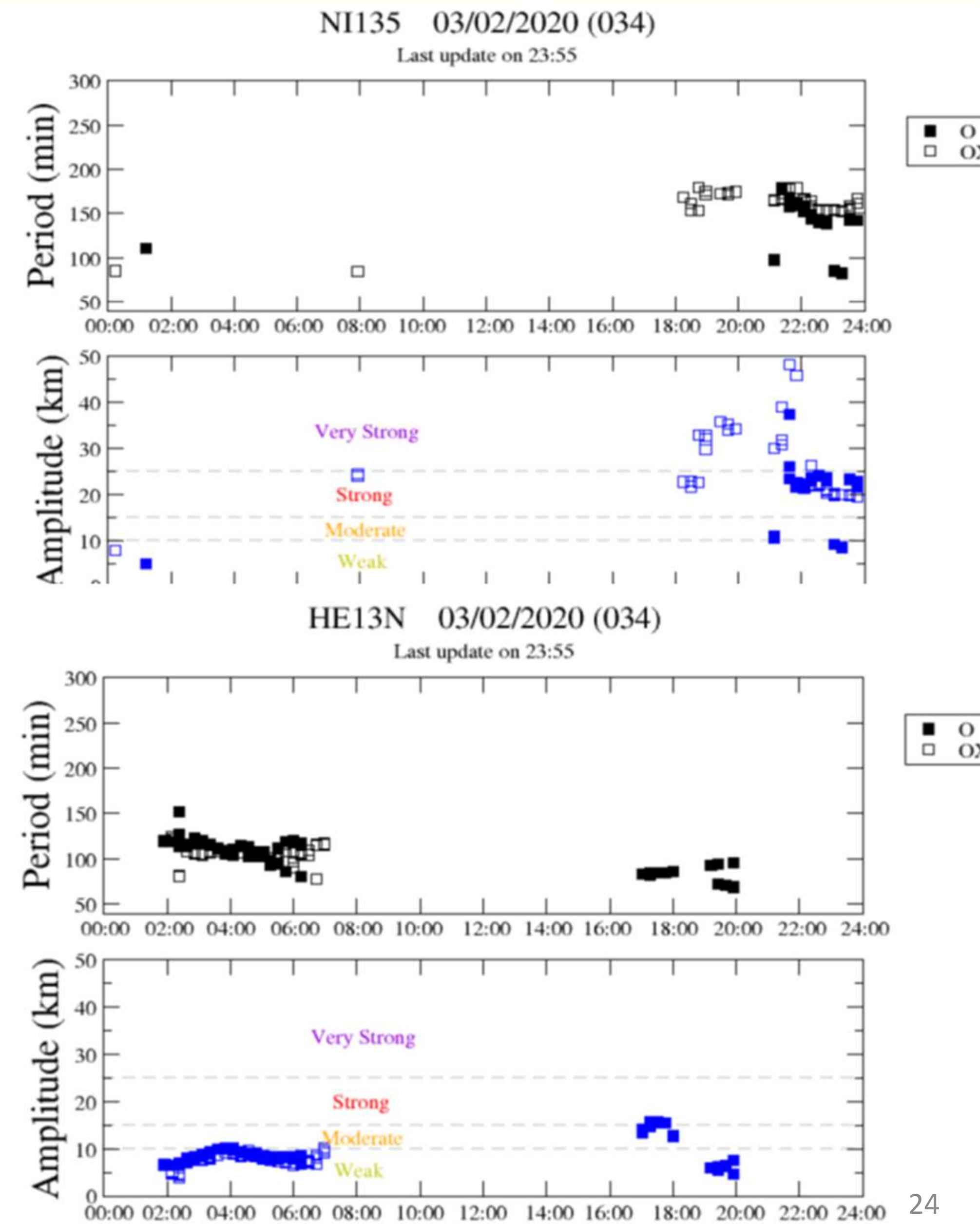




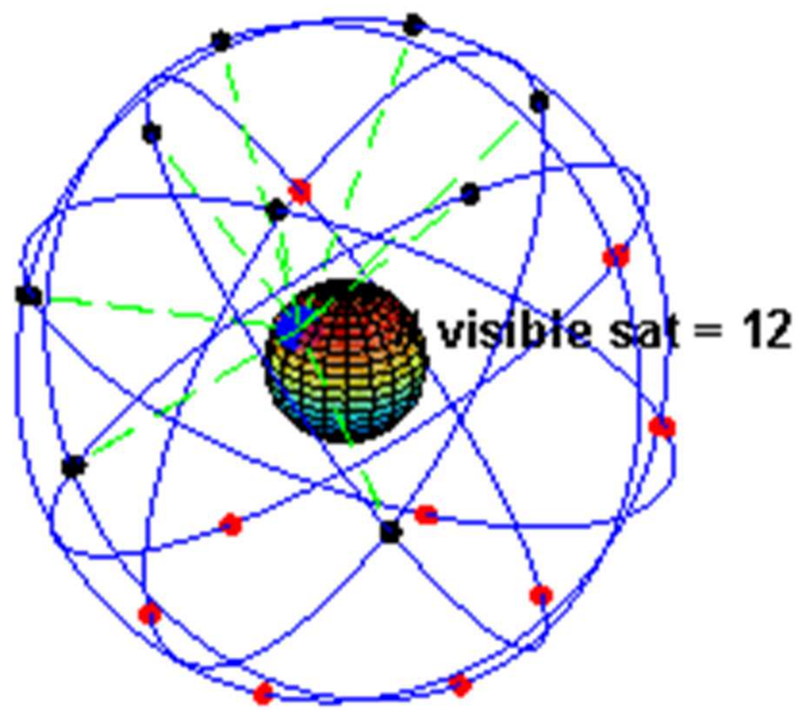


Warning and Mitigation Technologies for Travelling Ionospheric Disturbance (TID) monitoring





- The GPS constellation is constituted by a network of 24 satellites orbiting at 20,200 km from the Earth surface. They are evenly distributed within 6 orbitals planes inclined 55° with respect to the Earth's equator and equally spaced at 60°. Each satellite has a period of 12 hours.
- GPS satellites transmit two simultaneous PRN signals whose carrier frequencies are 1575.42 MHz and 1227.60 MHz, respectively. GPS receivers record these signals as Pseudo Range and Relative Phase.
- The major source of error in GNSS measurements is Ionosphere (in extreme cases the positioning error can exceed the 100 m).

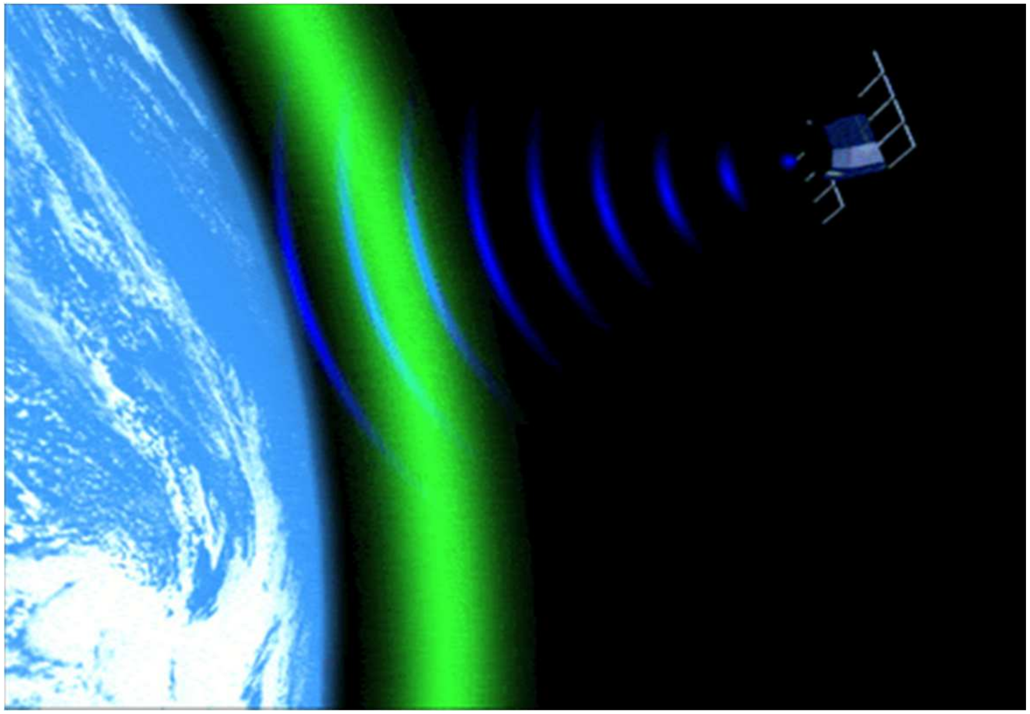


Ionospheric estimation by GNSS

Dual-frequency GPS data recorded by GPS receivers enable an estimation of ionospheric variability because of the frequency dependent delay imposed on the signal due to the ionosphere. By processing code and phase measurements on two frequencies in the L-band (L1=1575.42 MHz, L2=1227.60 MHz) it is possible to extract an estimate of the Total Electron Content (TEC) measured in total electron content units.

$$t_{ion} = \frac{40.3}{cf^2} TEC$$

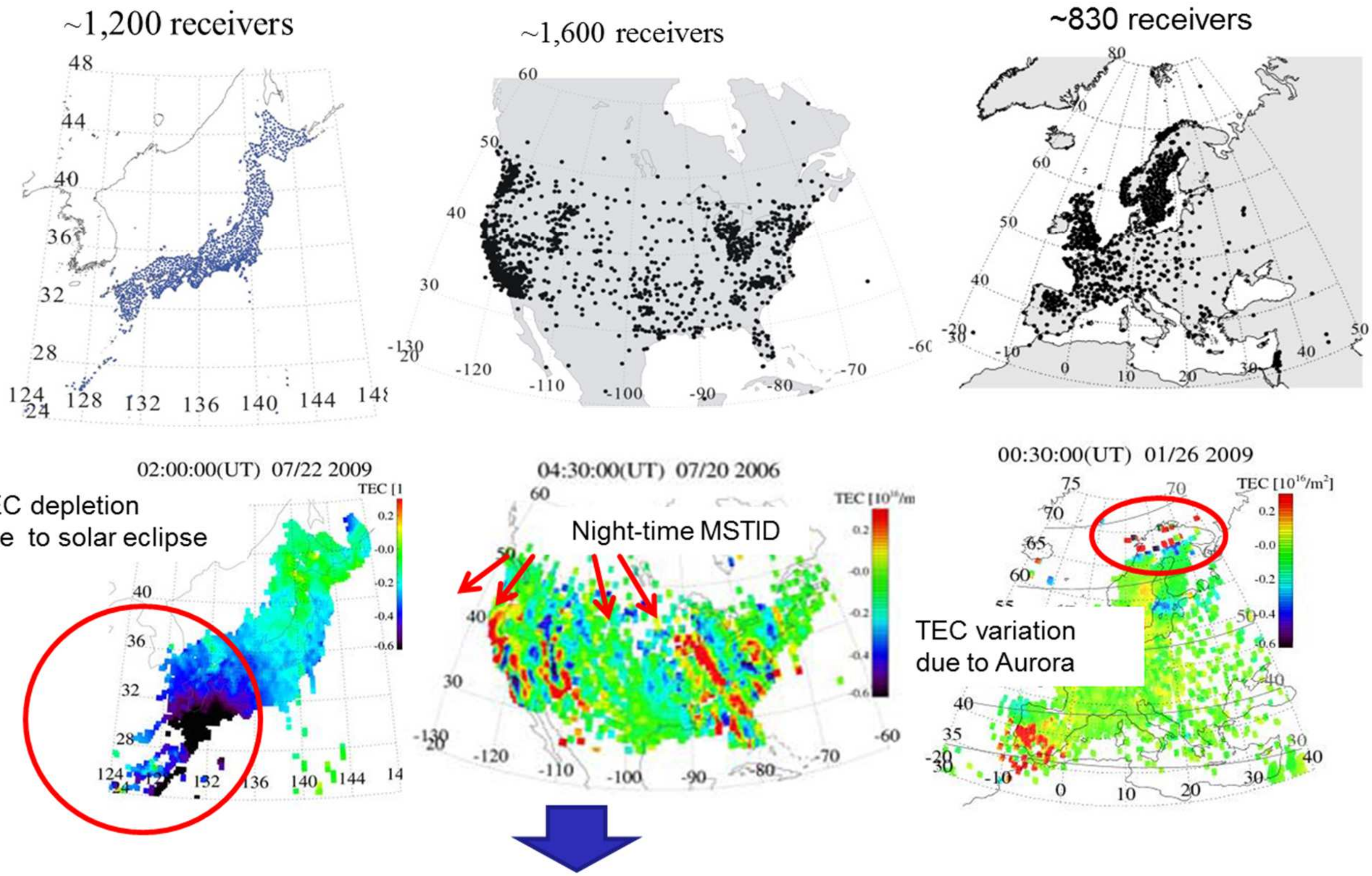
$$TEC = \int_{h1}^{h2} N(h).dh$$



High resolution GNSS maps

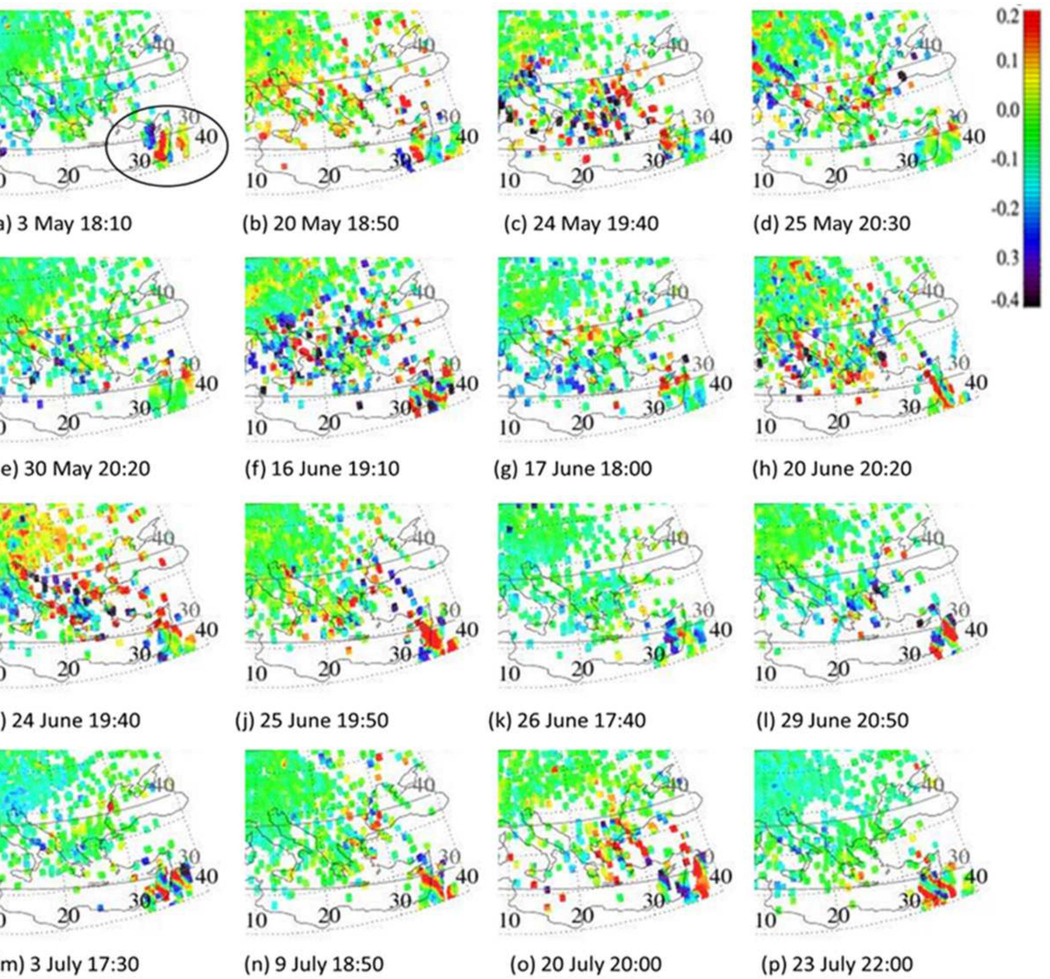
Number of GPS Receivers

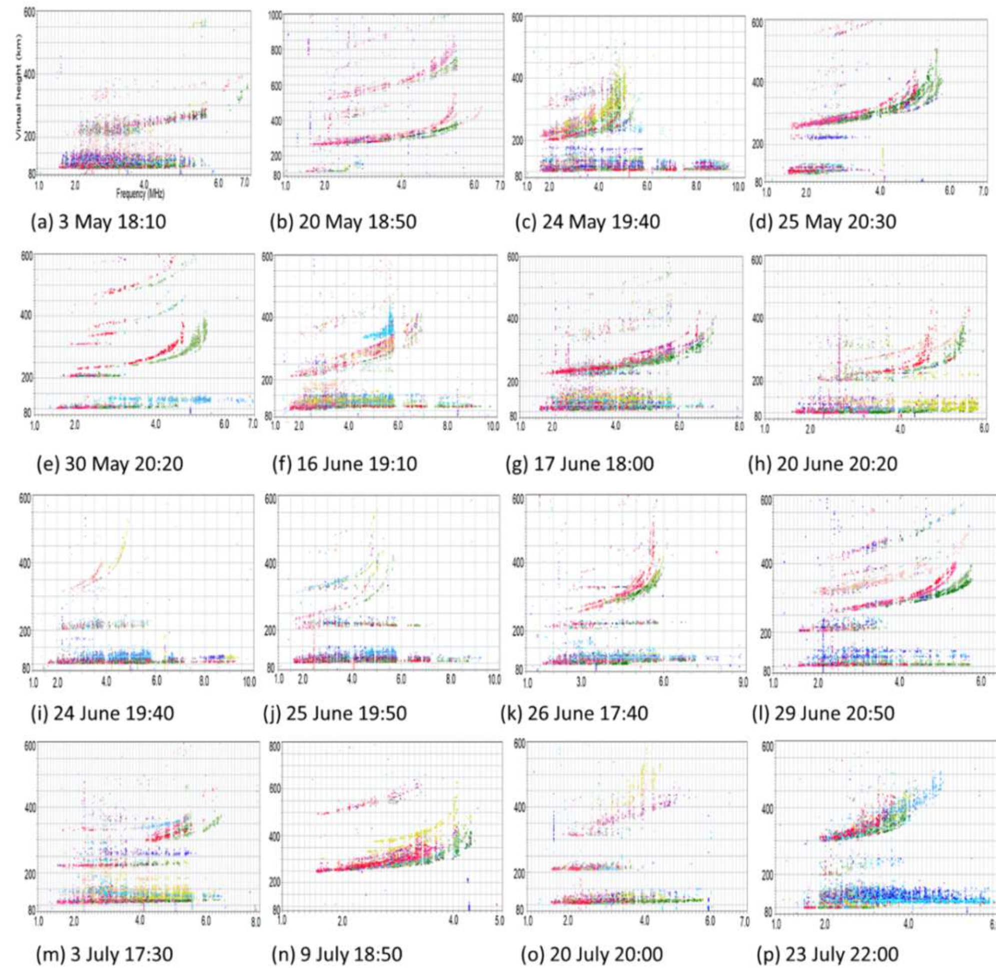
TEC Map
(30sec, 0.15°x0.15°)



Asia-Oceania GPS-TEC map…

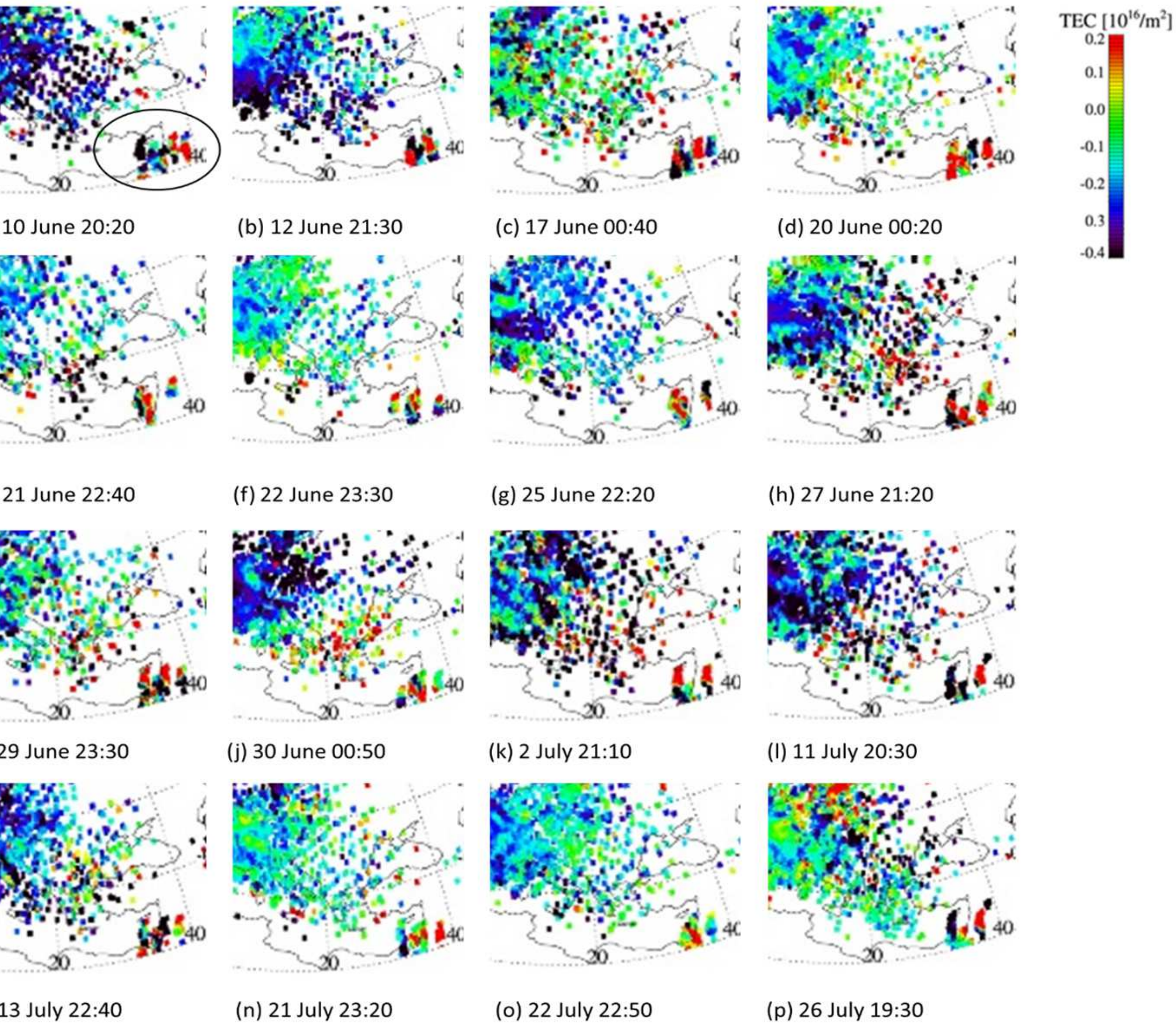
RAWING maps indicating MSTID activity during every spread F event over Cyprus (indicated wit
circle on the top left) during Summer of 2009 (low solar activity)

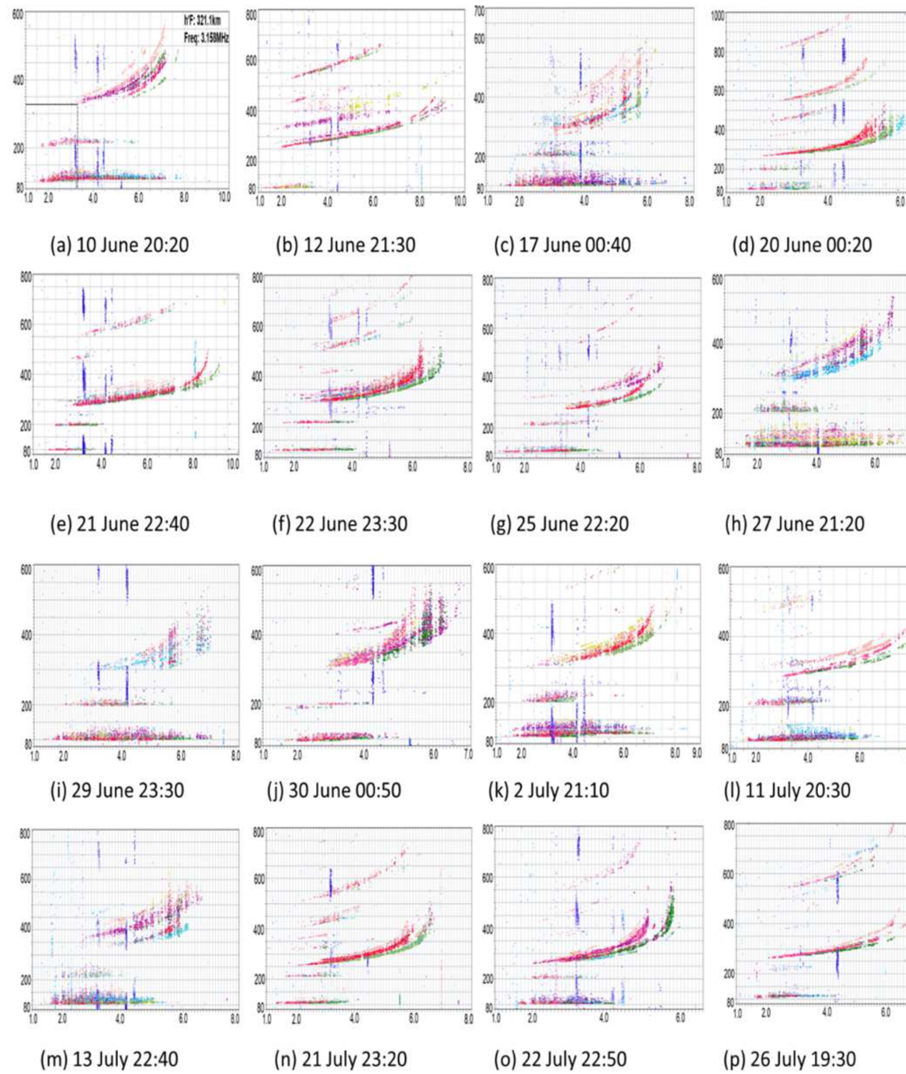




DRAWING maps indicating MSTID activity during every spread F event over Cyprus (indicated with a circle on the top left) during Summer of 2009 (low solar activity)

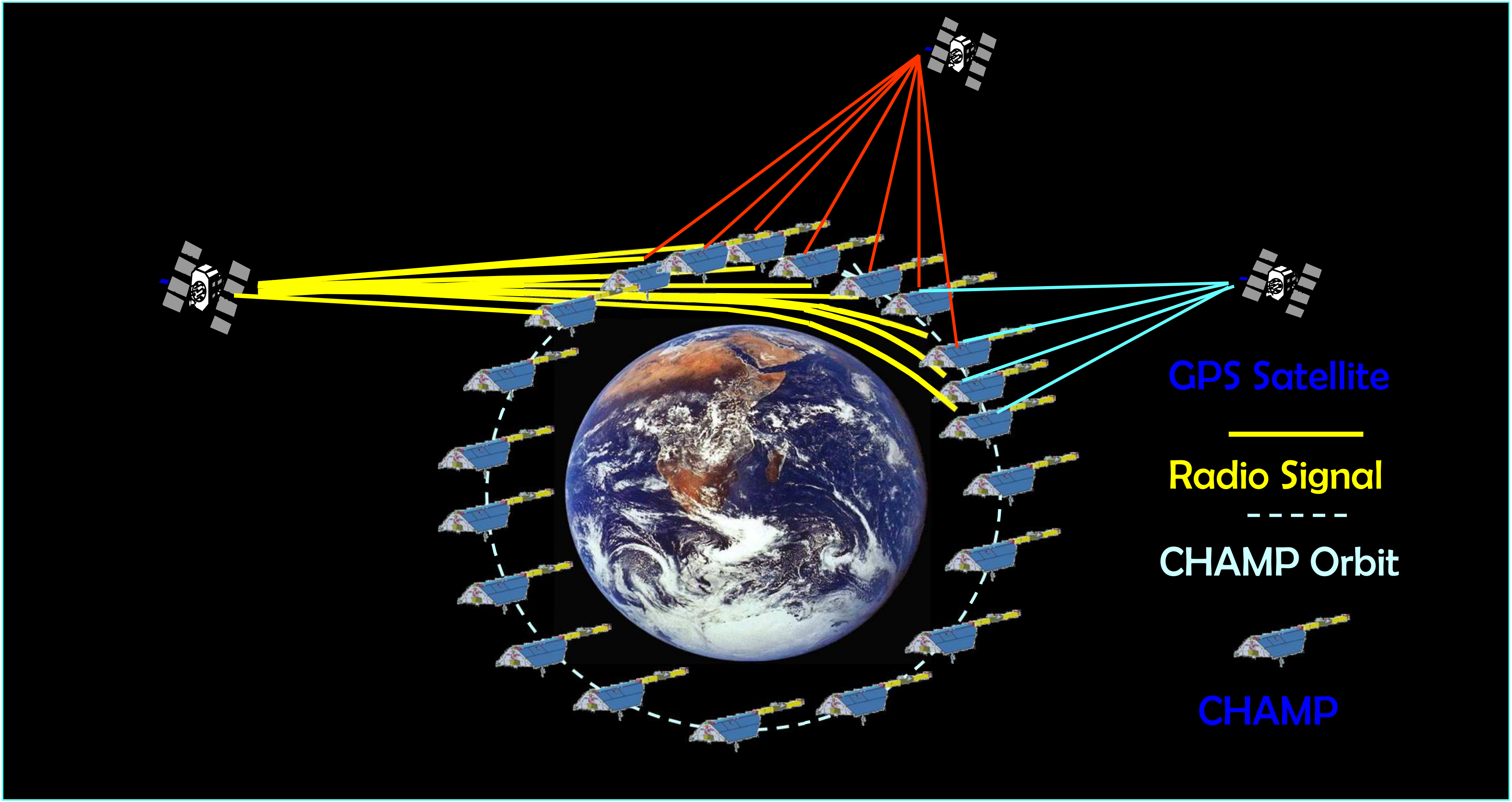
DRAWING maps indicating MSTID activity during every spread F event over Cyprus (indicated with a circle on the top left) during Summer of 2014 (high solar activity)





DRAWING maps indicating MSTID activity during every spread F event over Cyprus (indicated with a circle on the top left) during Summer of 2014 (high solar activity)

Ionospheric radio occultation



Ionospheric radio occultation (RO)

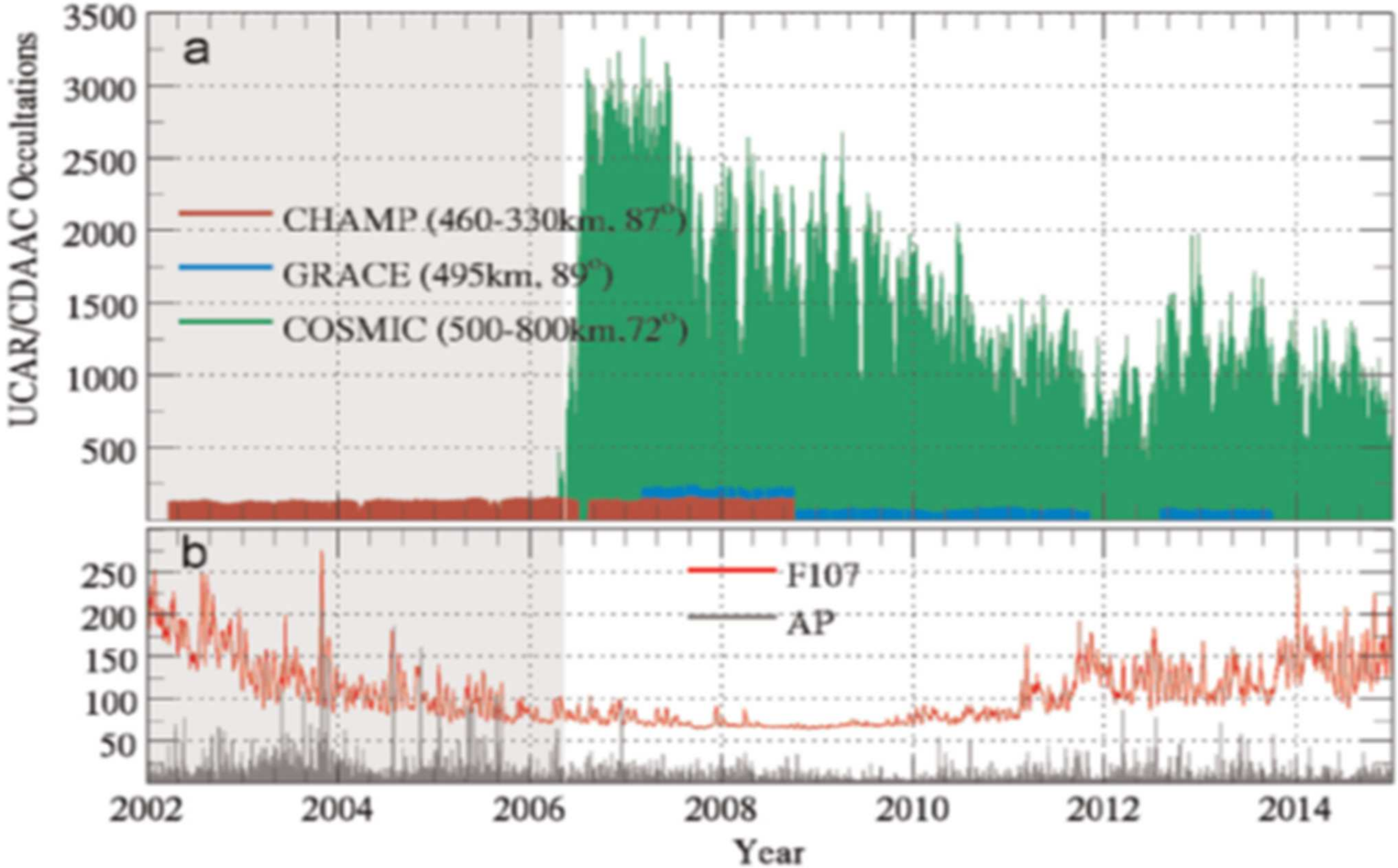
- Atmospheric probing by GNSS radio occultation (RO) measurements on board Low Earth Orbiting (LEO) satellites is a powerful technique for monitoring the vertical structure of the ionosphere and therefore to collect information on key ionospheric characteristics covering areas of the globe such as oceans where ground instrumentation such as GNSS receivers and radars are impossible to operate. Convincing evidence of the effective ionospheric sounding via RO was initially demonstrated through the GPS-Met experiment onboard Microlab-1 and further by following LEO missions such as CHAMP, GRACE, SAC-C, F3/C and C/NOFS.

- Numerous ionospheric studies have been performed on the extended dataset of more than **4 million ionospheric RO collected** by the six satellites of F3/C since 2006.

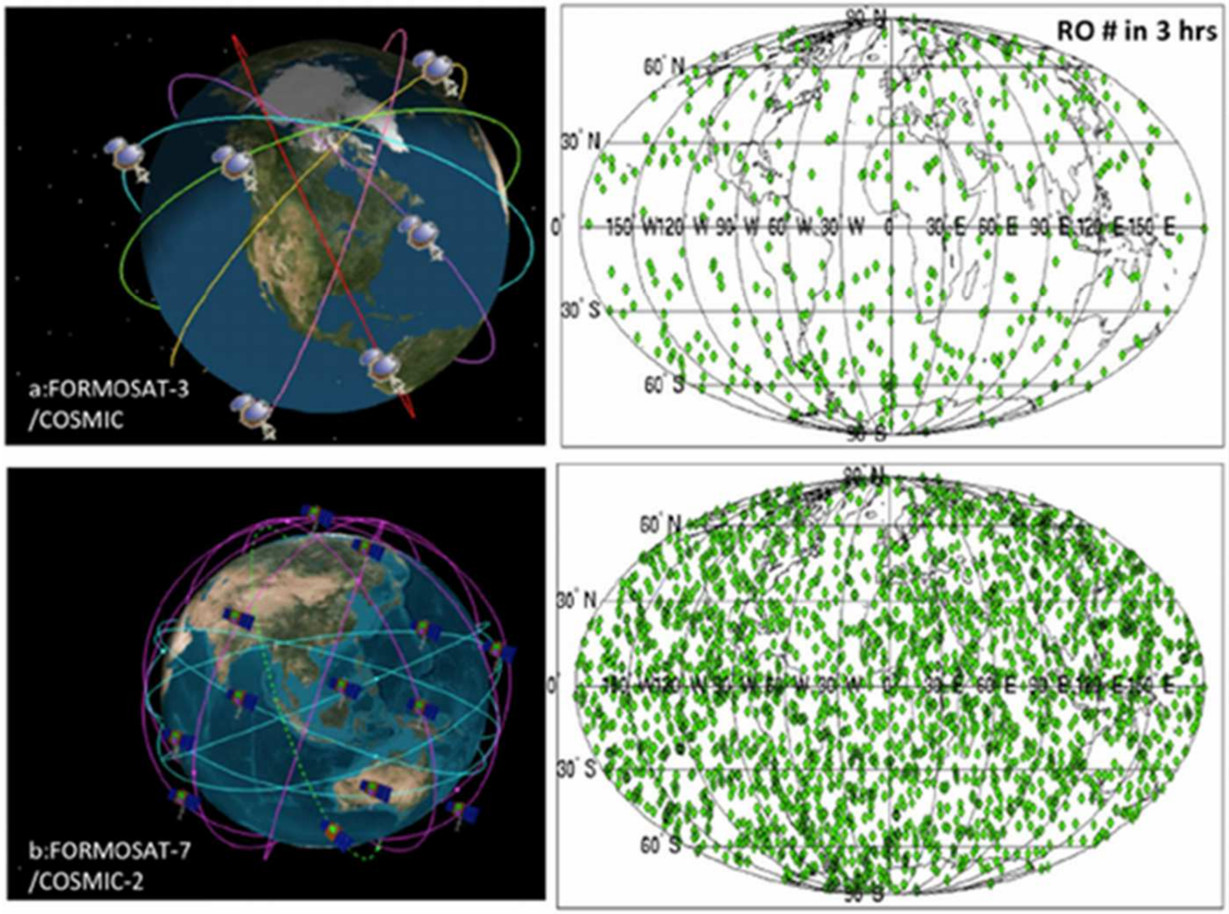
- Of particular interest are the **comparisons with ionosonde peak ionospheric characteristics and bottomside profiles** and full vertical profiles with **incoherent scatter radars** of collocated RO observations that served as a means to validate the RO technique under certain assumptions and data quality conditions over a limited geographical scale.

- Since the RO EDP is the result of two moving satellites **the actual tangent point during the RO event moves significantly in the horizontal** direction on the order of several **hundred km**. This results in **increased error as the bottomside or topside ionosphere** varies significantly from the vertical at the collocated NmF2-hmF2 point (normally <2-3 degrees) under these circumstances.

Daily RO events of CHAMP,GRACE and FORMOSAT3/COSMIC missions



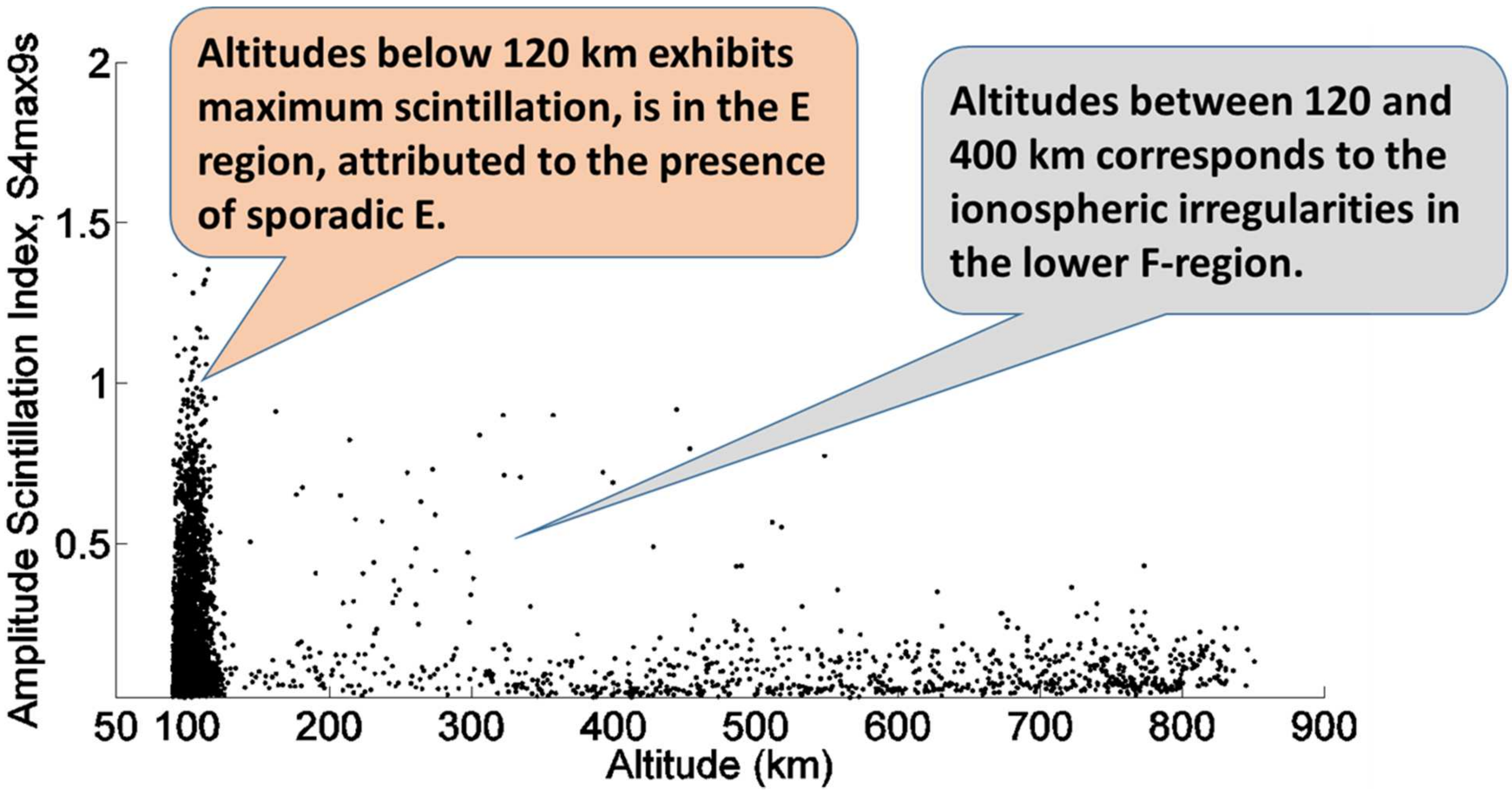
FORMOSAT-3/COSMIC vs FORMOSAT-7/COSMIC-2



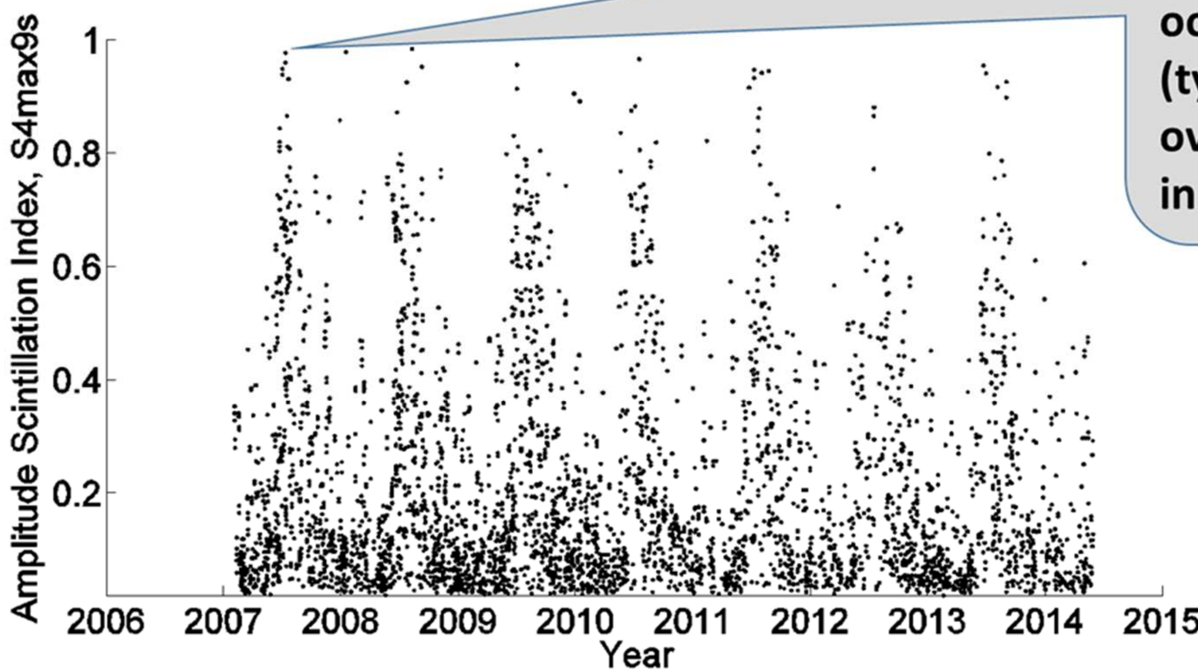
RO Payload	Satellite	Space Weather Payload
IGOR GPS ~2,000 per day	6 LEO satellites ~72° inclination ~800 km altitude ~61 kg >0.68 for 2 years launched 2006	TIP TBB
TriG GPS+ GLONASS >8,000 tropo per day >12,000 iono per day	First Launch 6 LEO satellites ~24° inclination ~520 km altitude ~215 kg >0.66 for 5 years ~launch 2016	IVM RF Beacon
	Second Launch 6 LEO satellites ~72° inclination ~720 km altitude ~215 kg >0.66 for 5 years ~launch 2019	TBD

Comparison between (a) FORMOSAT-3/COSMIC and (b) FORMOSAT-7/COSMIC-2 in (left) constellation, (middle) RO events during 3 h, and (right) key parameters.

RO signal Scintillation over Bangladesh

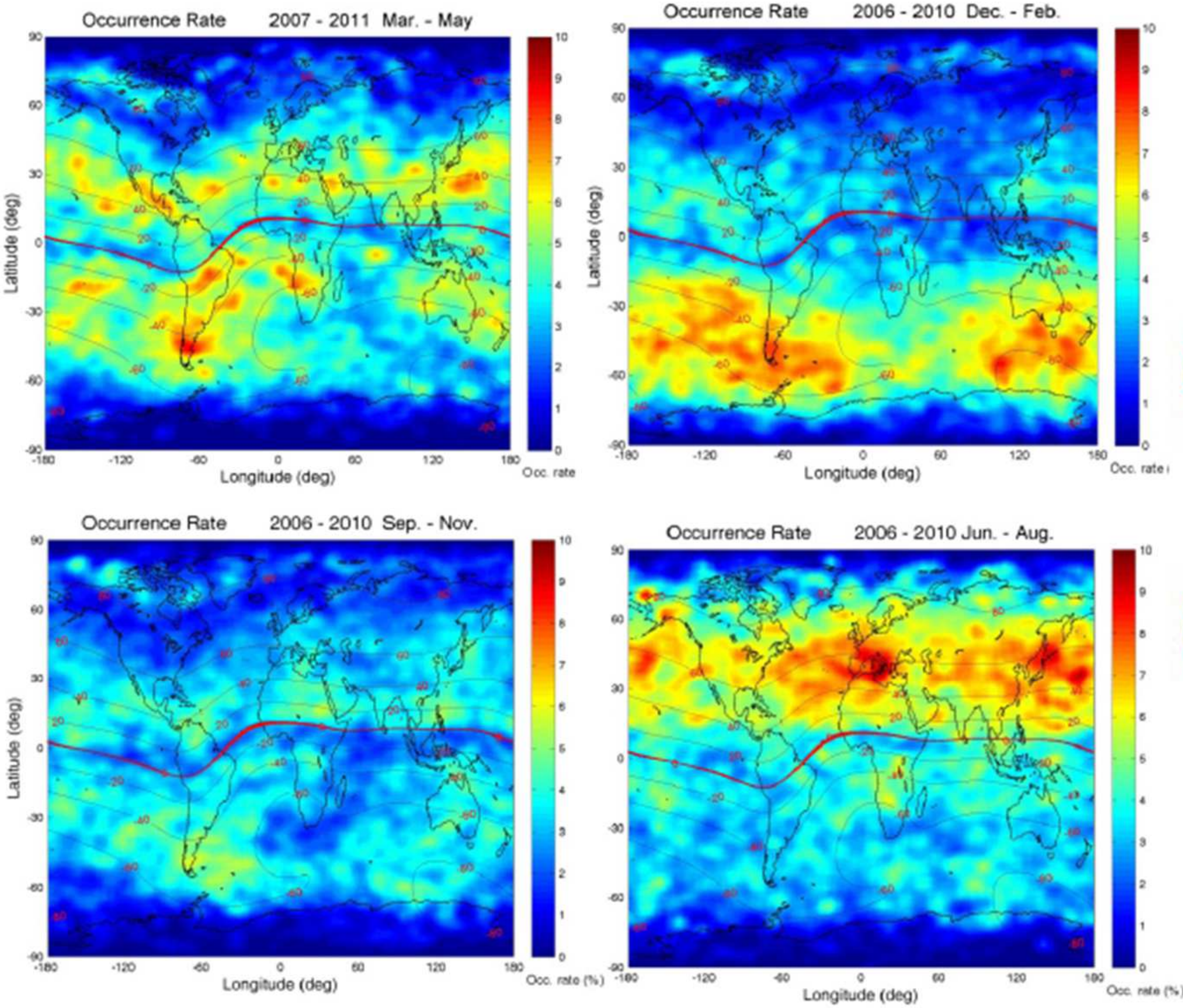


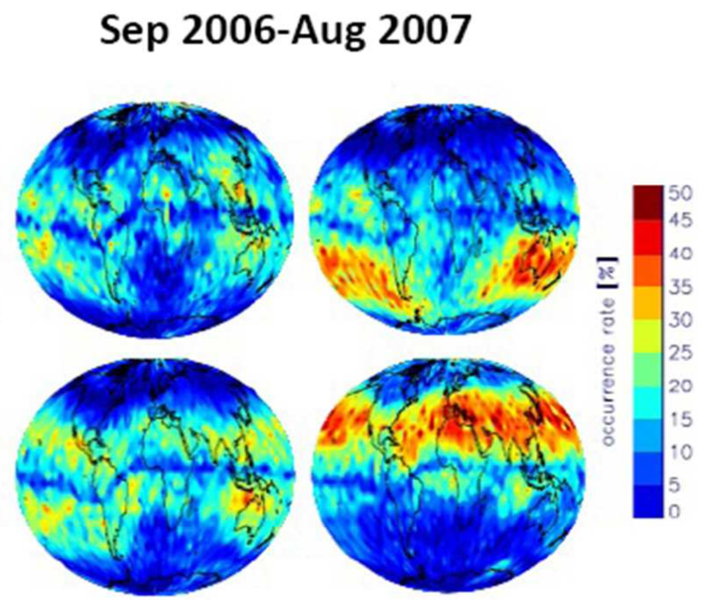
RO signal Scintillation over Bangladesh



Sporadic-E **is quite systematic over Bangladesh with a high occurrence during the summer. (typical behaviour reported over the northern hemisphere in other studies).**

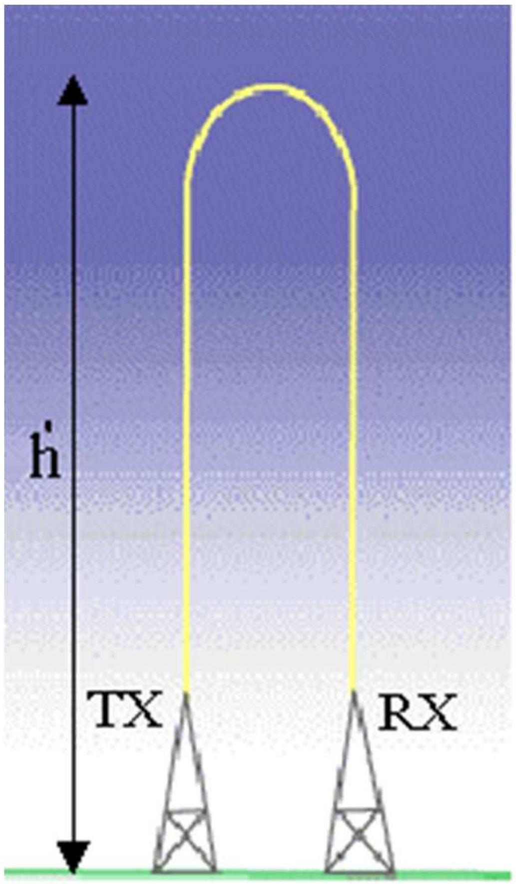
GLOBAL WINDSHEAR MECHANISMS OF Es FORMATION AS SEEN BY RO

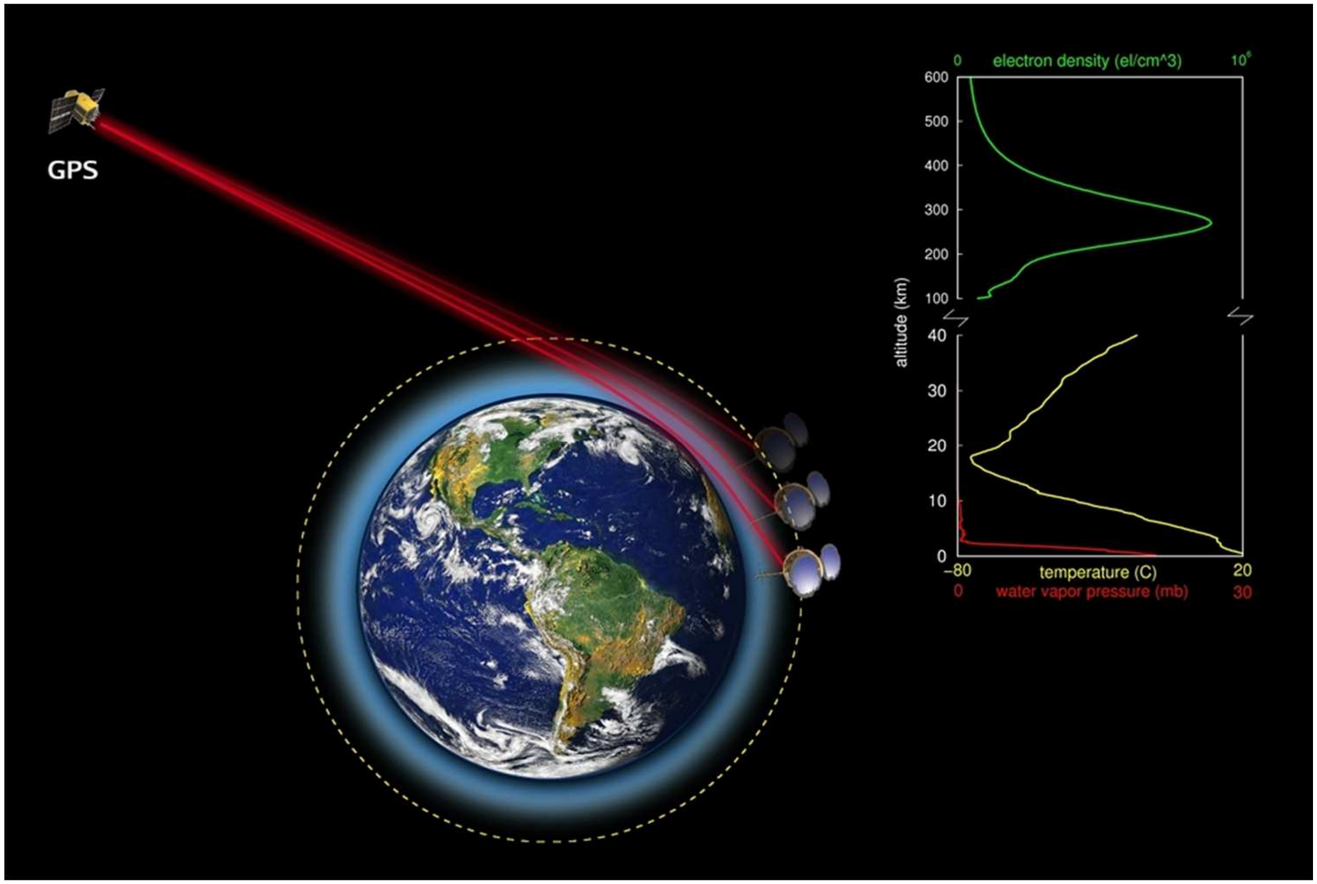




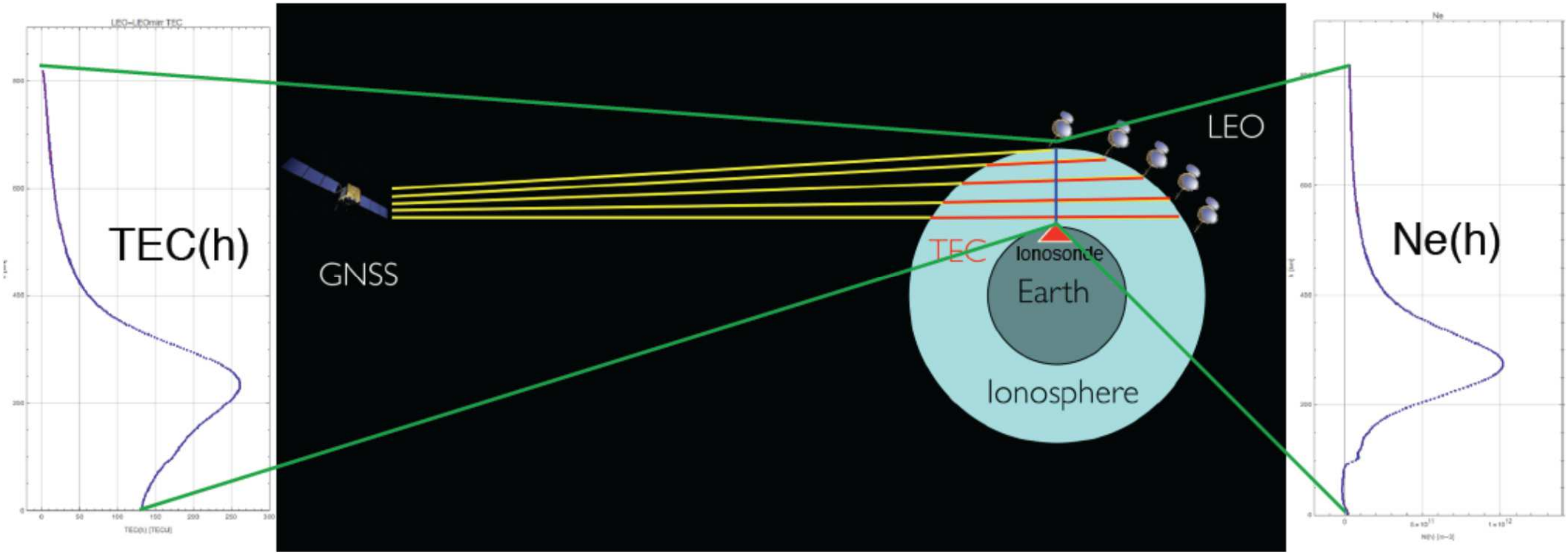
(Arras et al., 2008)

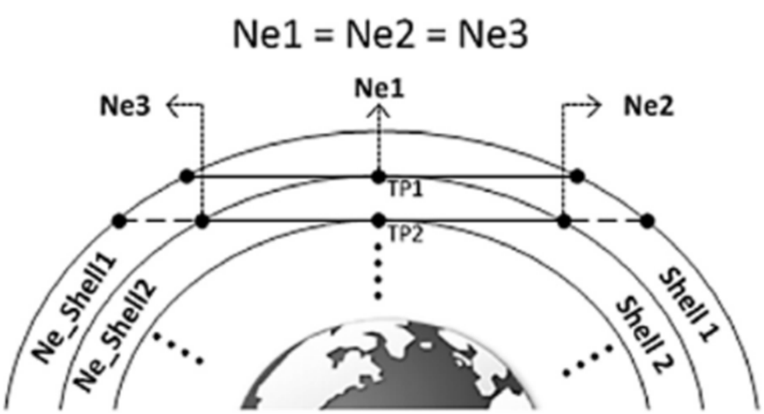
Measurement of electron density by Digisondes and RO



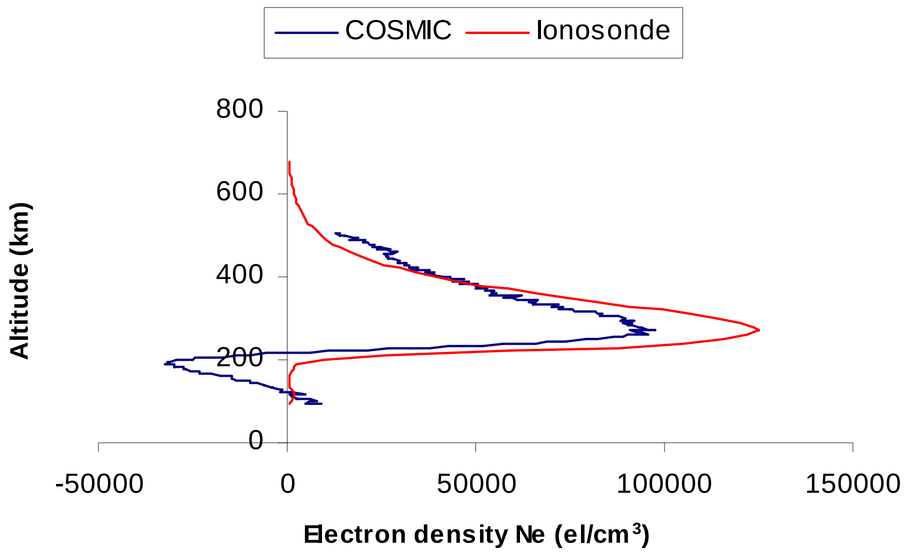


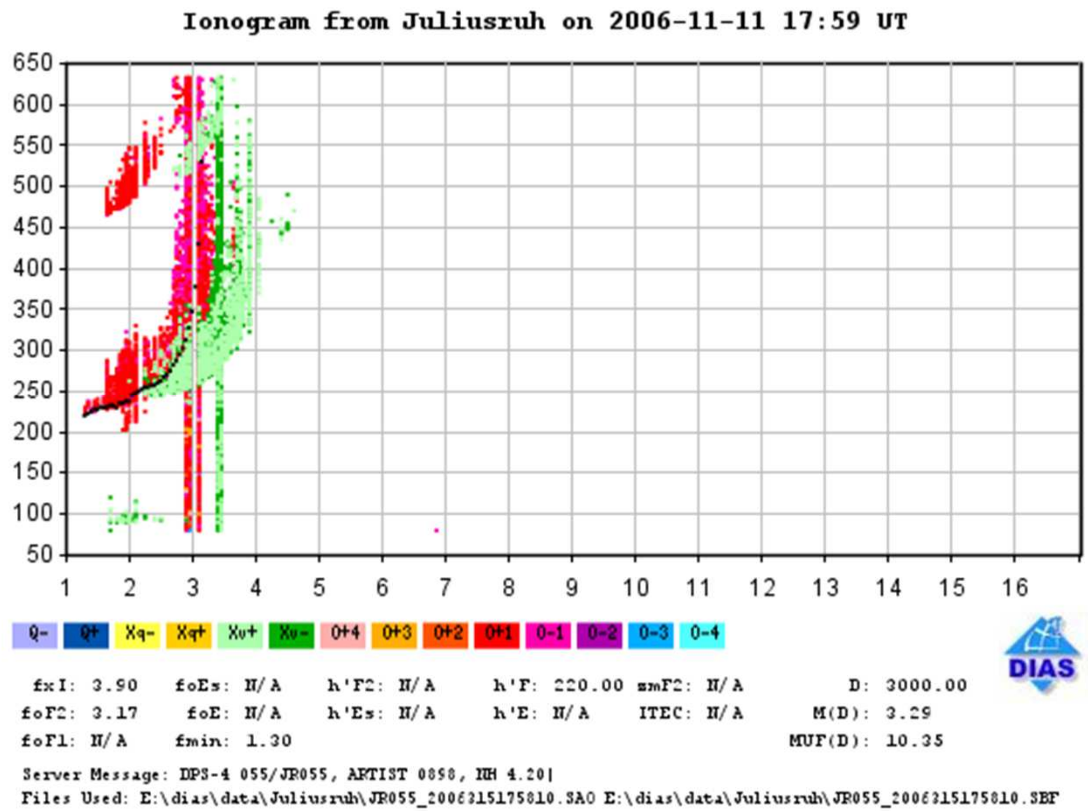
Spherical asymmetry issue in the standard Abel inversion



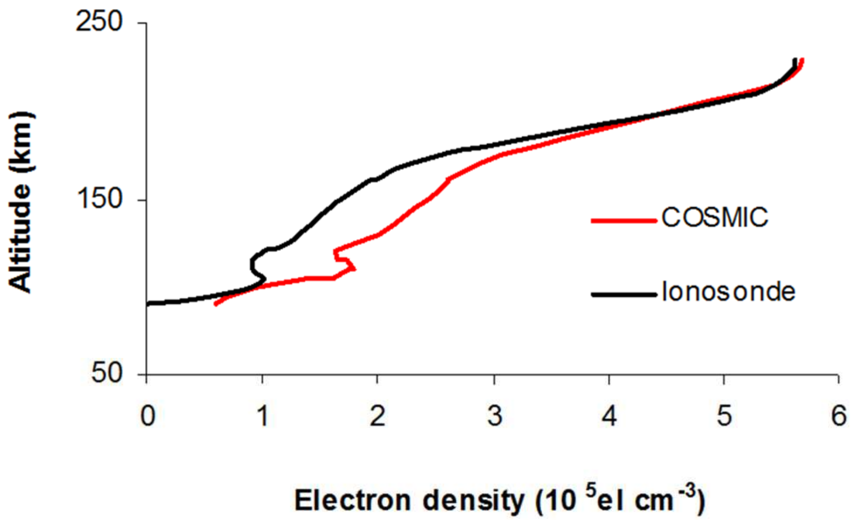


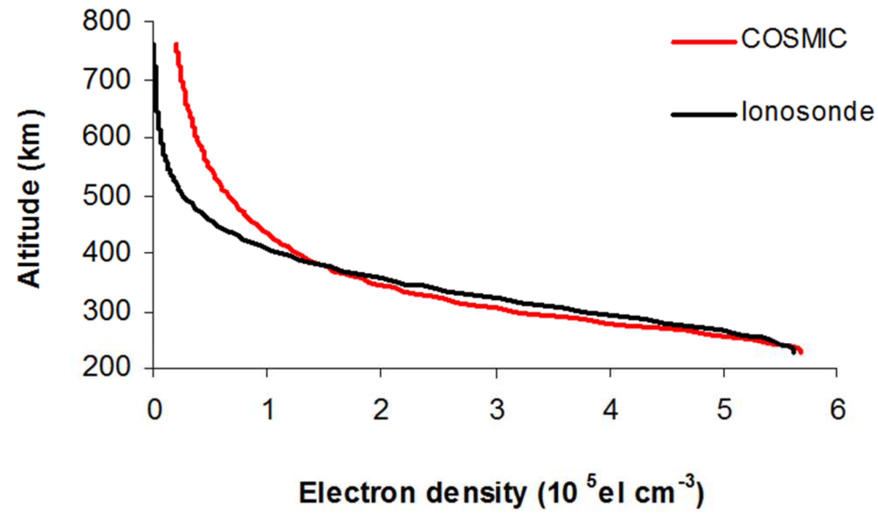
Spherical asymmetry issue in the standard Abel inversion

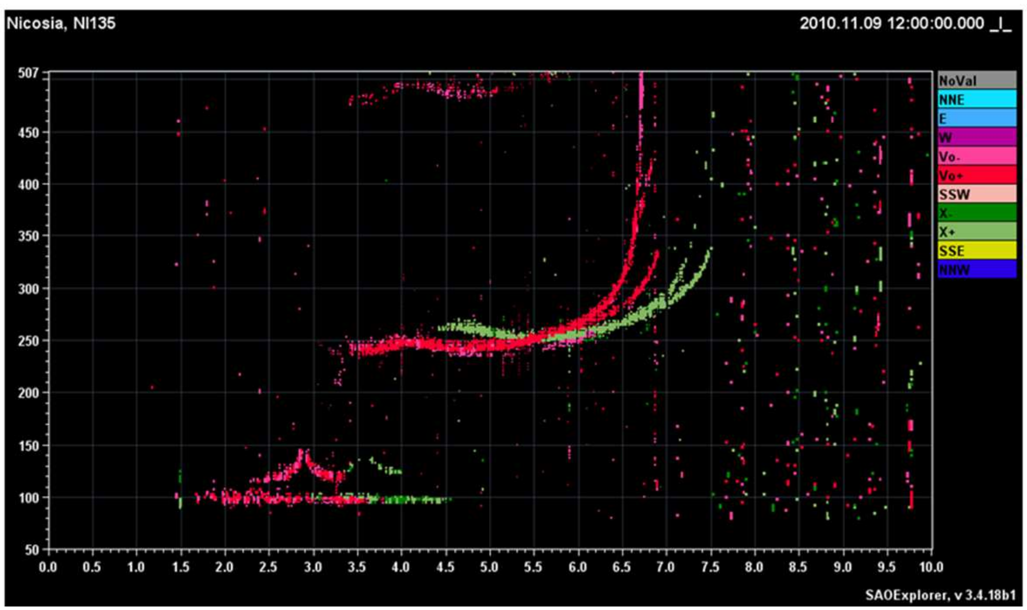




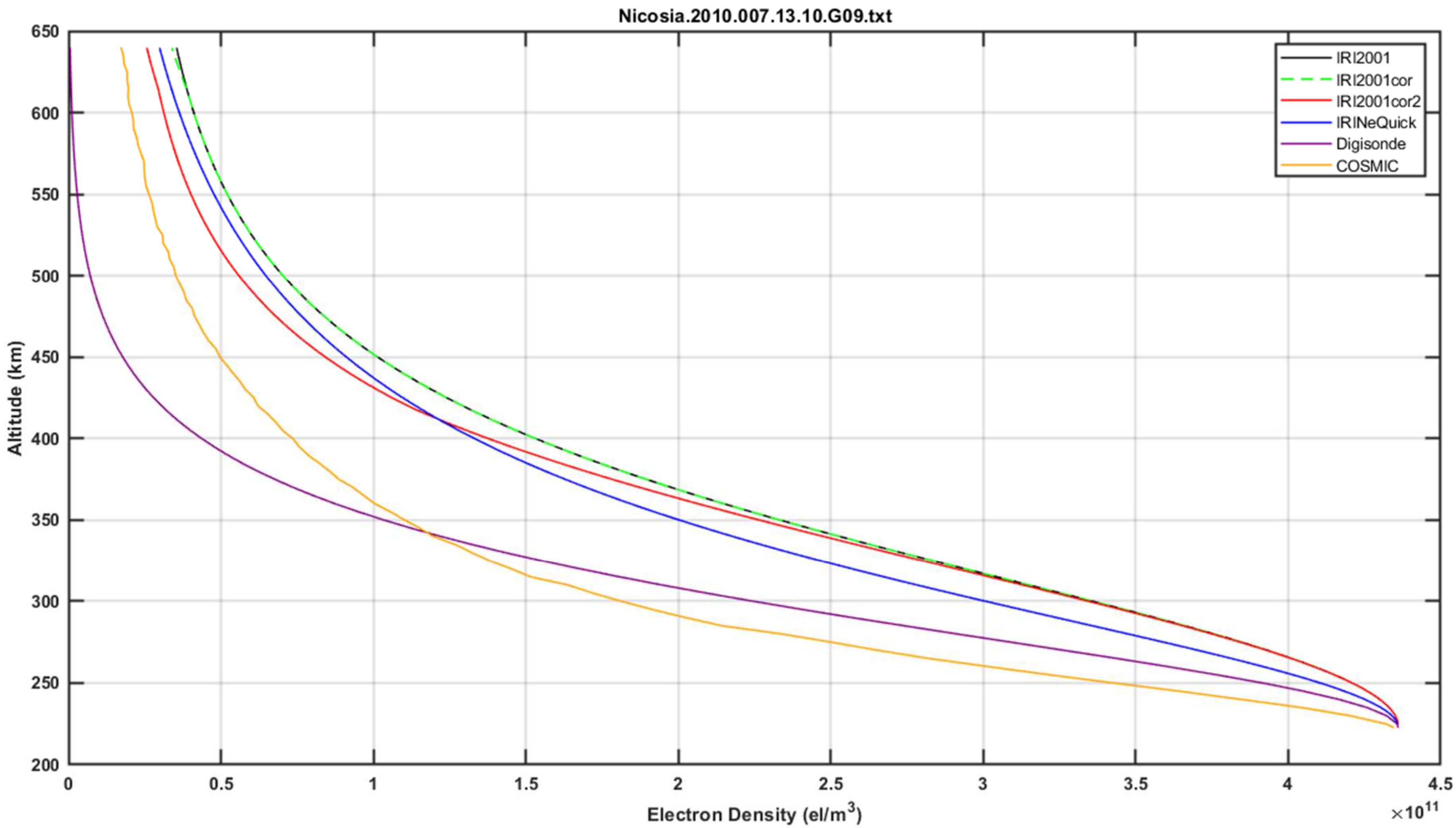
Spherical asymmetry issue in the standard Abel inversion



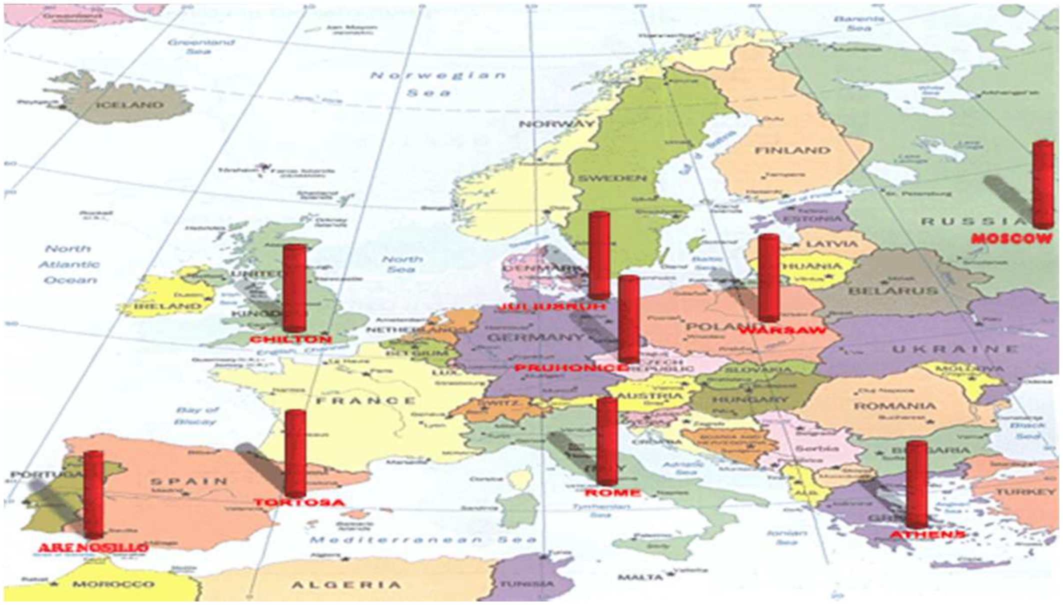


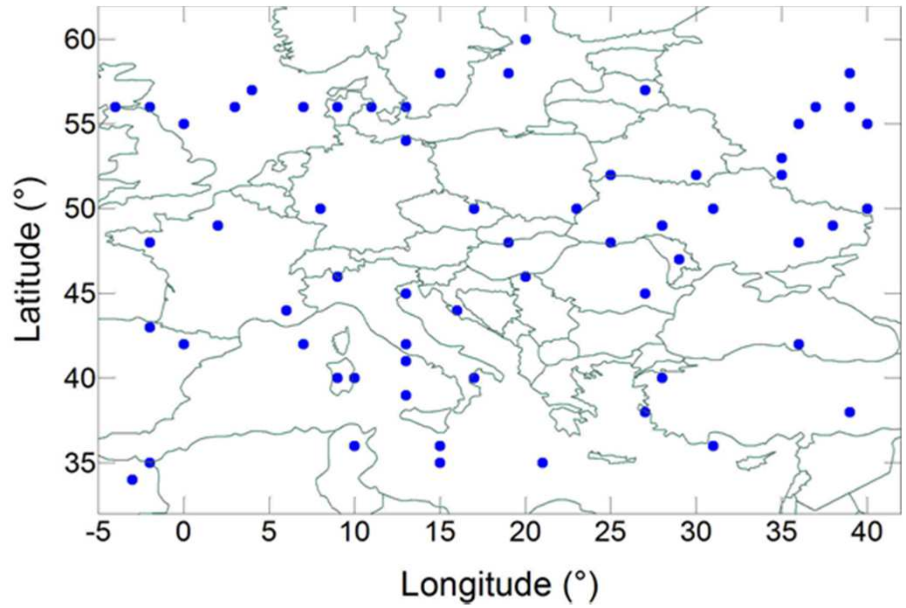


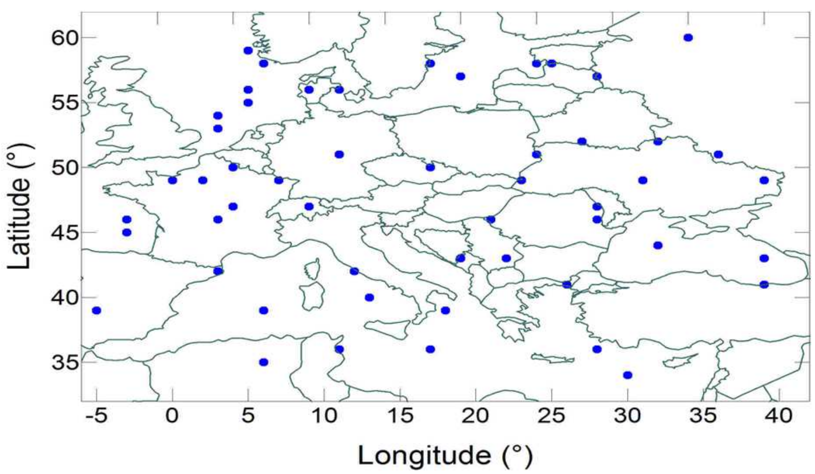
Topside model validation

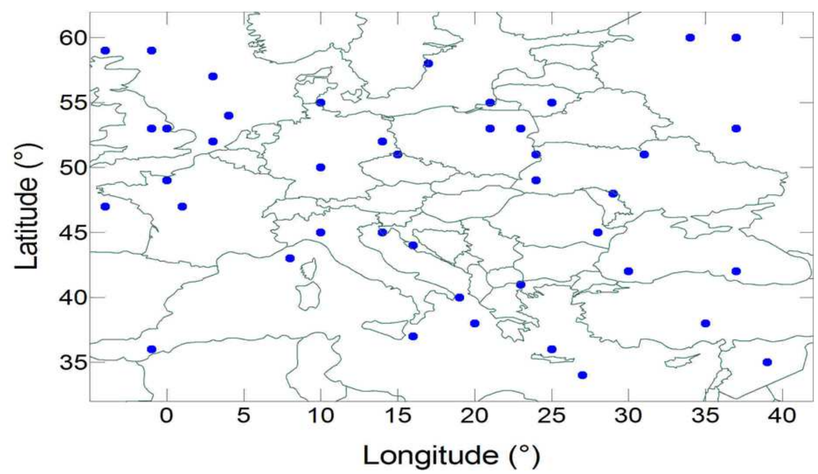


ropean Ionospheric Stations - Radio occultation investigation

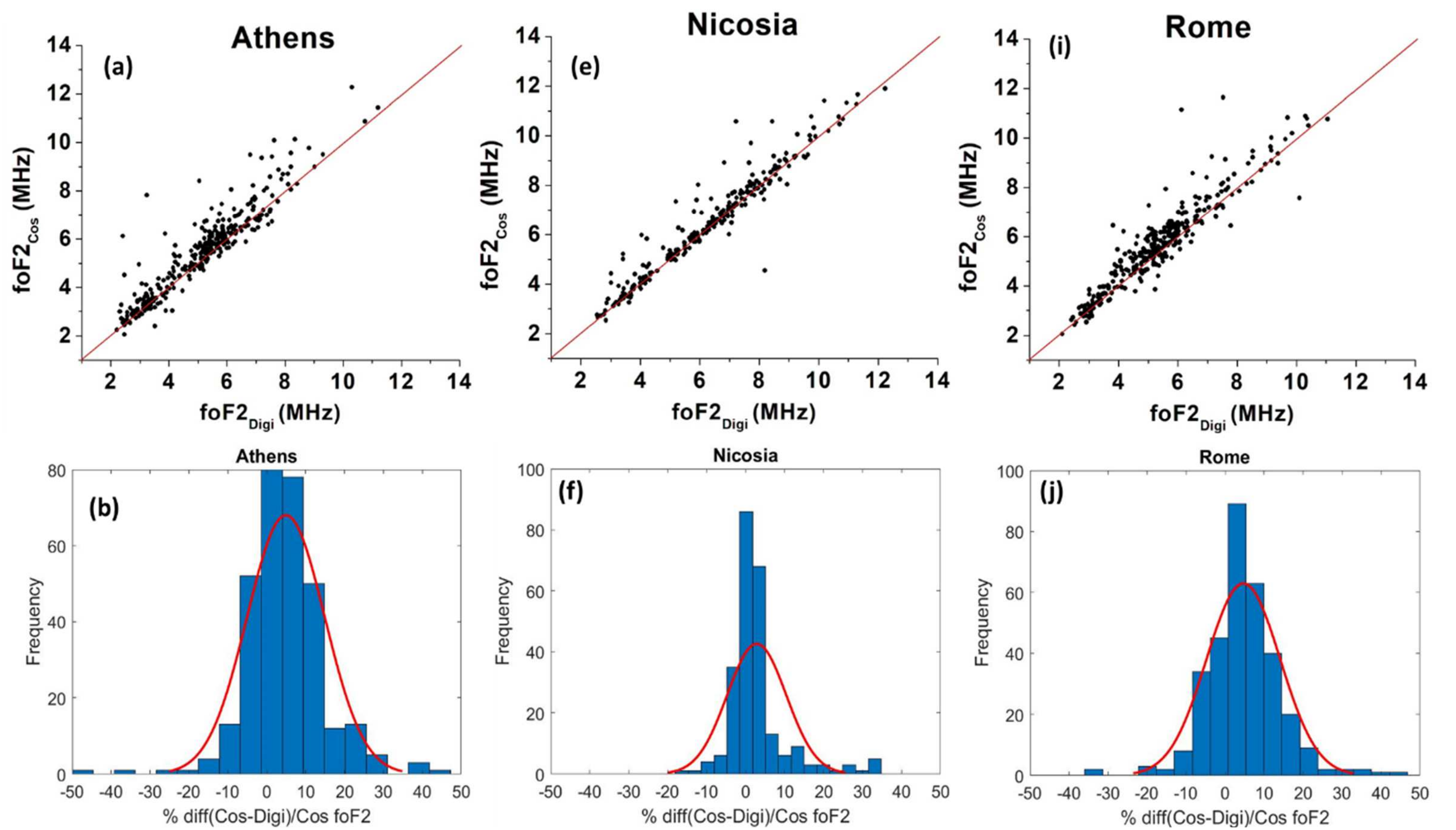




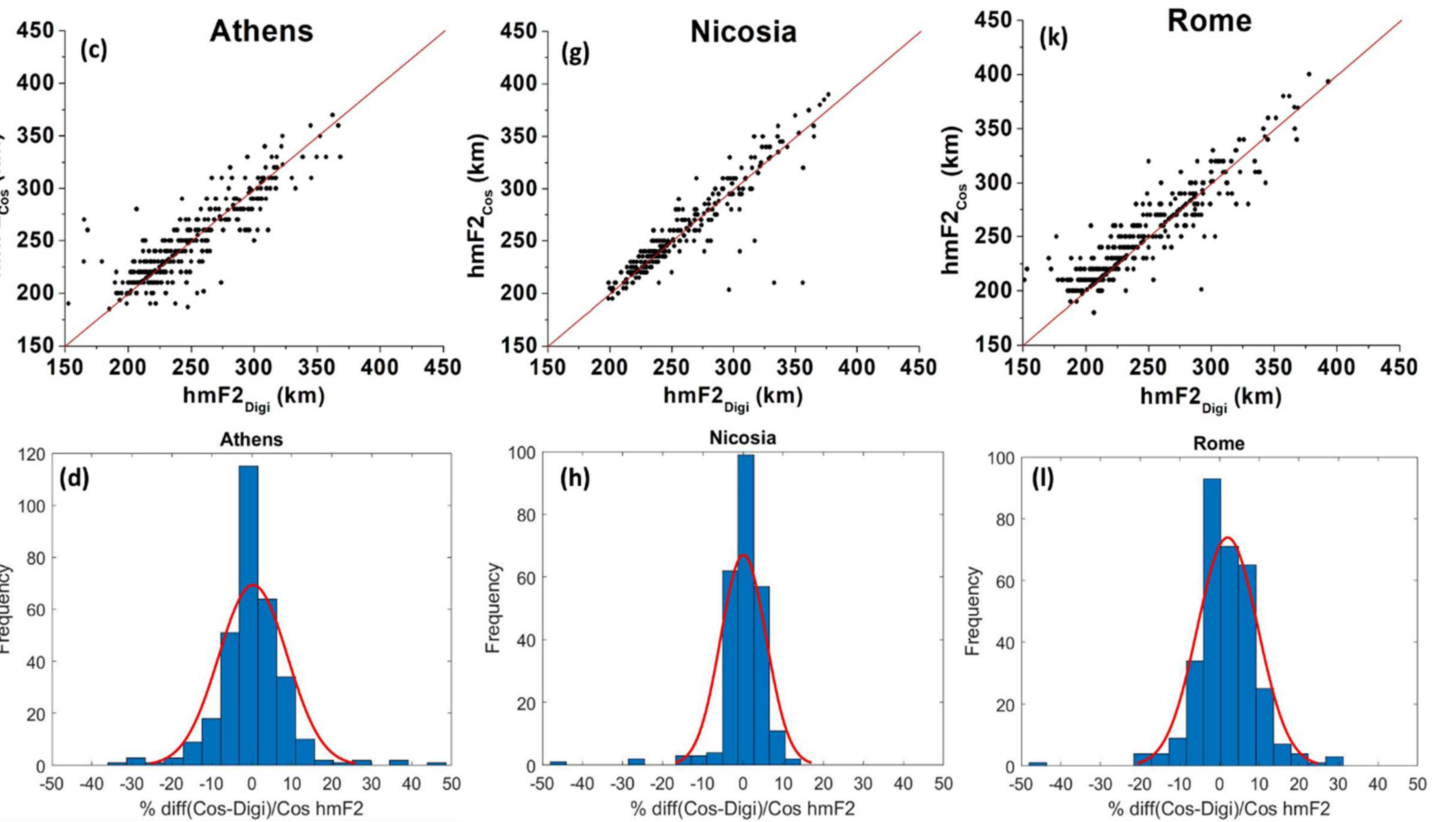




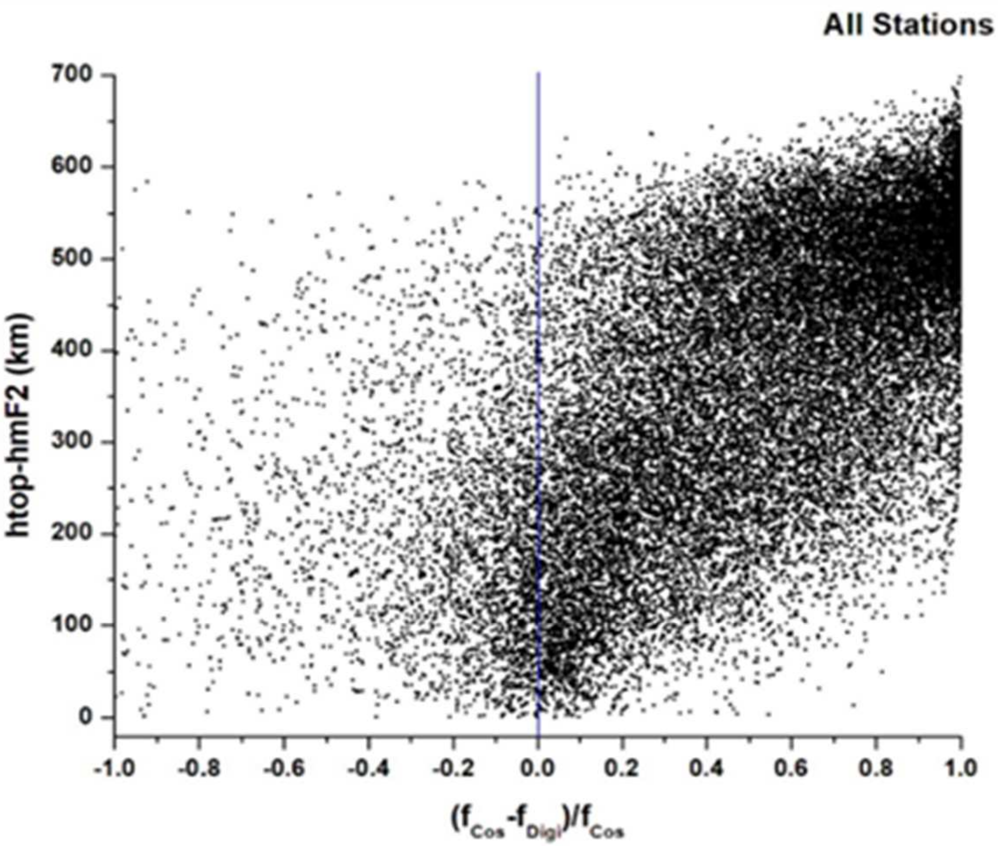
catter plots and relative difference histograms for foF2 from COSMIC and gisonde colocations around the peak for southern stations



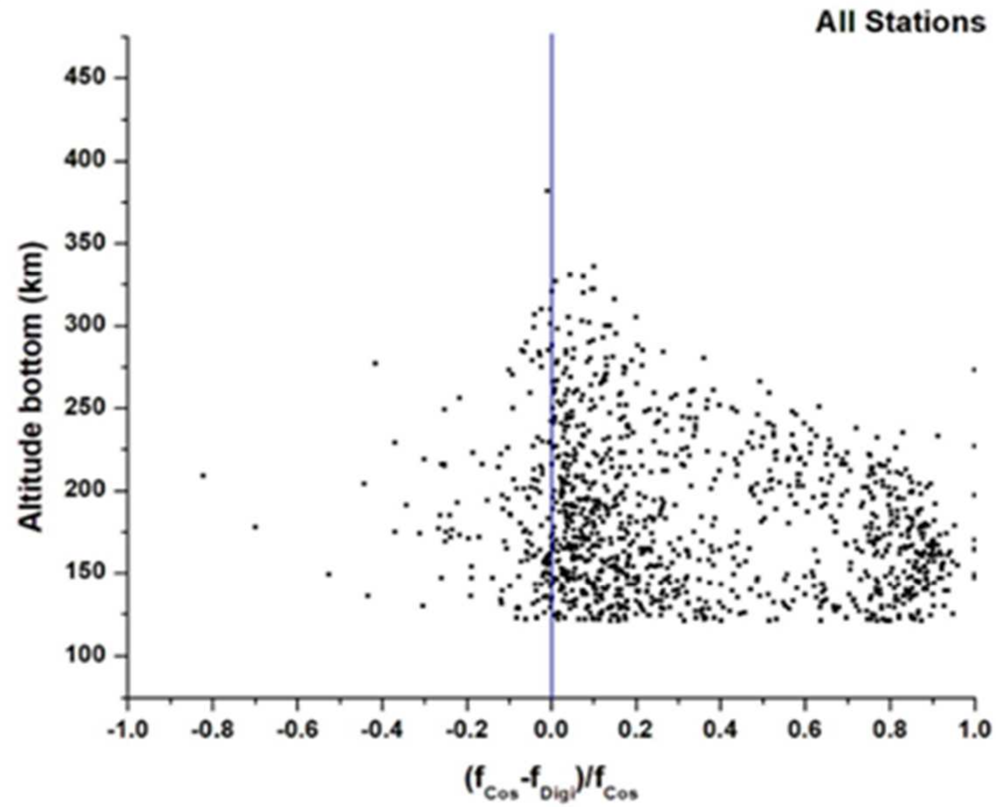
atter plots and relative difference histograms for hmF2 from COSMIC and gisonde colocations around the peak for southern stations



opside and Bottomside plasma frequency relative difference from colocated gisonde and COSMIC RO EDPs over all stations

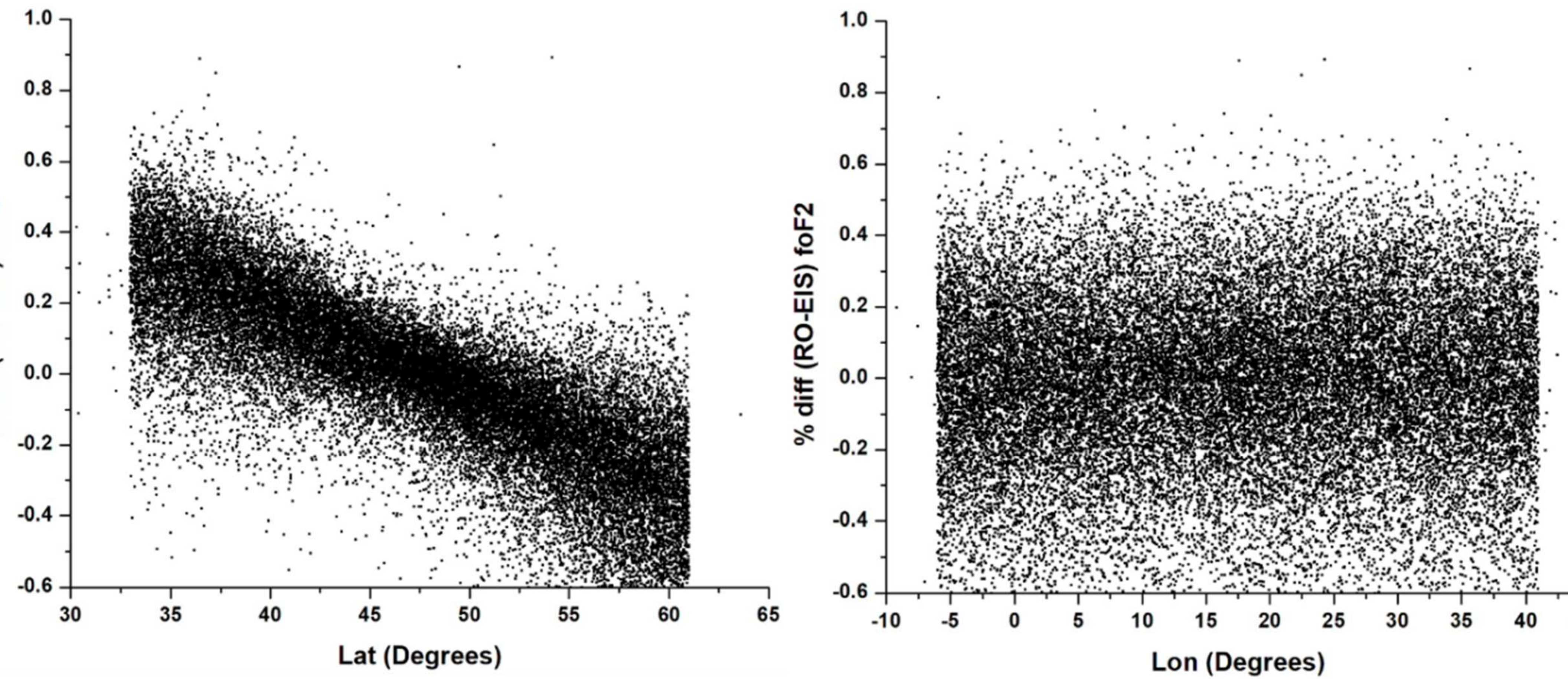


(a) Topside

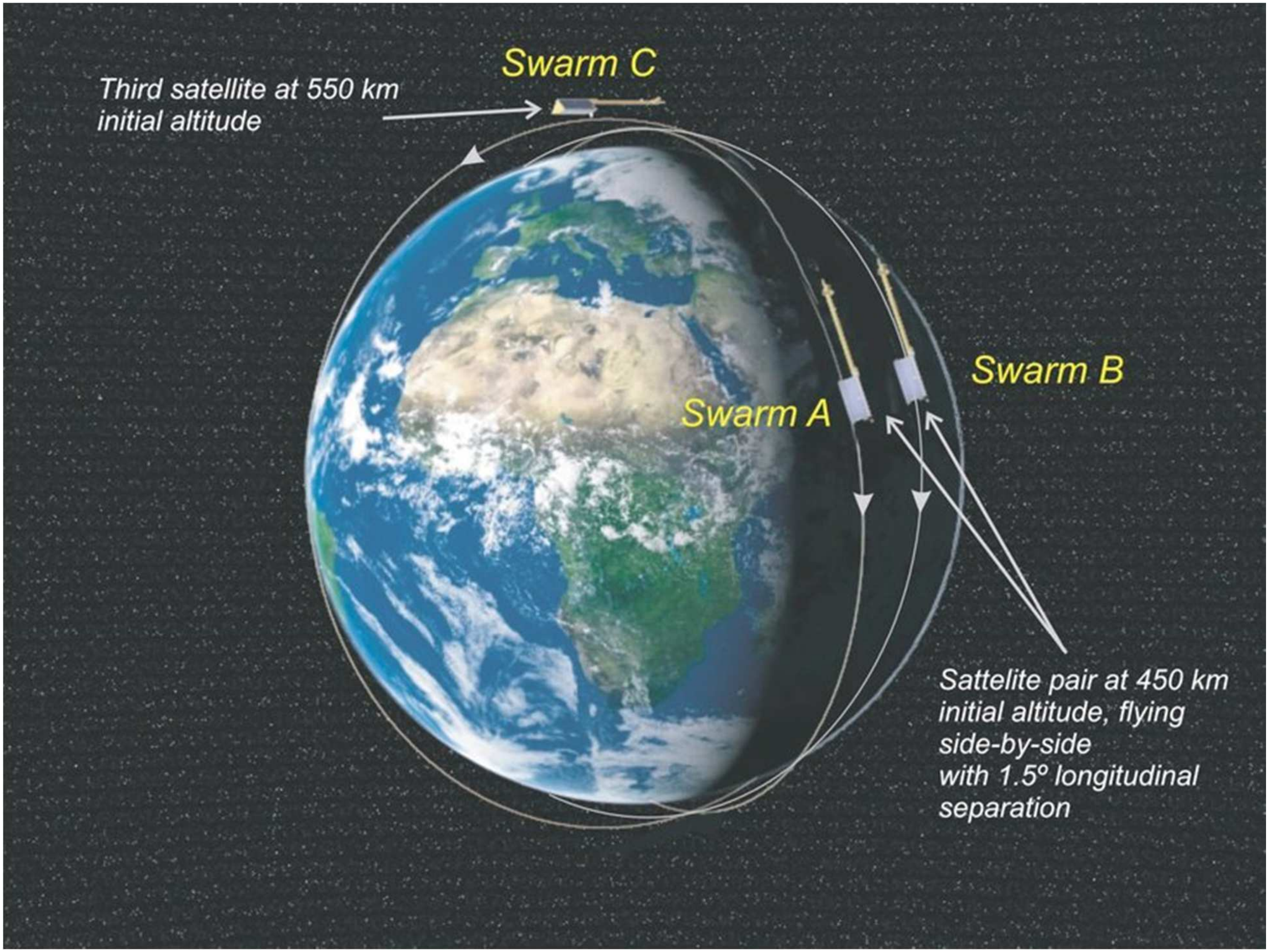


(b) Bottomside

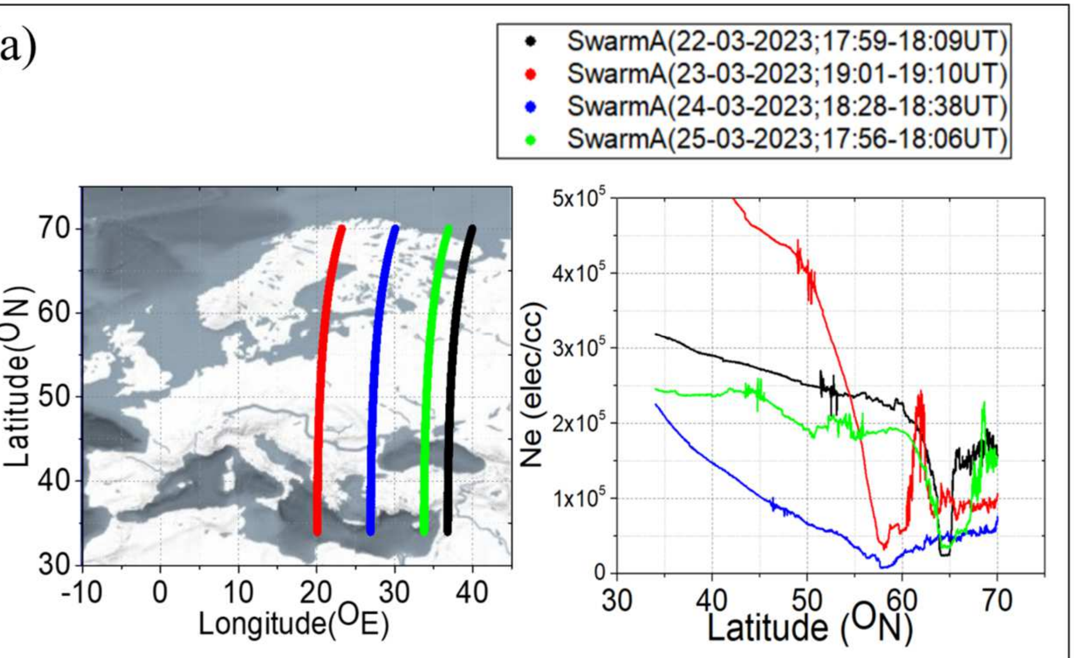
D-EIS foF2 relative difference vs latitude - longitude

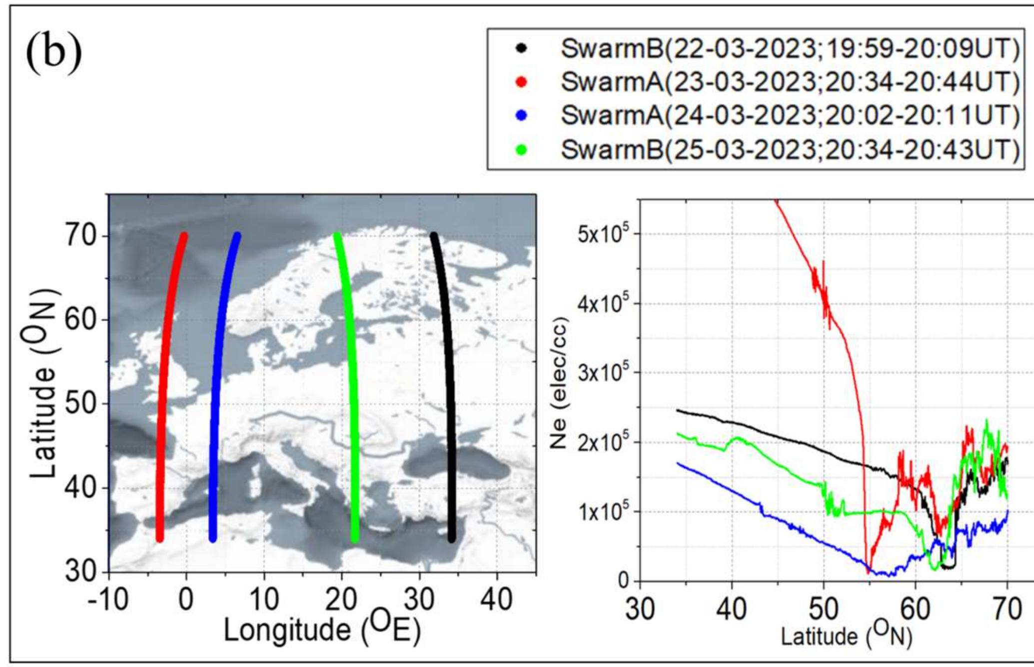


LEO Swarm mission (Langmuir probes)

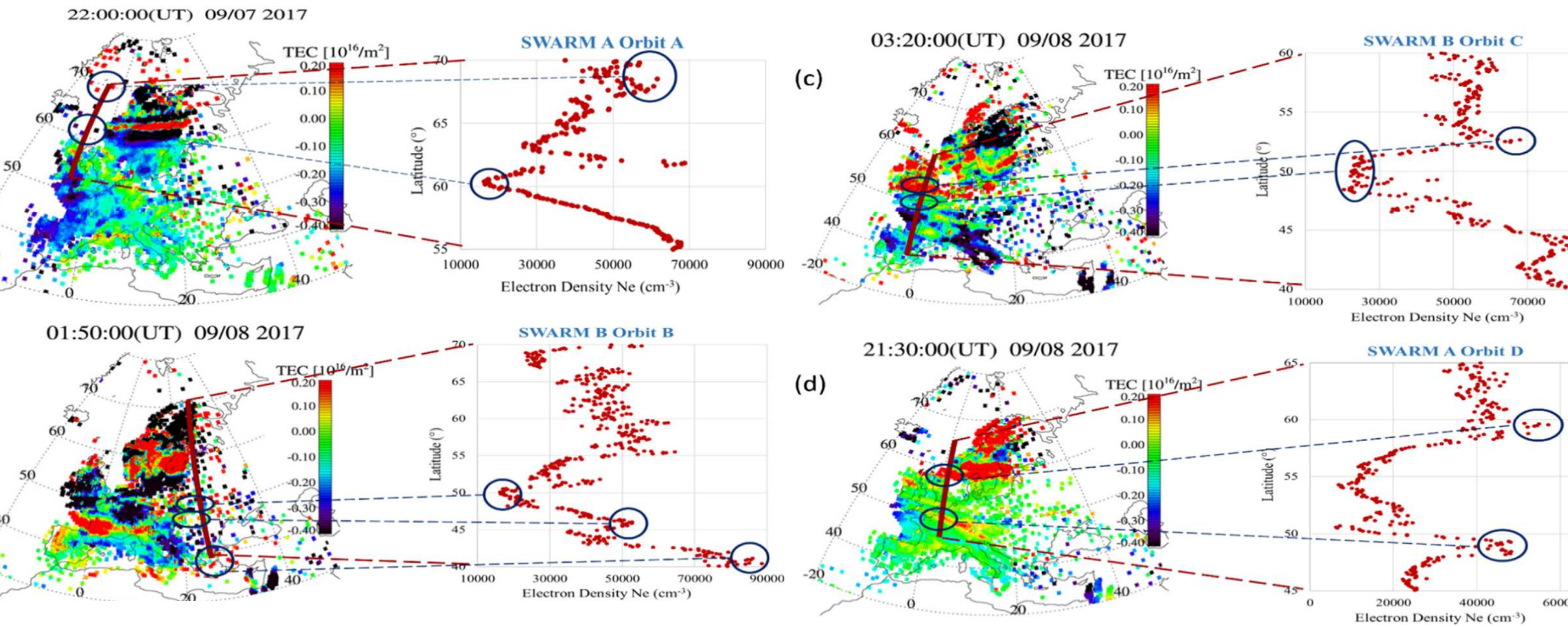


Ionospheric trough displacement in LEO (Swarm) in-situ measurements

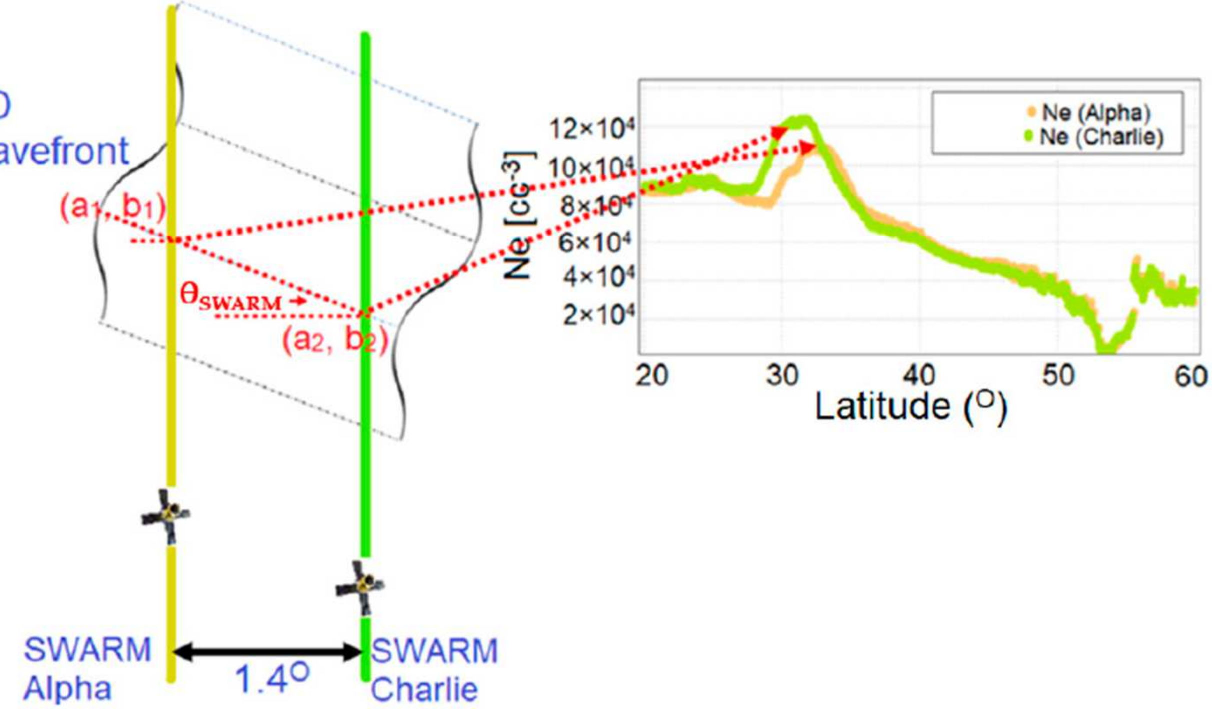


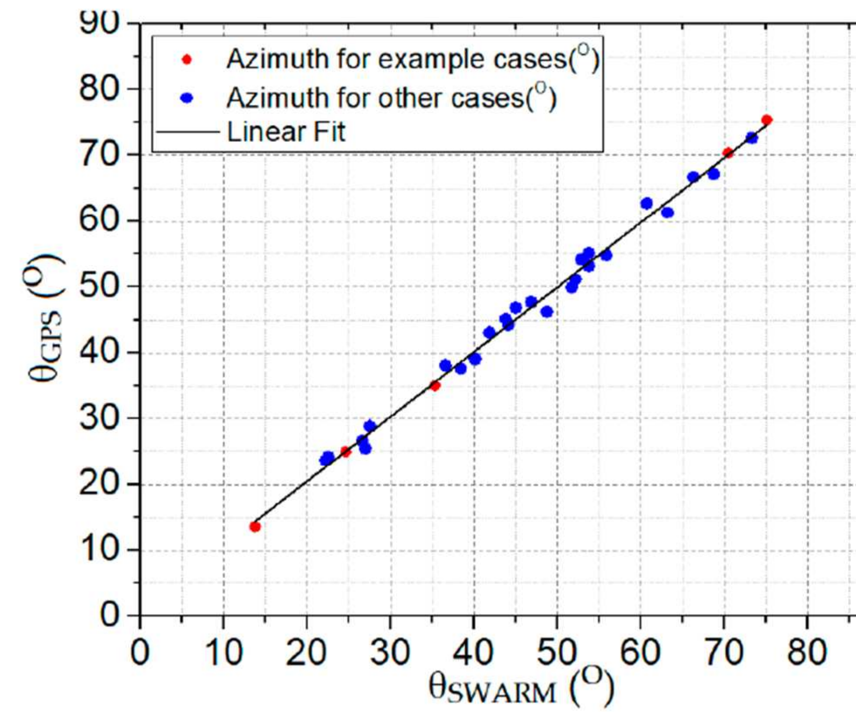


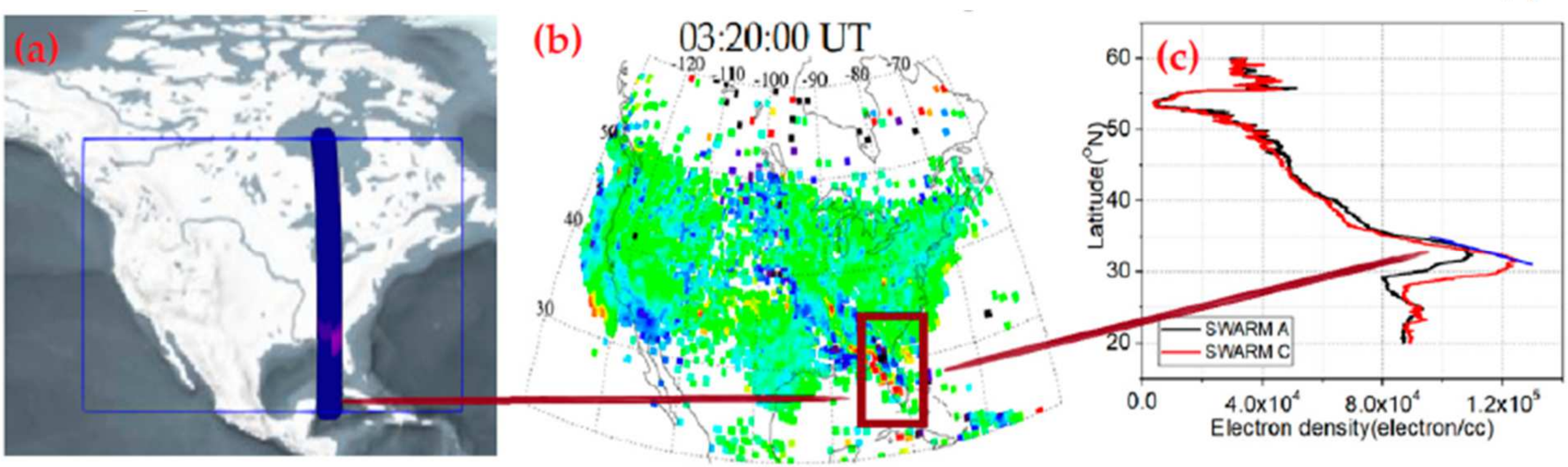
LEO (Swarm) compared to GNSS TID detection



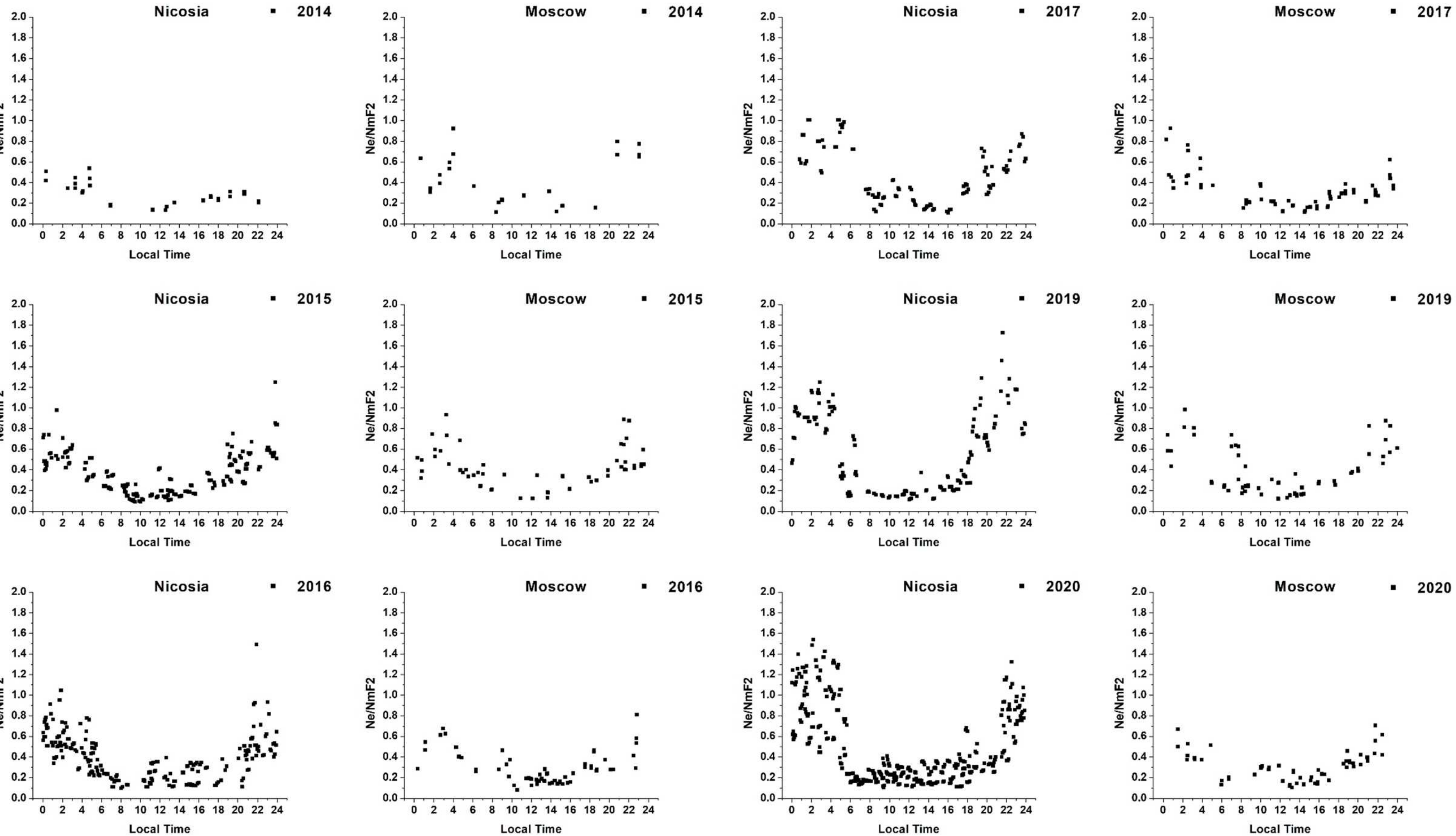
LEO (Swarm) compared to GNSS TID detection



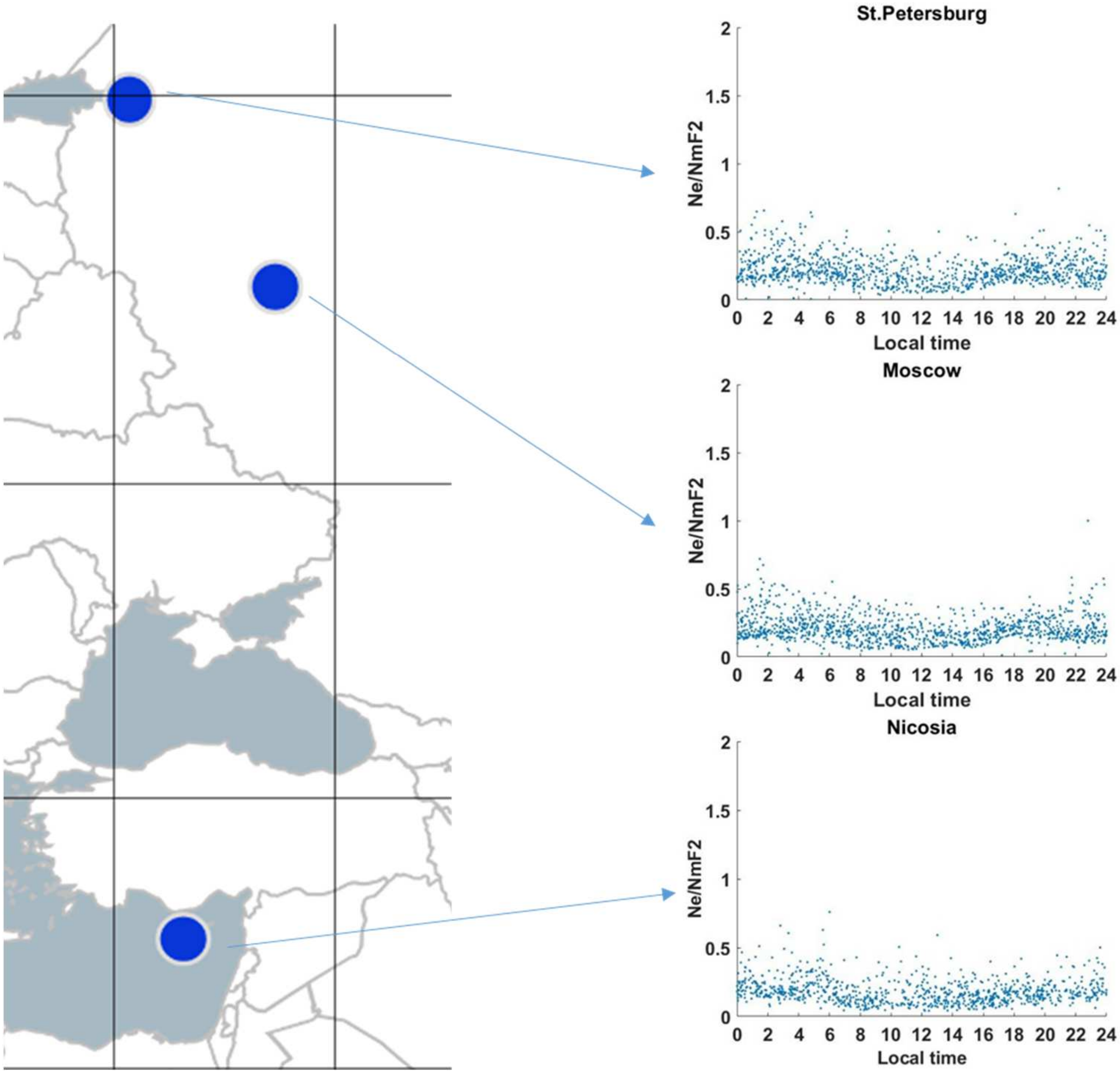




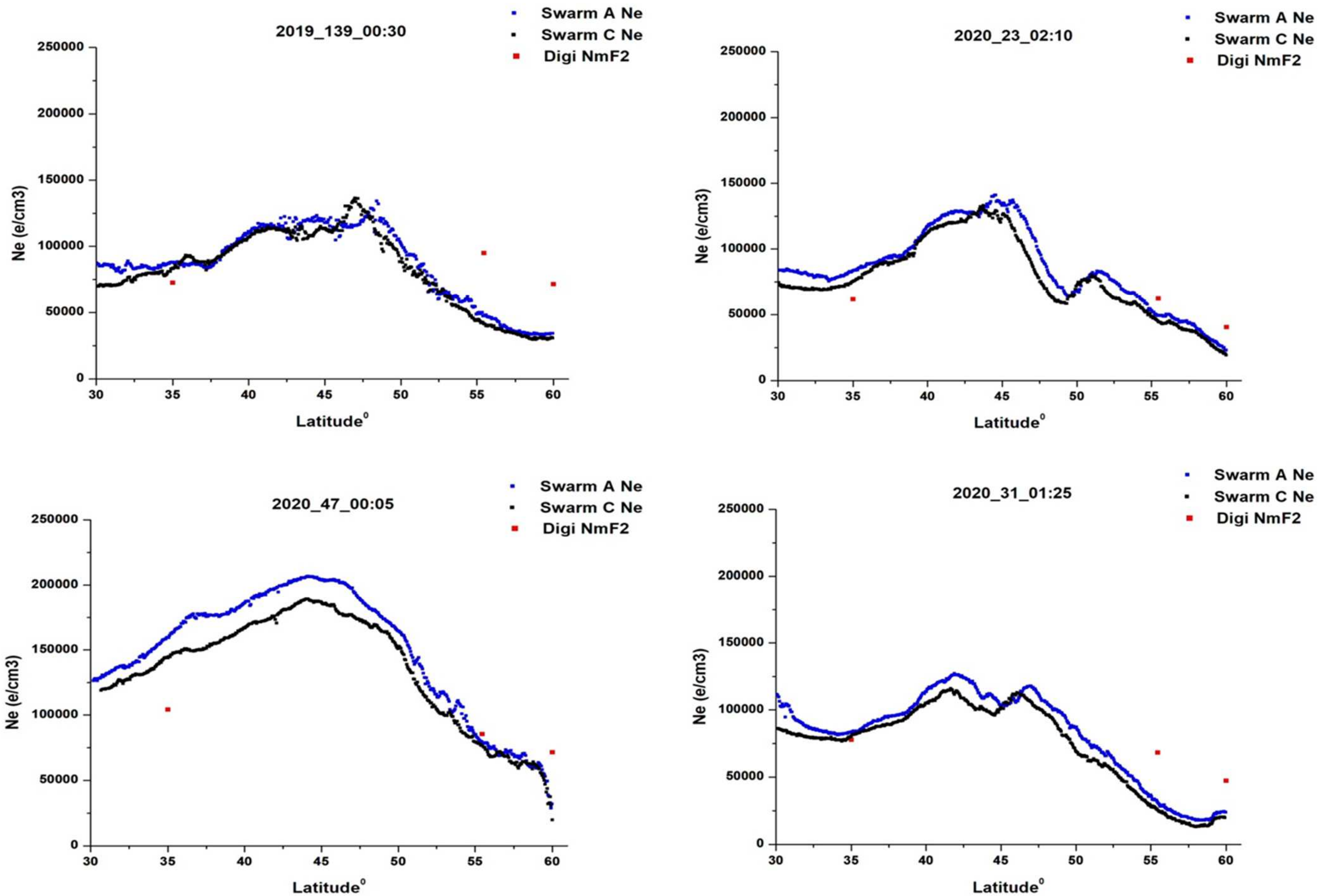
Colocation studies based on COSMIC-1, Swarm and Digisonde datasets



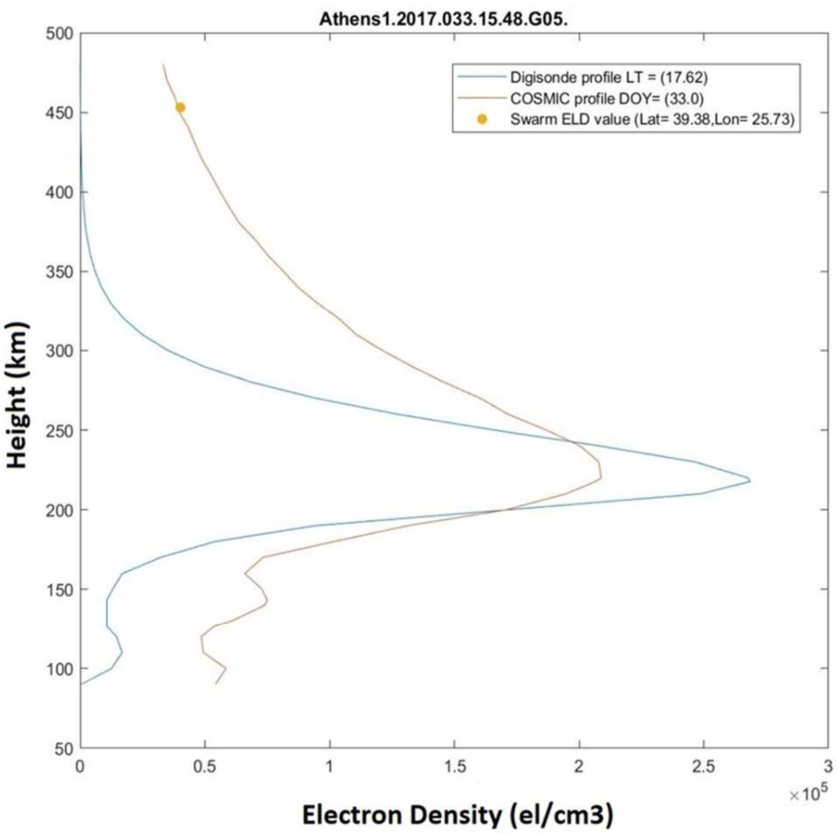
Colocation studies based on COSMIC-1, Swarm and Digisonde datasets

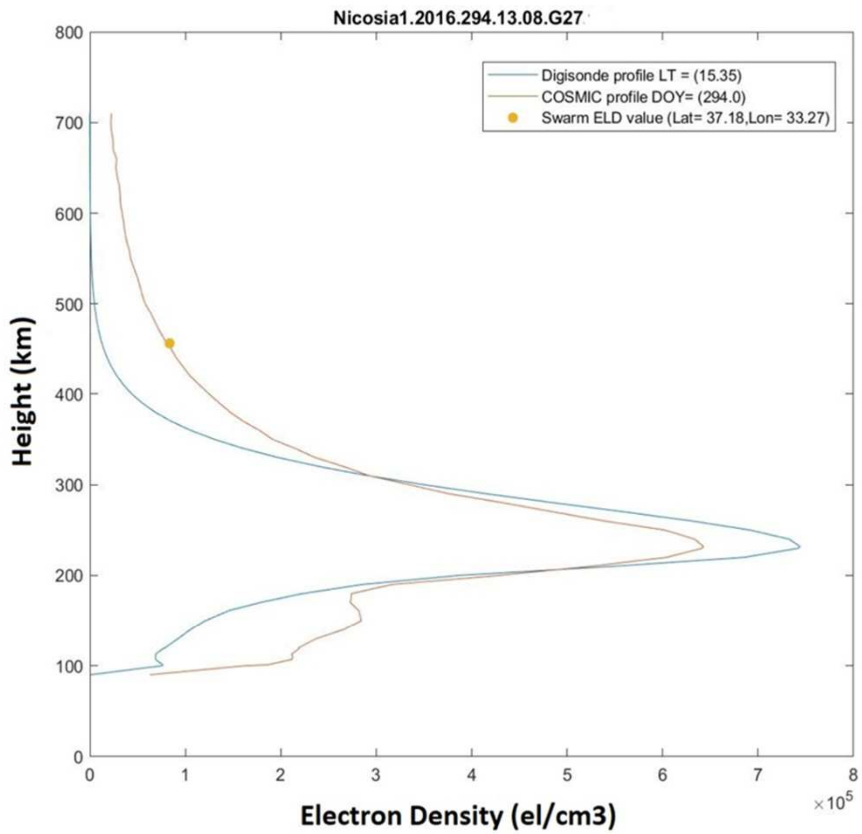


Colocation studies based on COSMIC-1, Swarm and Digisonde datasets



Colocation studies based on COSMIC-1, Swarm and Digisonde datasets

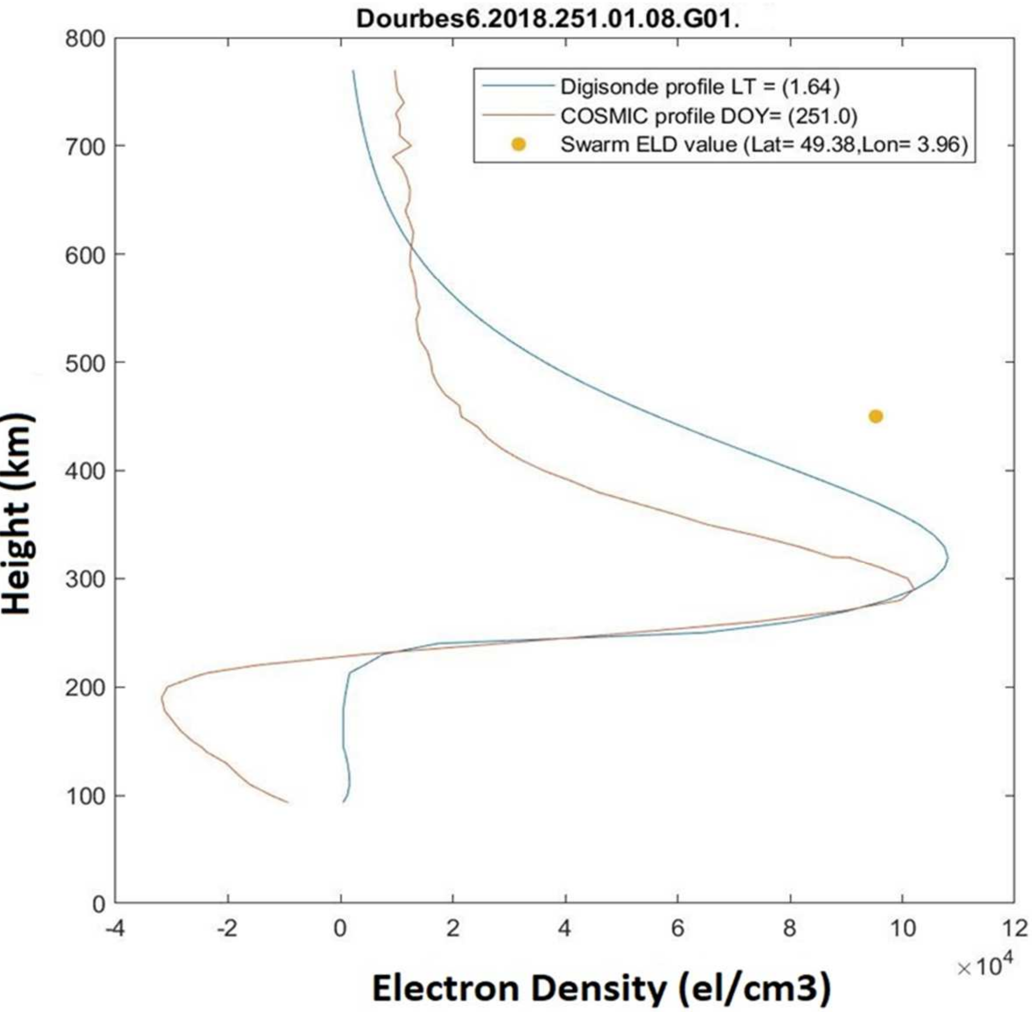


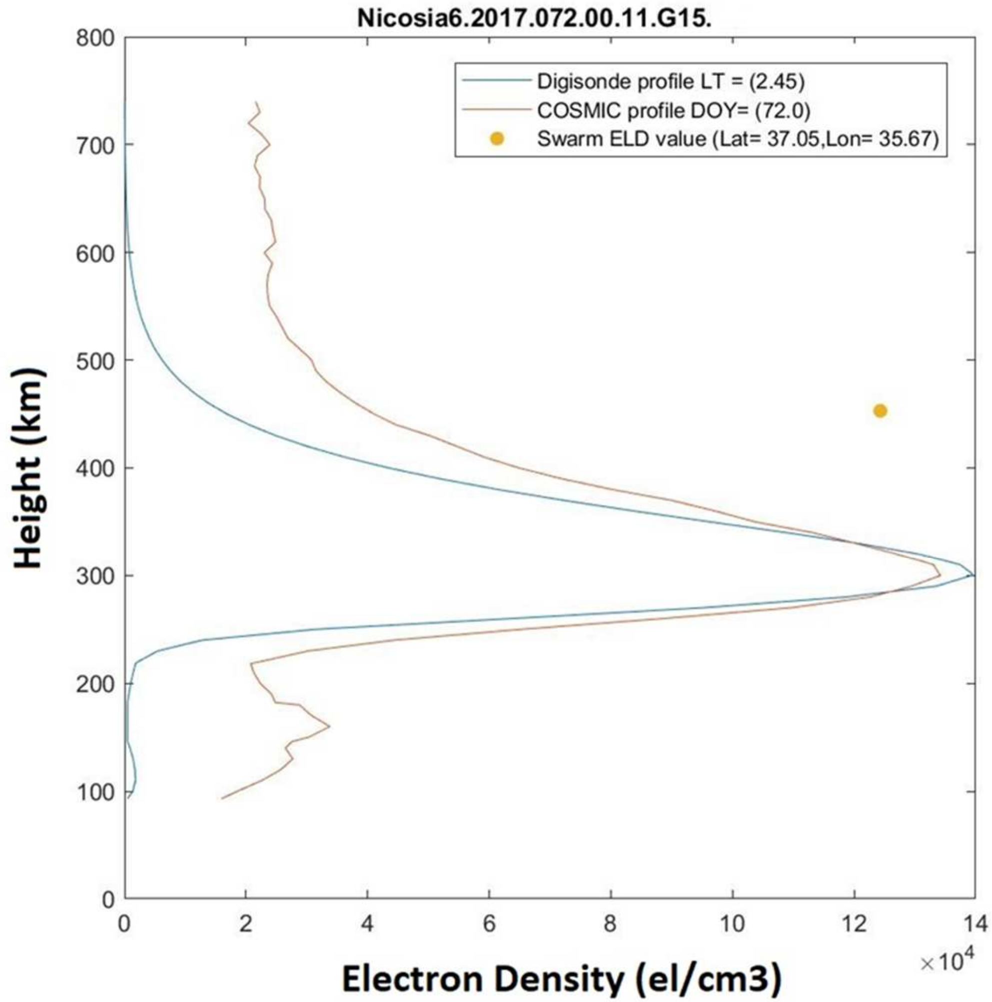


RO-COSMIC-Digisondes topside difference investigation

Colocated EDPs in space and time from COSMIC and Digisondes and Swarm Ne

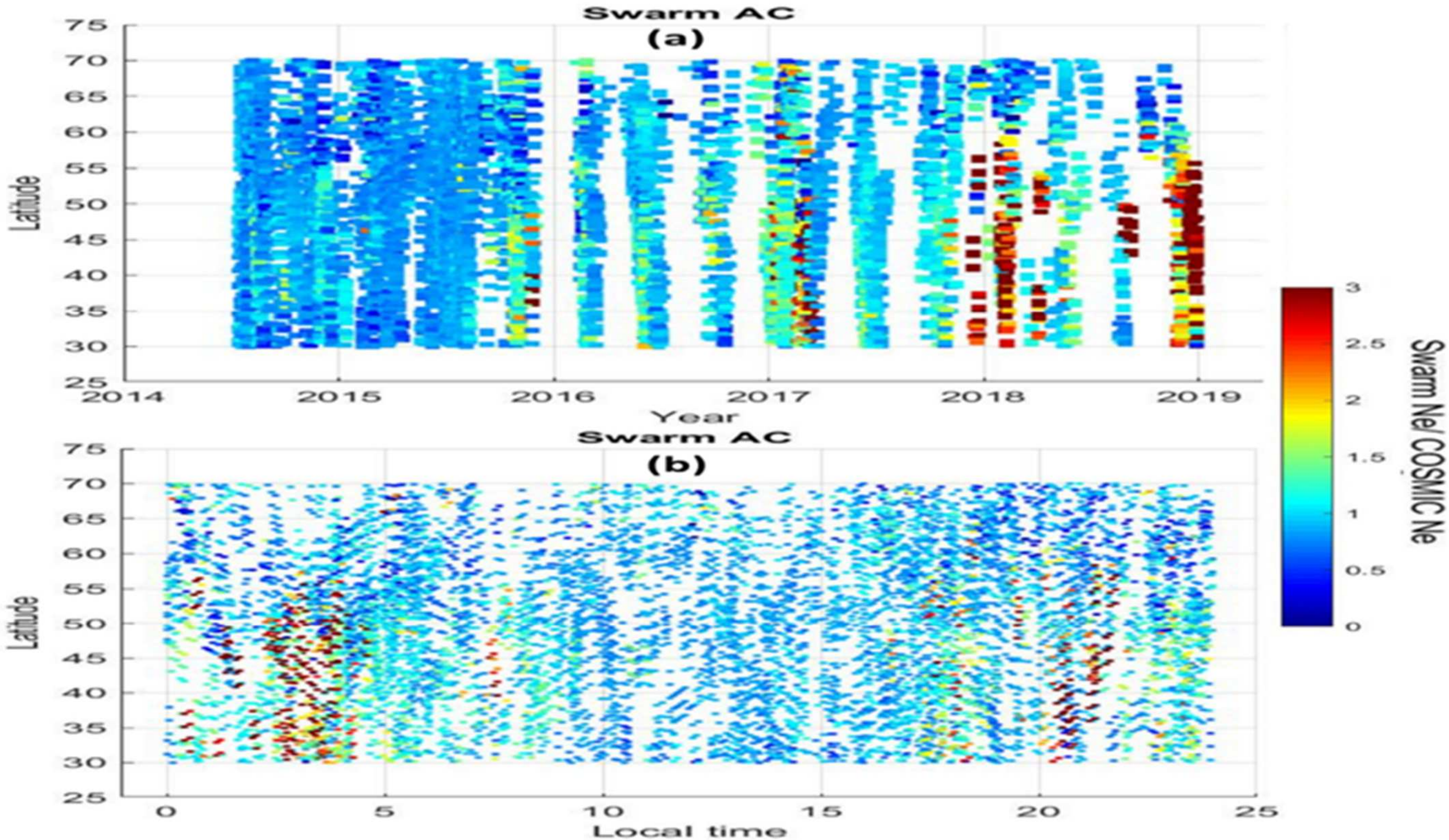
Colocation studies based on COSMIC-1, Swarm and Digisonde datasets





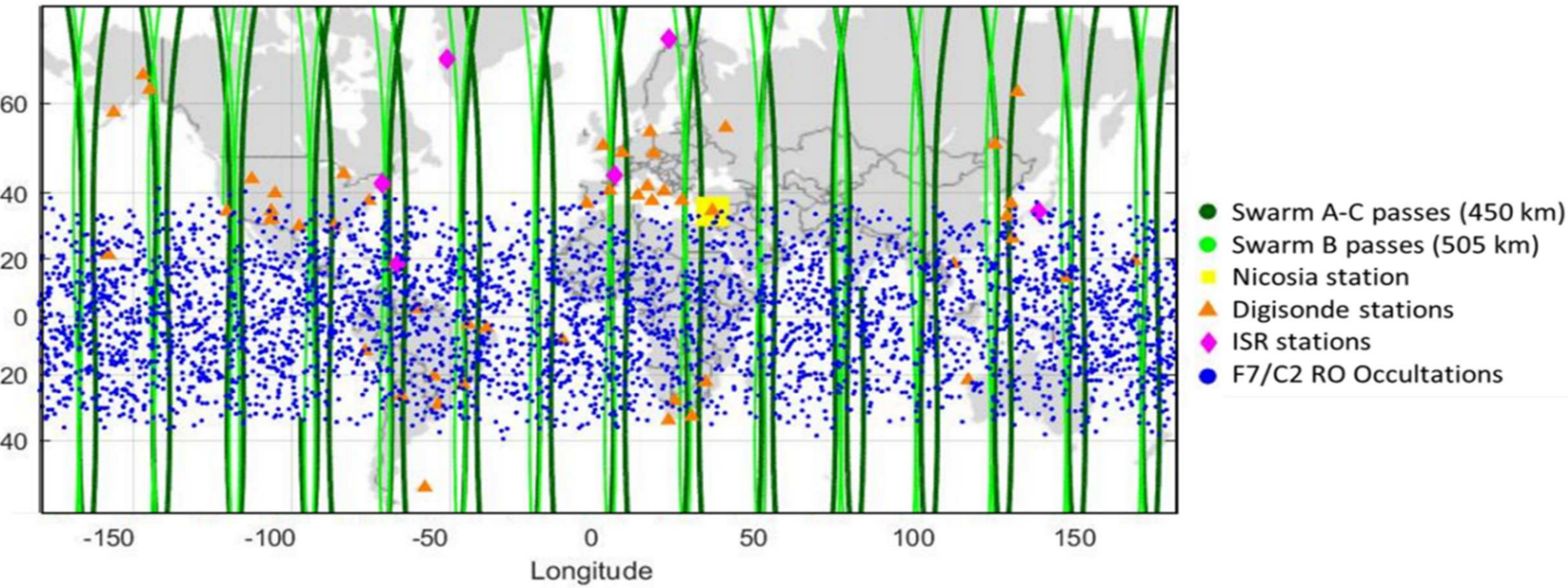
Colocated EDPs in space and time from COSMIC and Digisondes and Swarm Ne

Colocation studies based on COSMIC-1, Swarm and Digisonde datasets

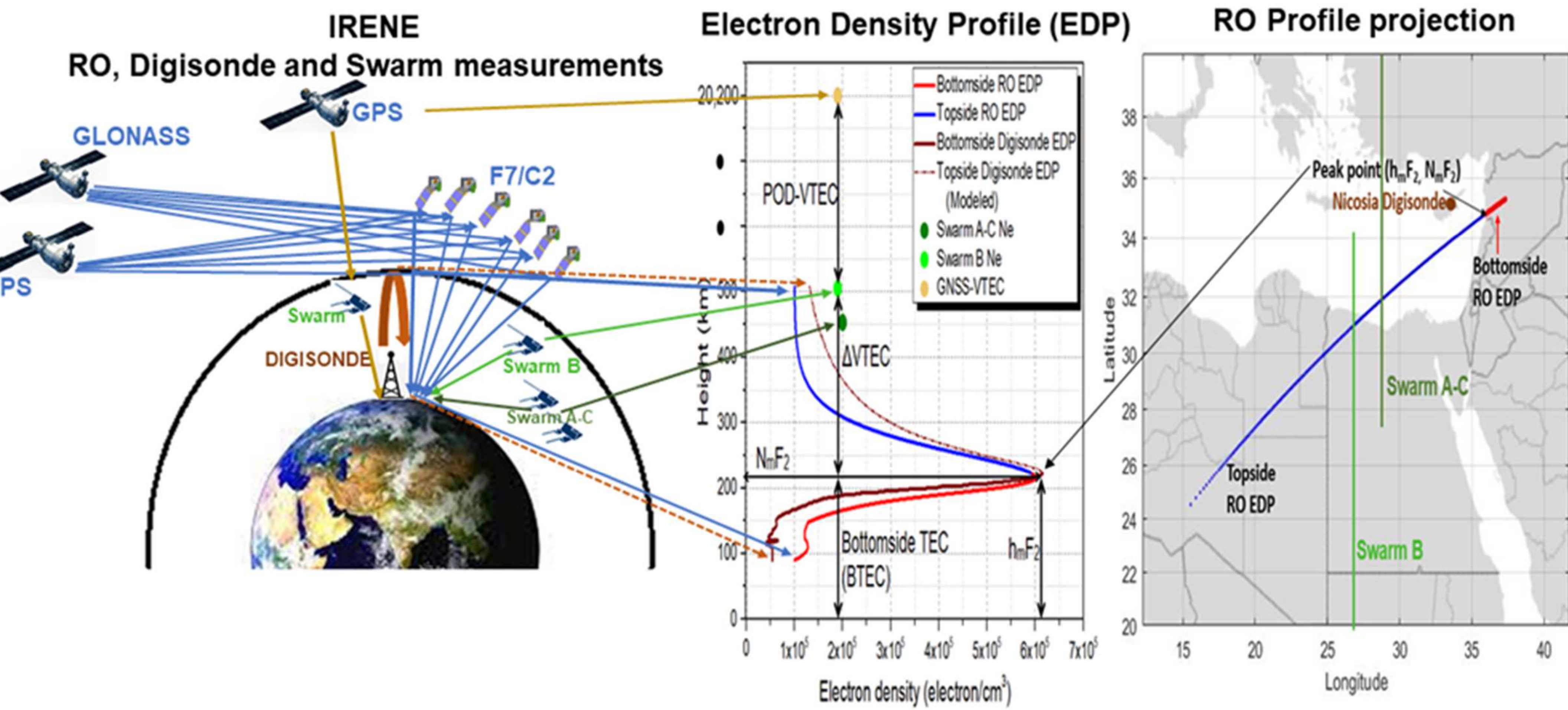


Latitude variation of the ratios of Swarm AC Ne to F3/C Ne at 460 km and their variation w.r.t. ***(a)*** *Year and* ***(b)*** *Local Time over the European region for years 2014-2018.*

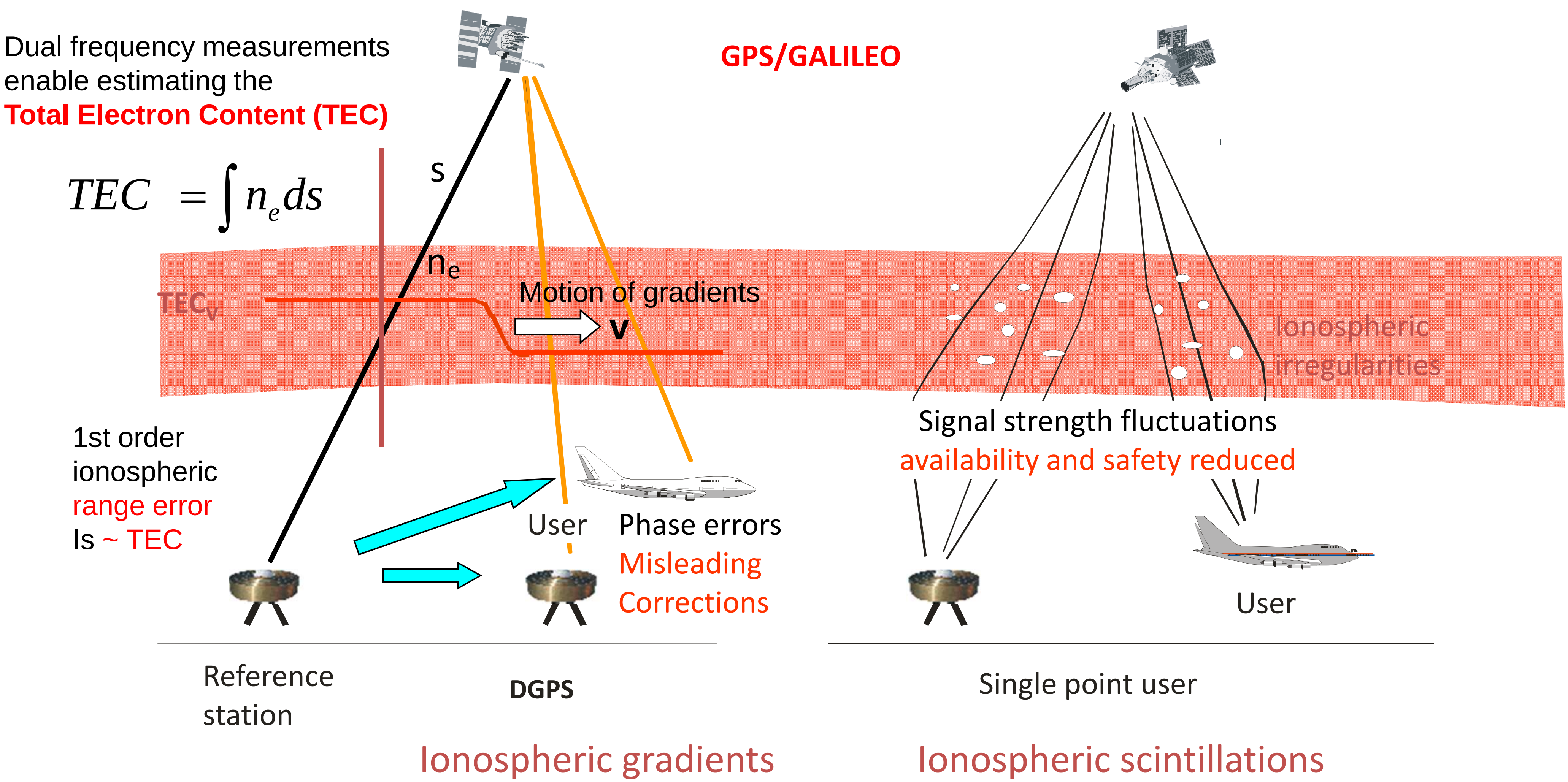
Colocation studies based on COSMIC-2 and Swarm datasets



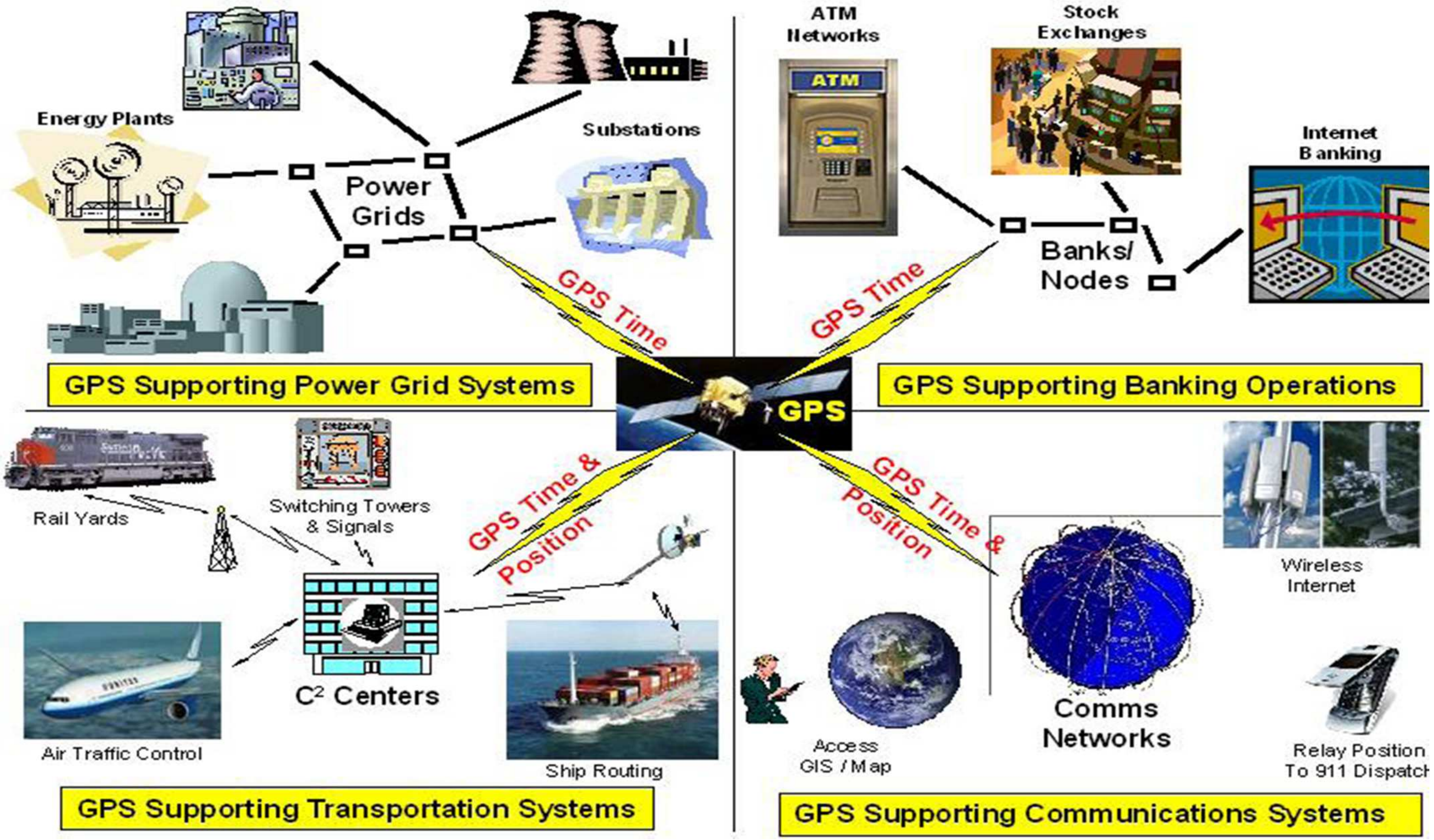
Colocation studies based on COSMIC-2 and Swarm datasets



Ionospheric impact on aviation

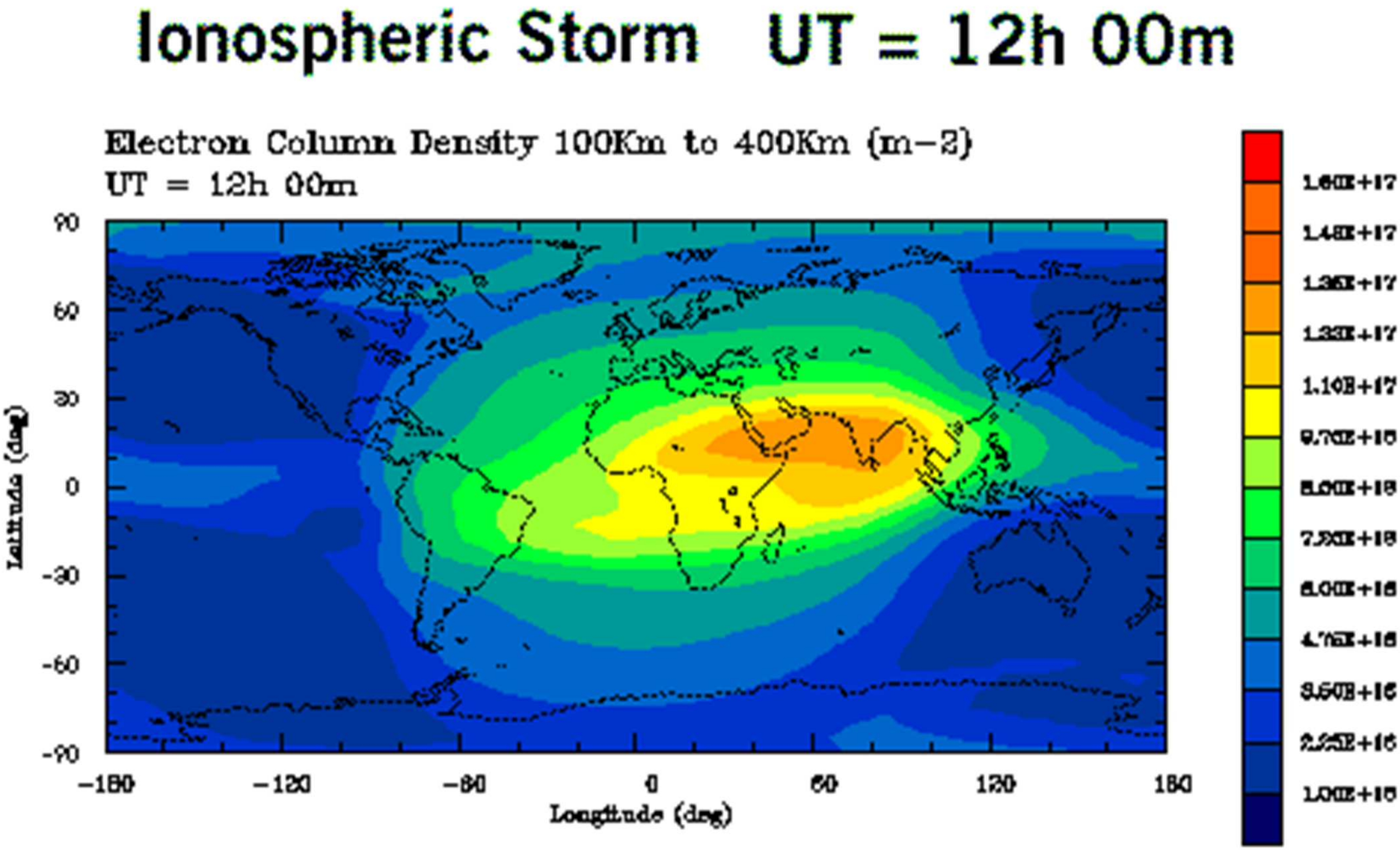


Civilian GPS Applications Potentially Impacted



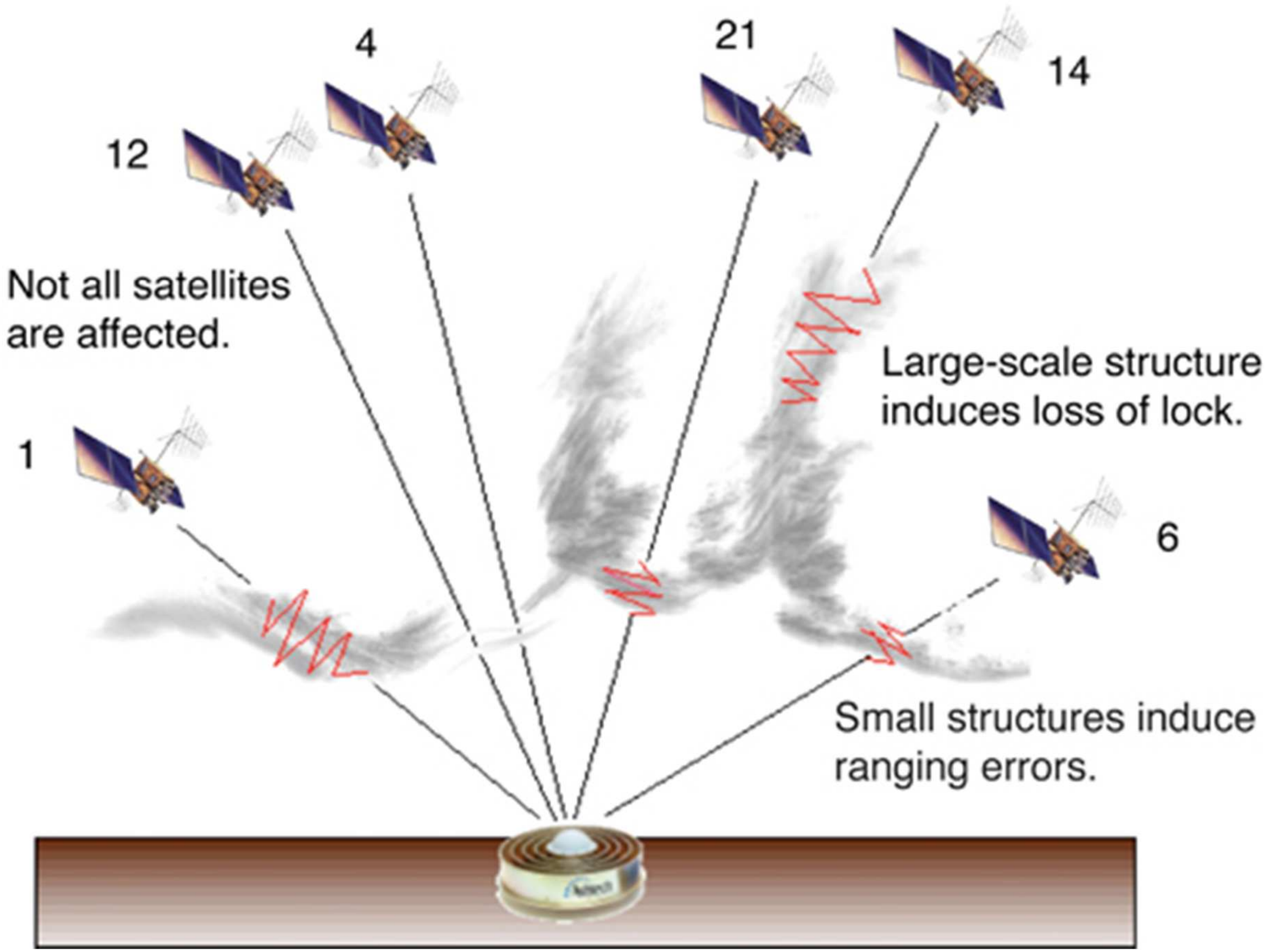
Present and future precision guidance

Guidance Applications

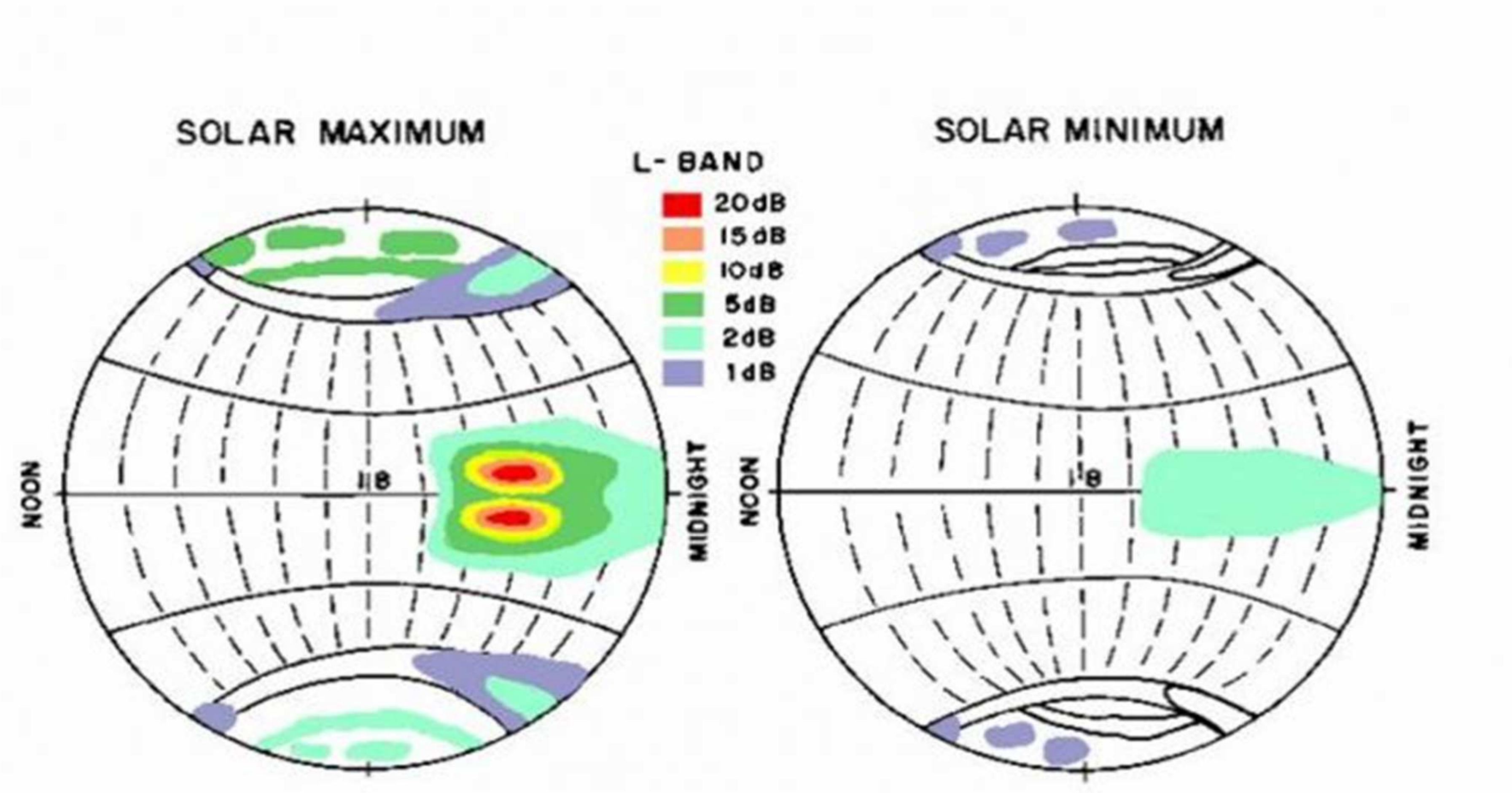


Ionospheric Storm UT = 12h 00m
Electron Column Density 100Km to 400Km (m−2)
UT = 12h 00m
Latitude (deg)
Longitude (deg)
90
60
30
0
-30
-60
-90
−180
−120
−60
0
60
120
180

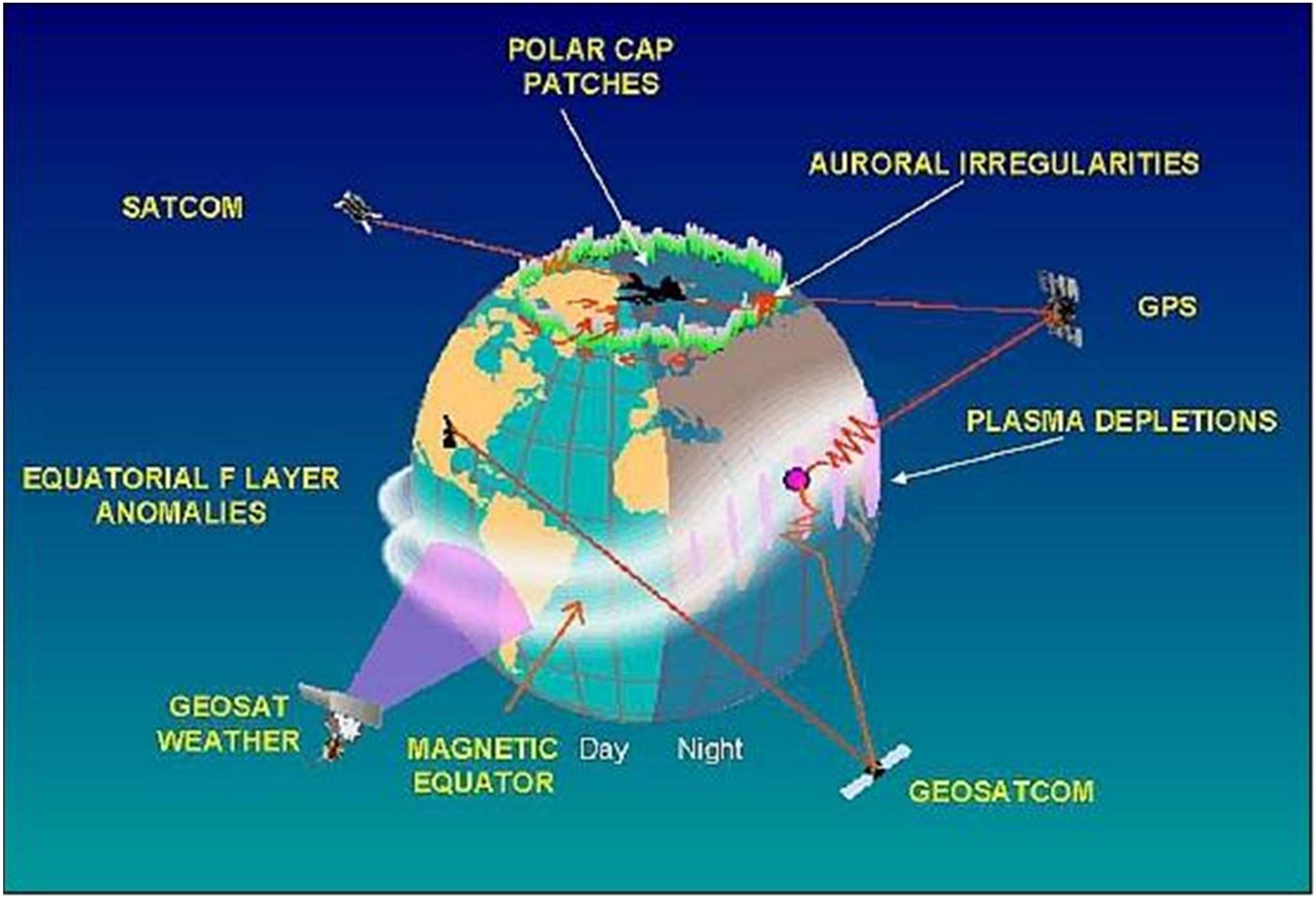
Potential loss-of-lock of GNSS systems due to ionospheric scintillations



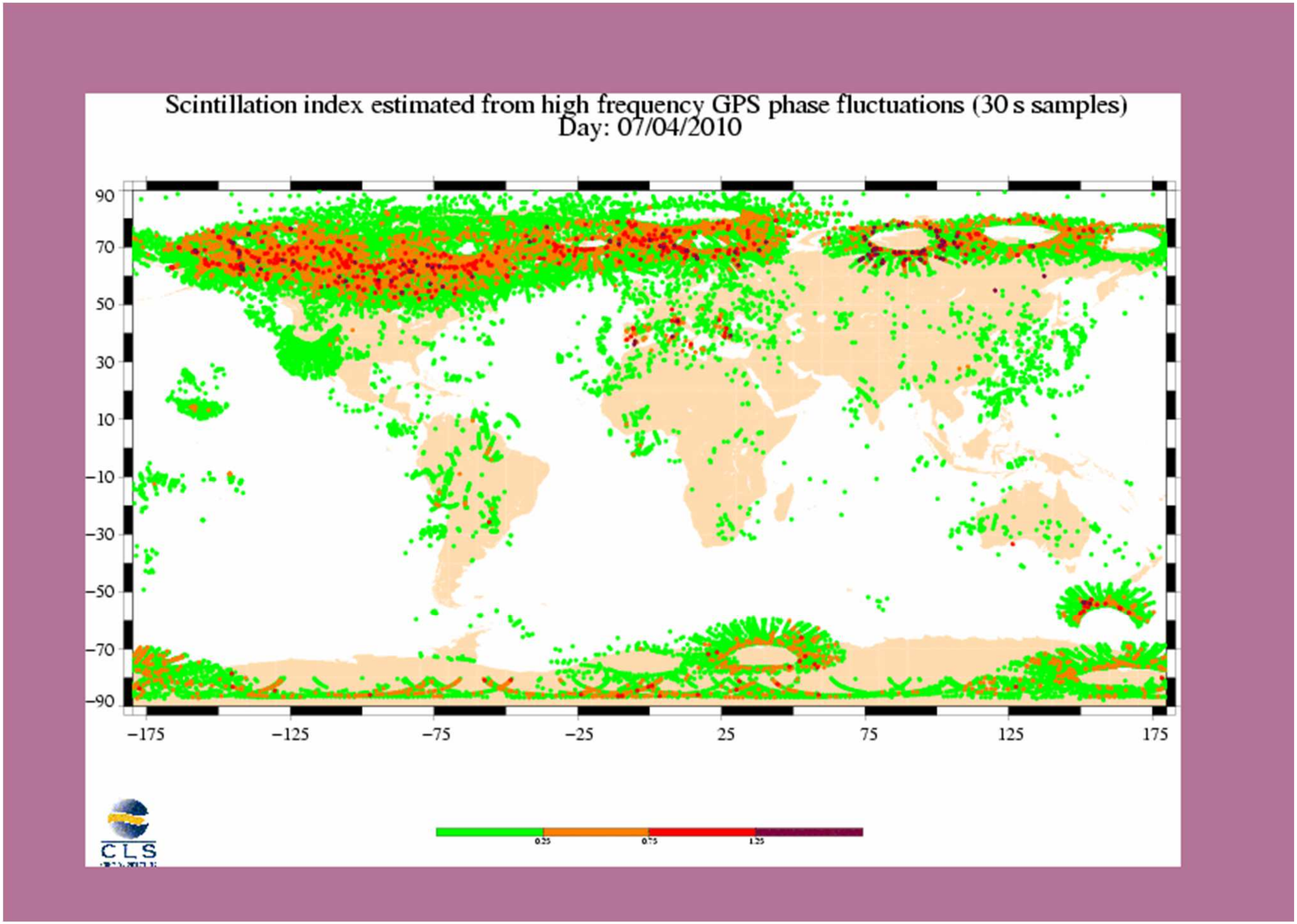
Temporal and spatial aspects of ionospheric scintillations



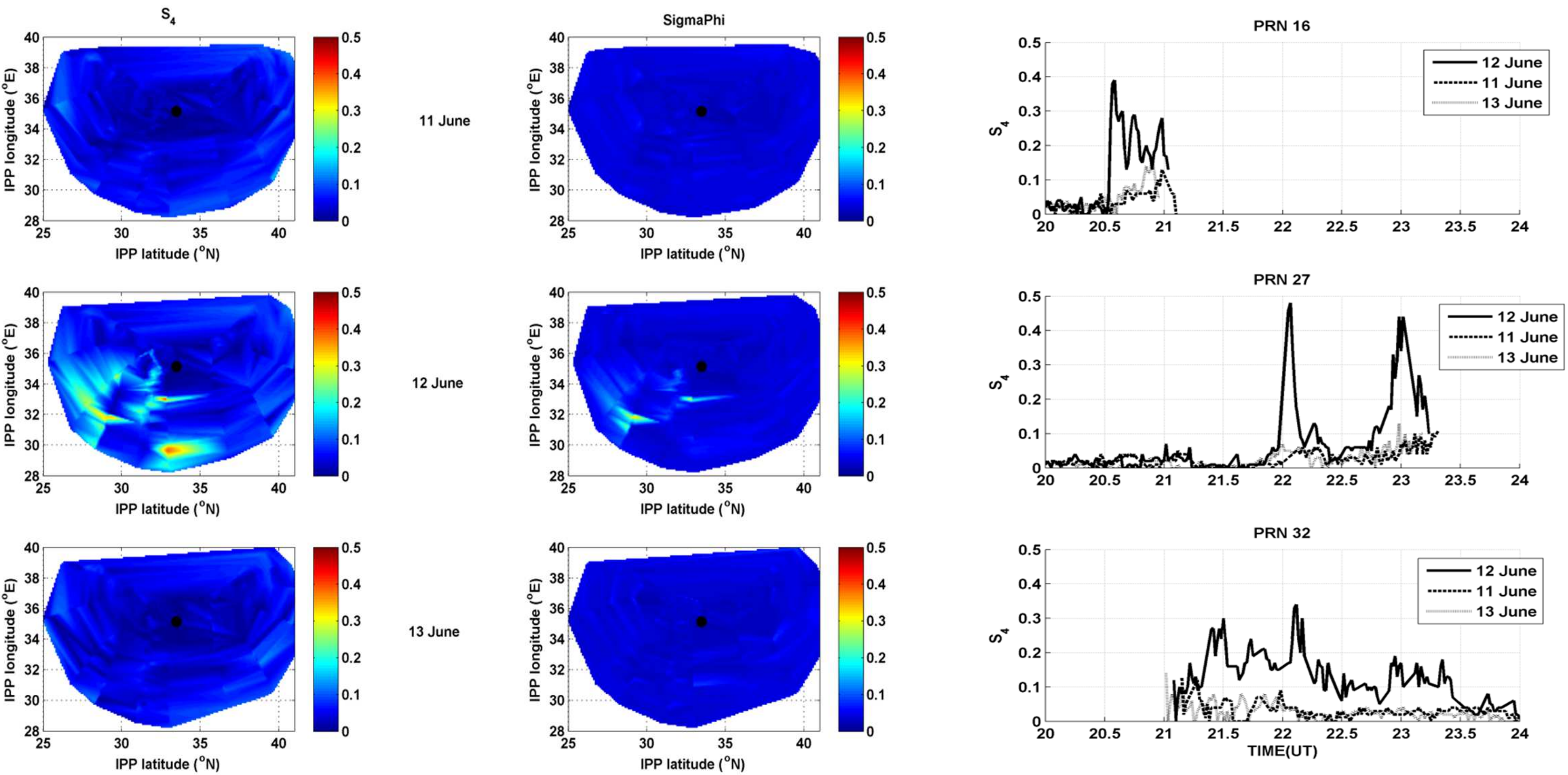
Ionospheric scintillations affect civilian and military operations



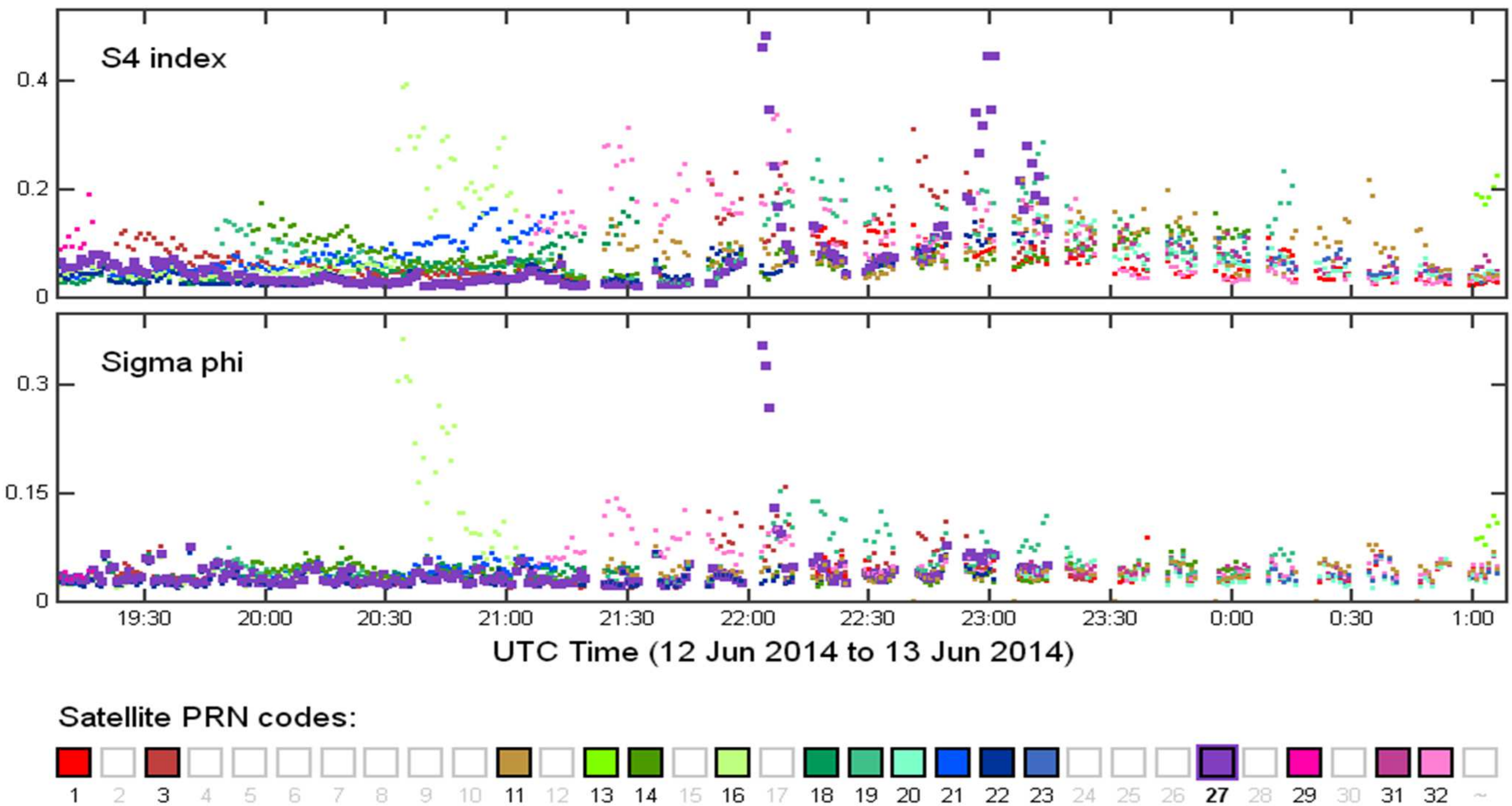
Temporal and spatial aspects of ionospheric scintillations



Ionospheric scintillations over Cyprus



Ionospheric scintillations over Cyprus



SERVice for **I**mproví**N**g **G**alileo operation over Cyprus (**SERVING**)

Specific Scientific and Technological Objectives:

✓ Explore techniques to improve and optimize the Galileo single frequency users' positioning algorithm in a context of assisted GNSS driven by a regional and therefore more accurate ionospheric representation

Basic idea

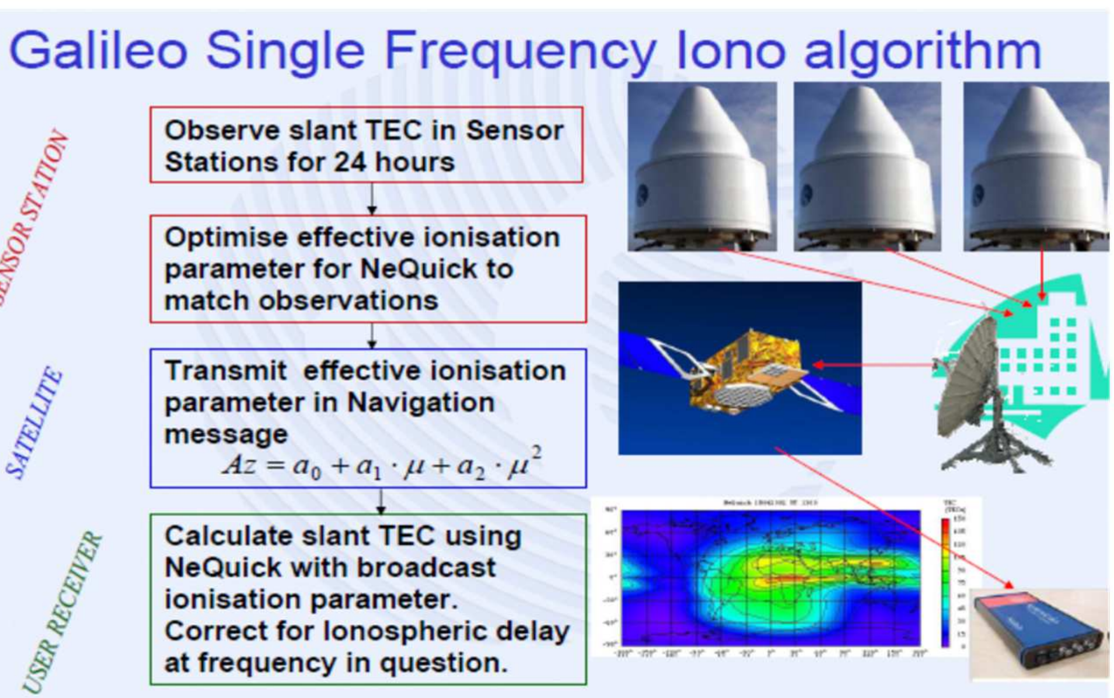
✓ On a long-term scale this improvement is achieved through updating of the long-term median ionospheric characteristics (in the form of 12 files)
✓ On a short-term scale this improvement is enhanced by driving the NeQuick-G algorithm with a more accurate estimation of the ionisation level obtained with a GNSS receiver in Cyprus on a local scale as opposed to a less accurate global scale estimation which is applied in the context of Galileo

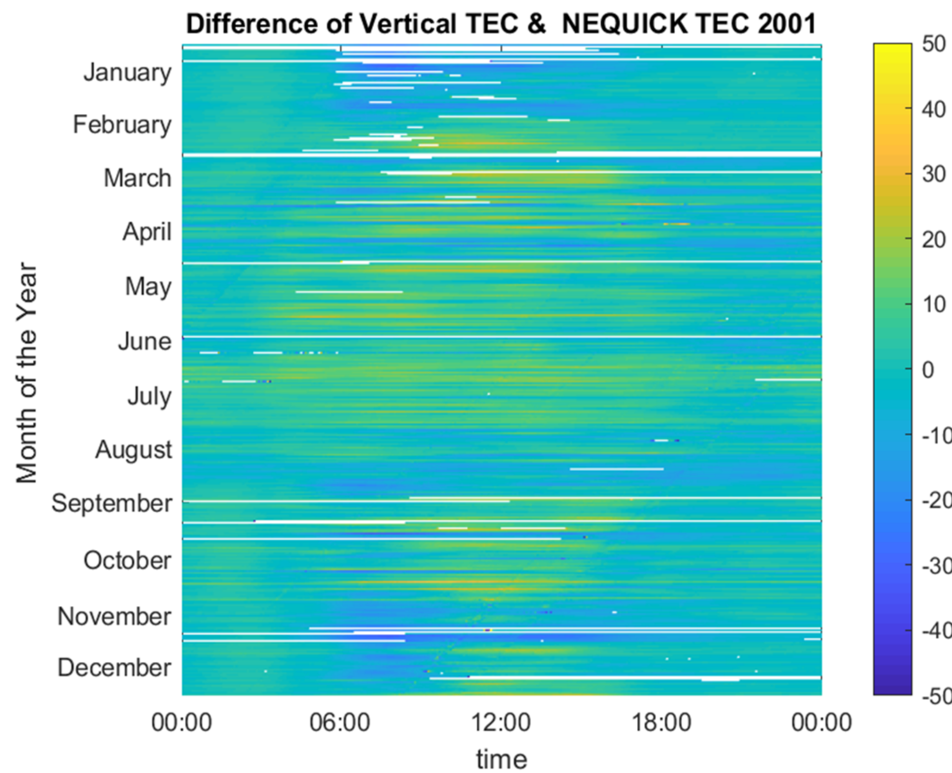
Measure sTEC

Optimise *Az(μ)*

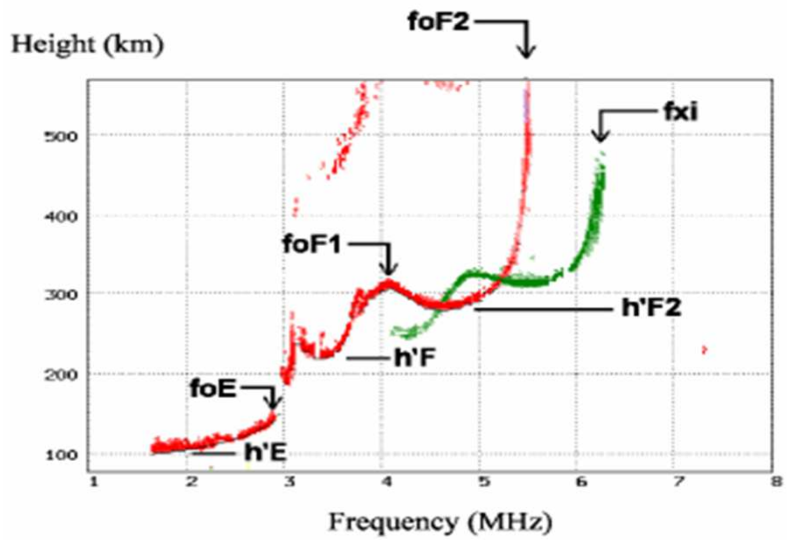
Run NeQuick

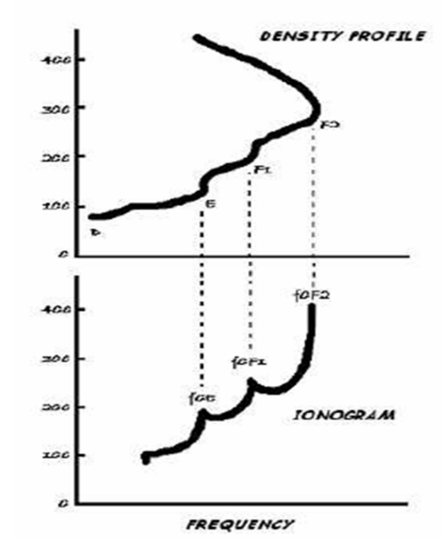
SERVice for **I**mproviNg **G**alileo operation over Cyprus (**SERVING**)





SERVice for **I**mprovi**N**g **G**alileo operation over Cyprus (**SERVING**)



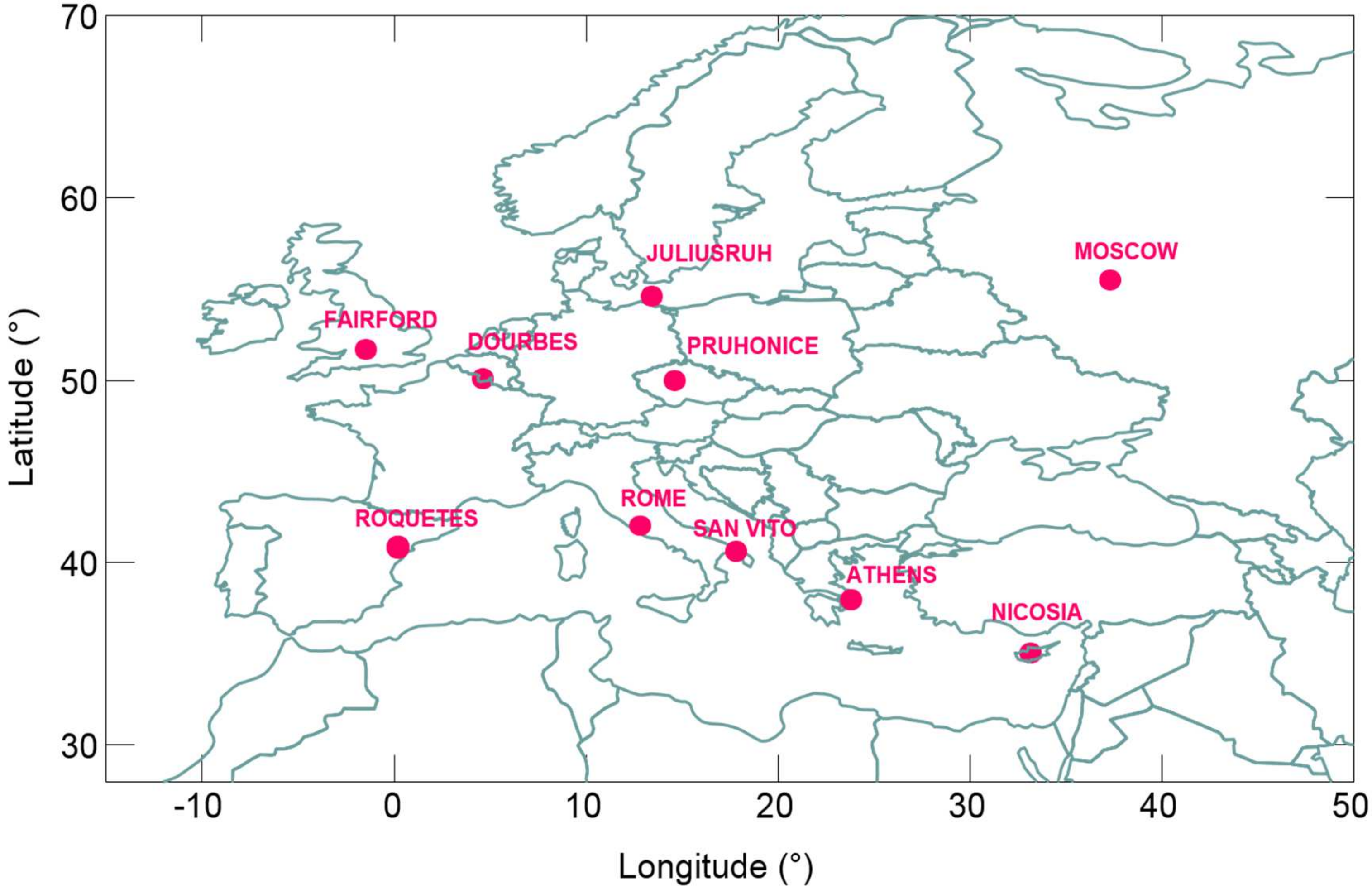


Get all ionograms from previous day → Autoscale ionograms → Extract foF2 and M(3000)F2 values → Determine **Short CCIR files** using χ2 minimisation

Estimate calibrated VTEC from local GNSS receiver from previous day RINEX file → Run NeQuick-G to determine optimum ionization level **Az**

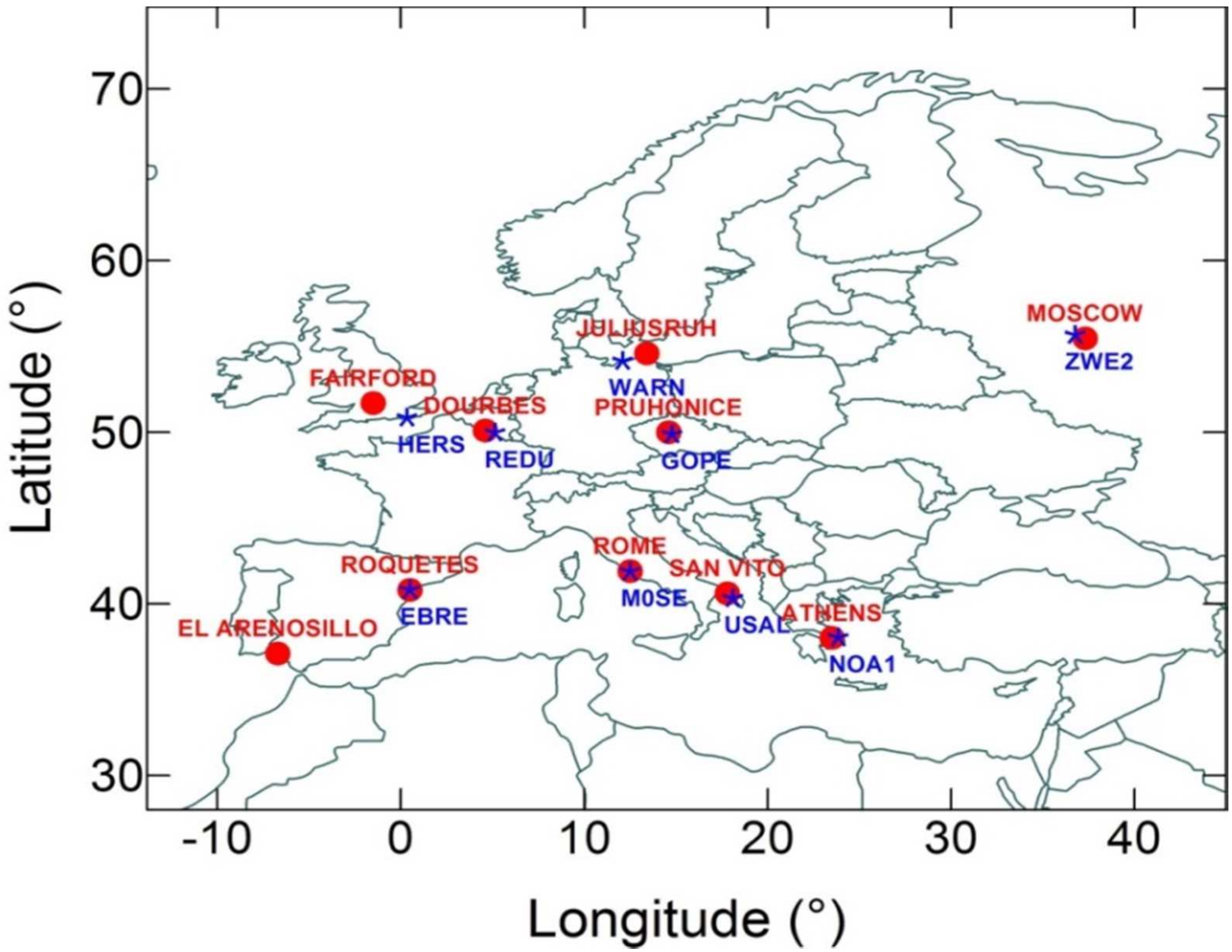
Use optimized **Az** and **CCIR** to run NeQuick-G next day

SERVING prospects over Europe



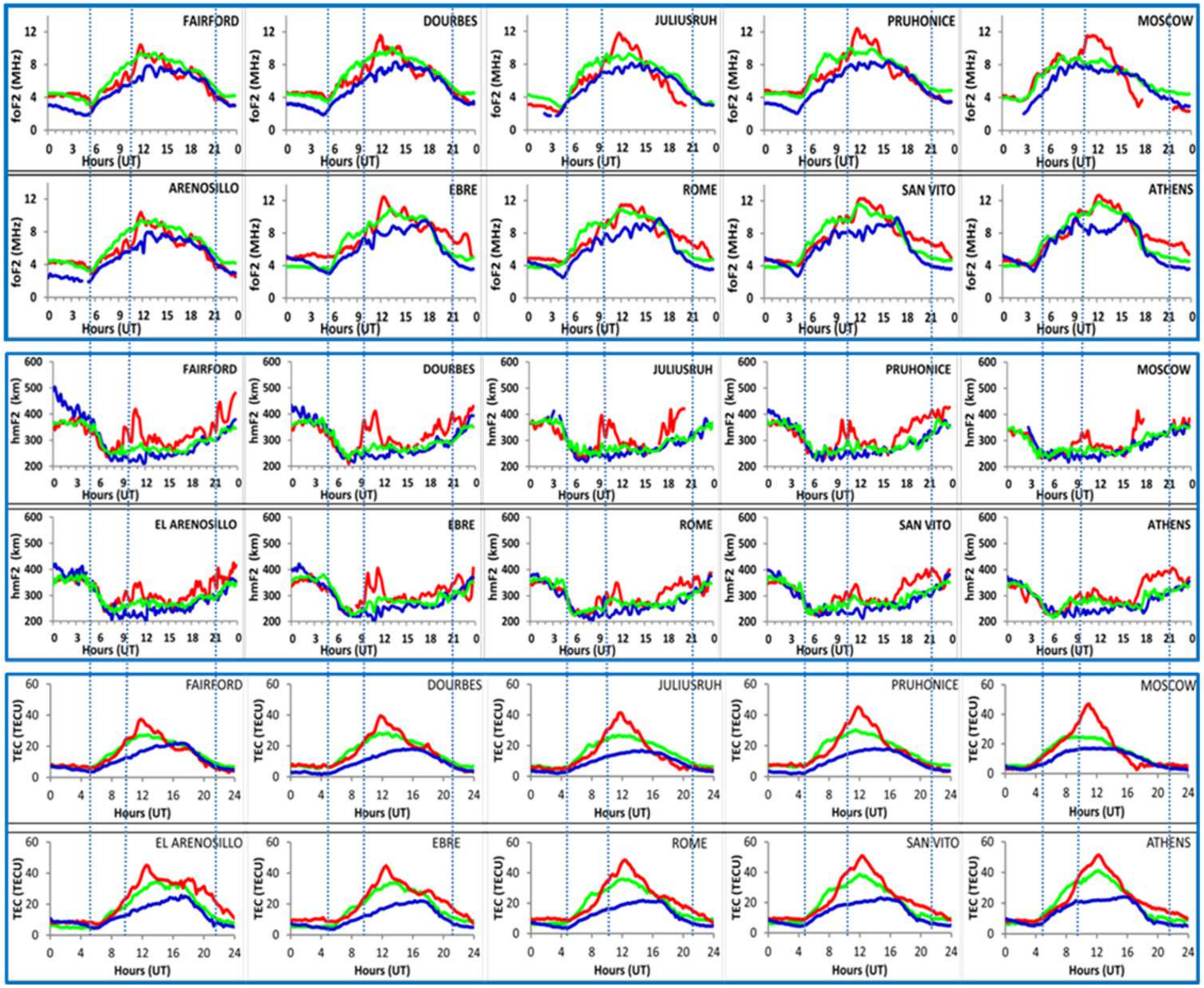
We can apply the SERVING concept over Europe with good ionosonde coverage

GNSS receiver stations (blue) and Digisonde stations (red)



GNSS and Digisonde observations on St. Patrick's Day 2013 Storm

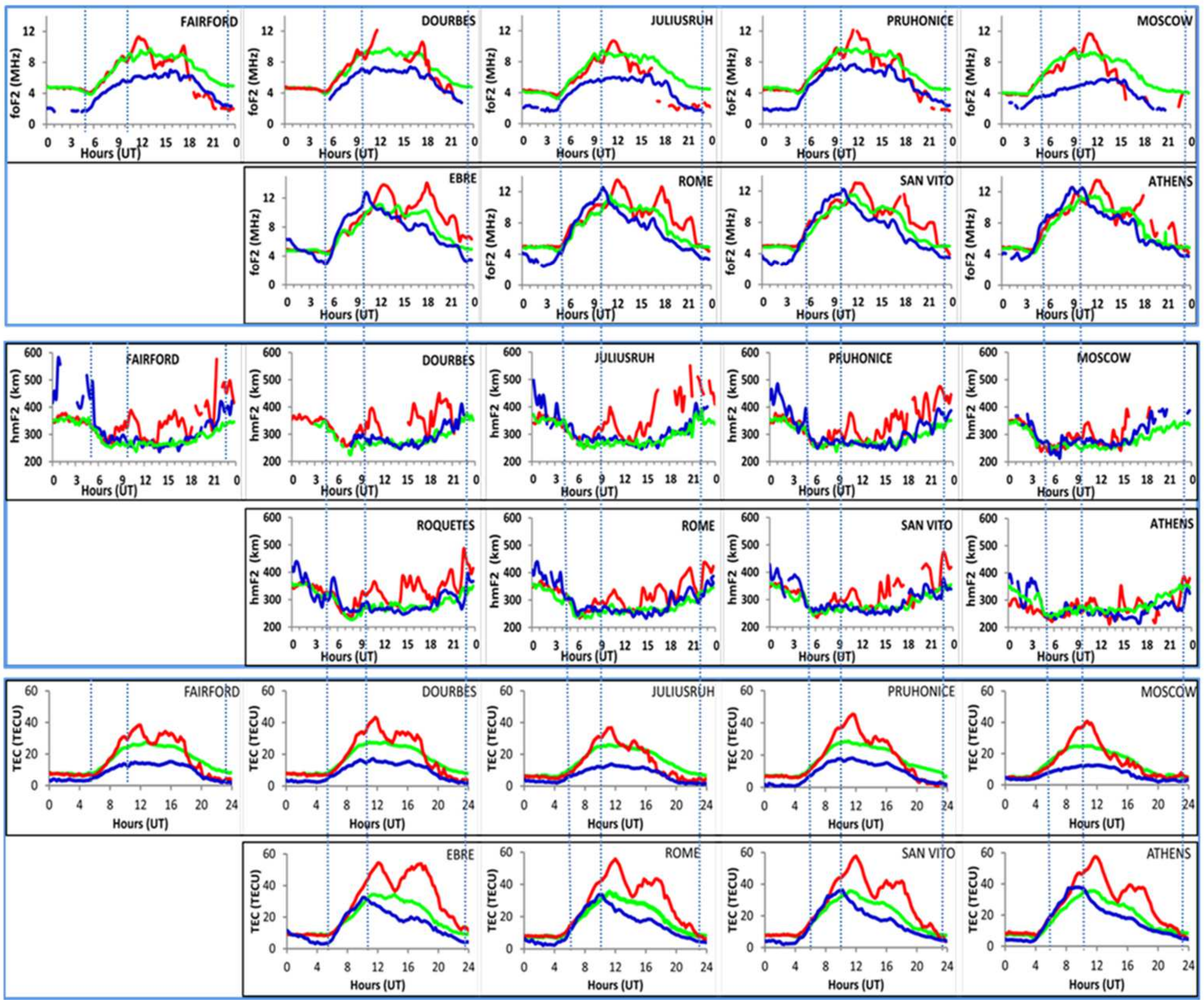
Temporal variations of ionospheric F region characteristics



16-17 March 2013

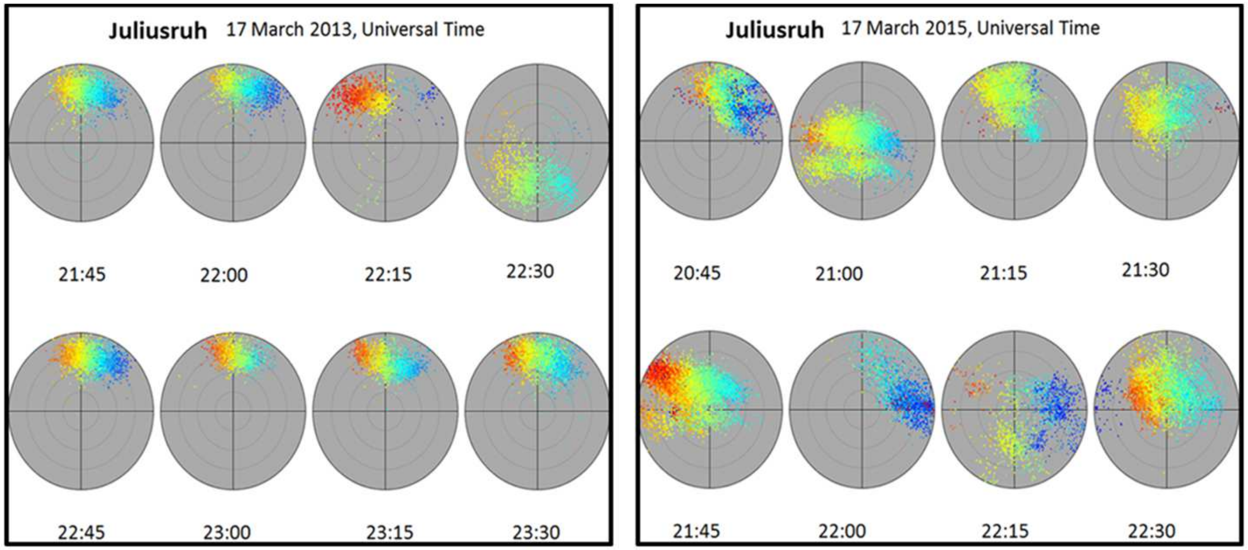
GNSS and Digisonde bservations on St. Patrick's Day 2015 Storm

Temporal variations of ionospheric F region characteristics



16-17 March 2015

Digisonde plasma drift observations on St. Patrick's Day 2013 and 2015 Storms

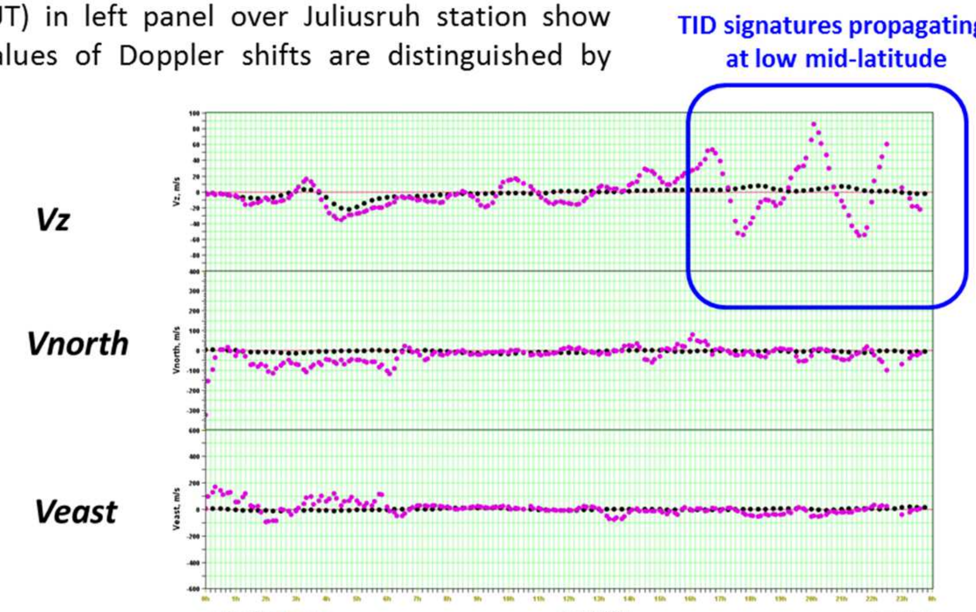


F-region 15 min skymaps recorded of a) March 17, 2013 (21:45 to 22:30 UT) in right panel, and b) March 17, 2015 (20:45 to 22:30 UT) in left panel over Juliusruh station show horizontal location of reflection points. Values of Doppler shifts are distinguished by different colors.

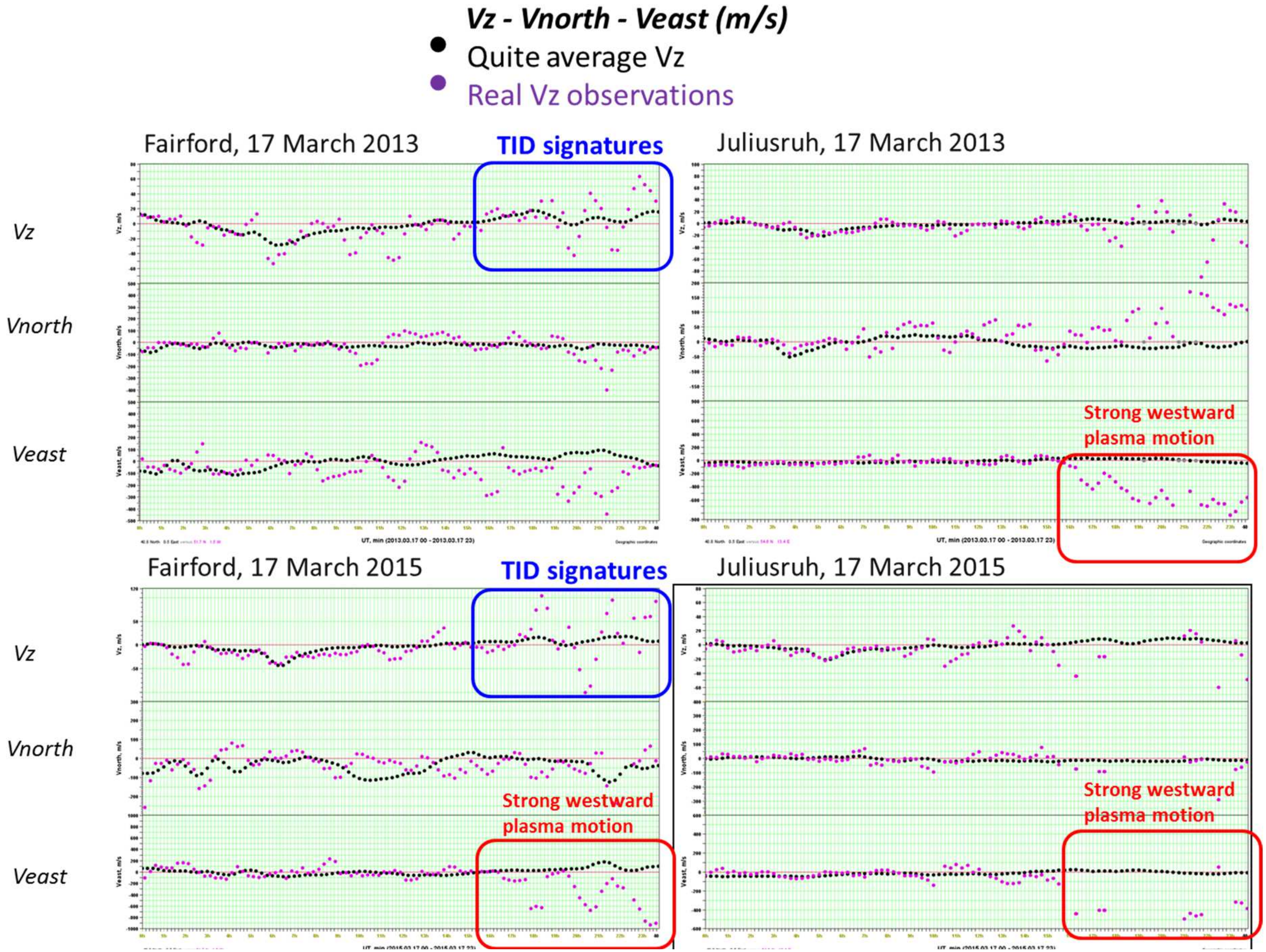
Athens 17 March 2015

Vz - Vnorth - Veast (m/s)

- Quite average Vz
- Real Vz observations

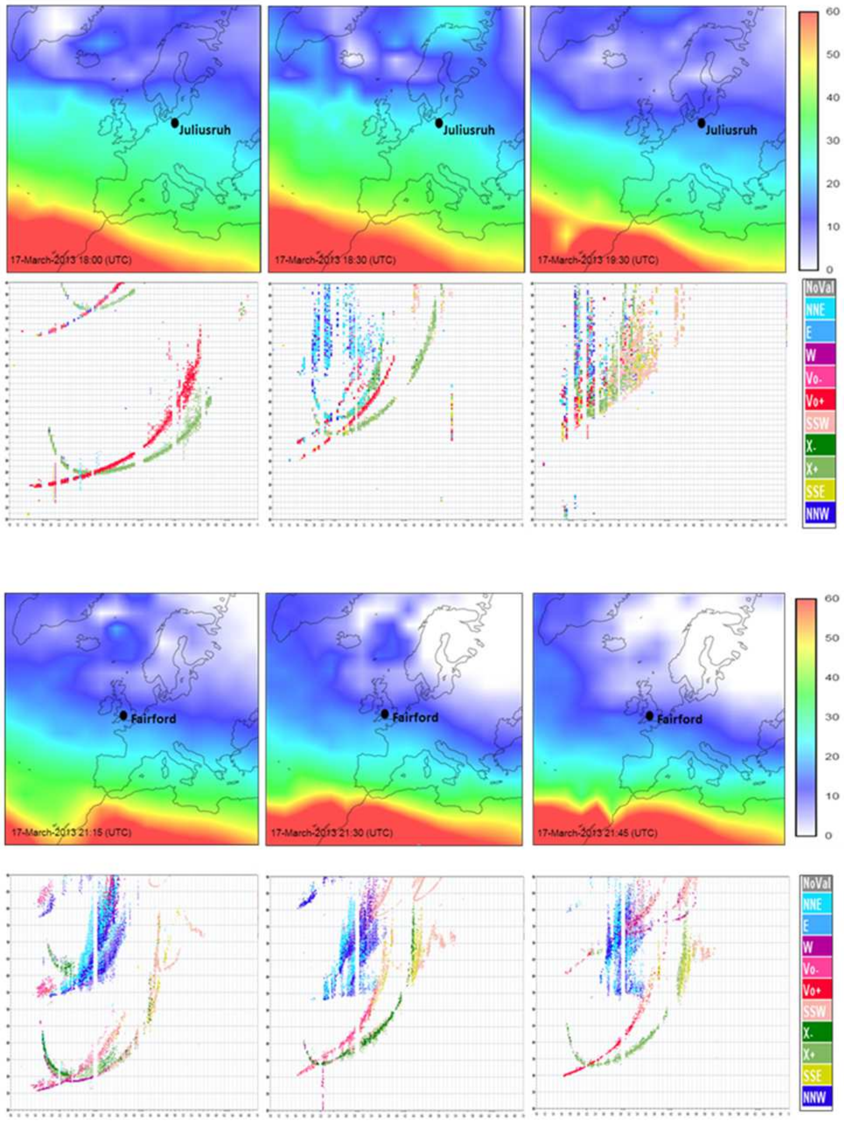


St. Patrick's Day 2013 and 2015 Storms

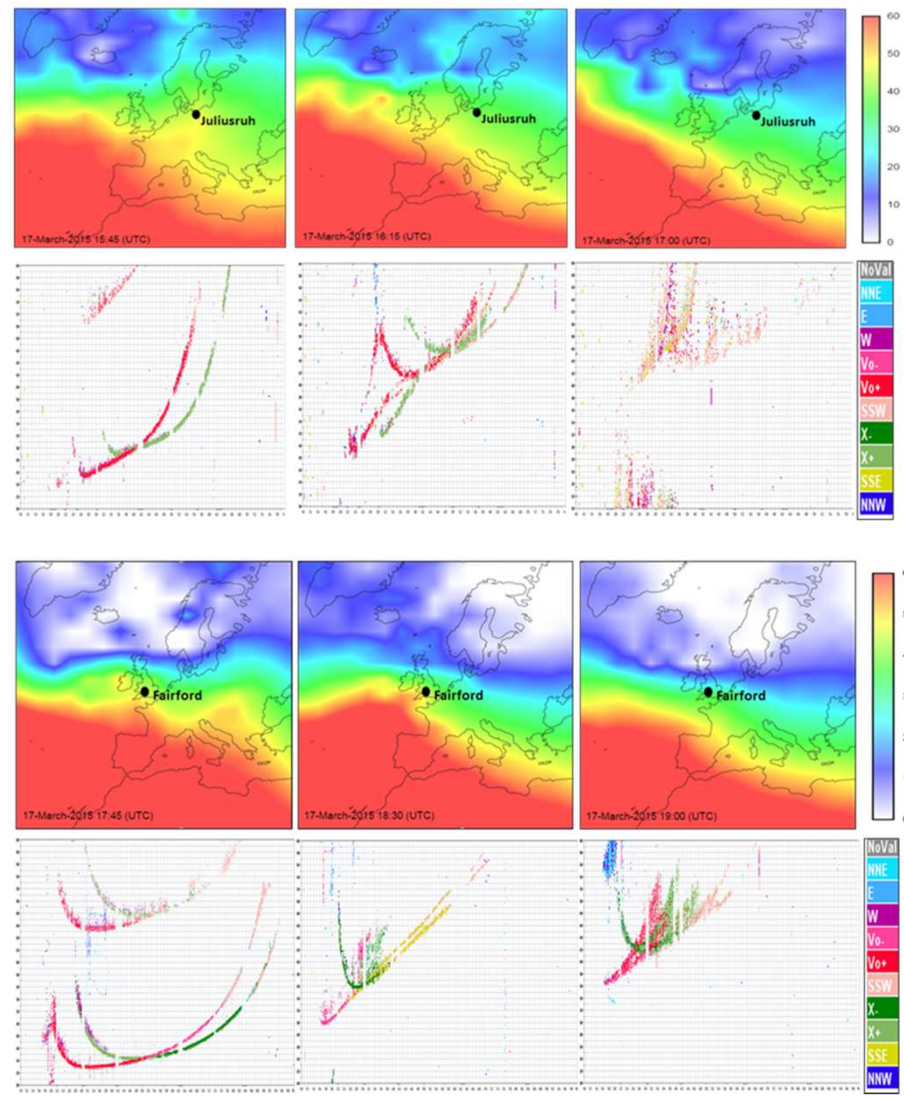


Digisonde spread F observations St. Patrick's Day 2013 and 2015 Storms

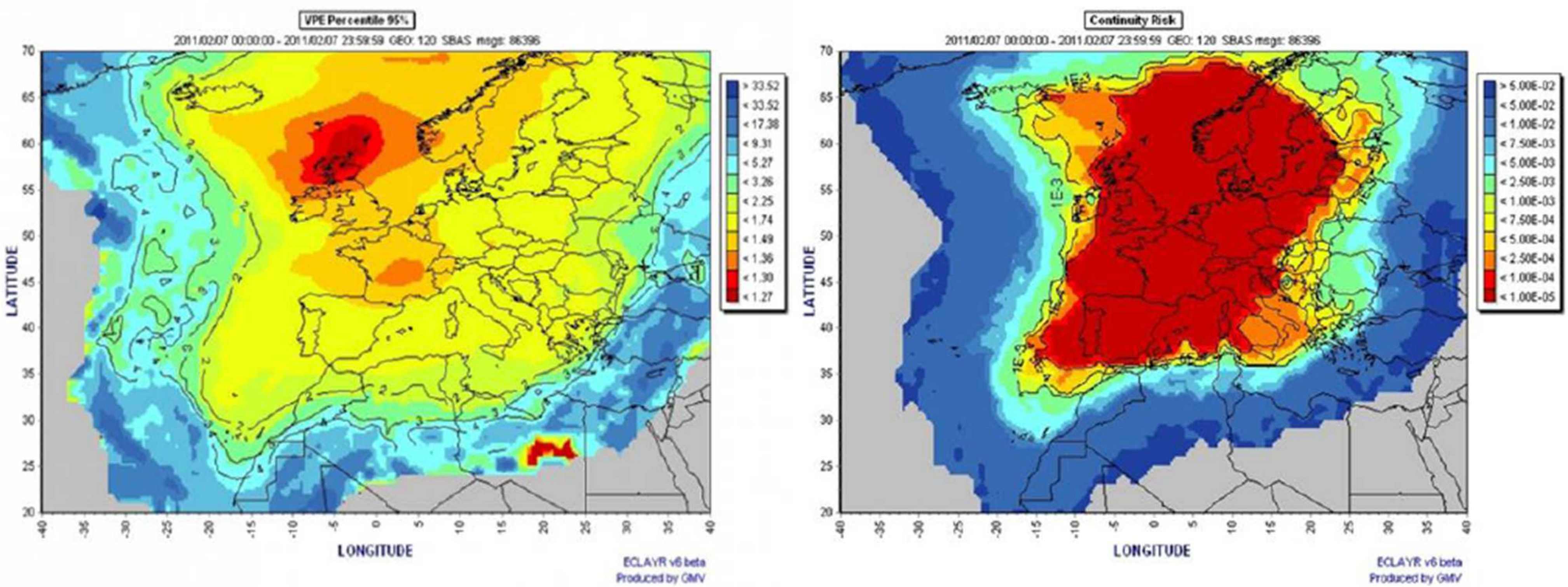
Spread F phenomena in March 2013 storm event



Spread F phenomena in March 2015 storm event

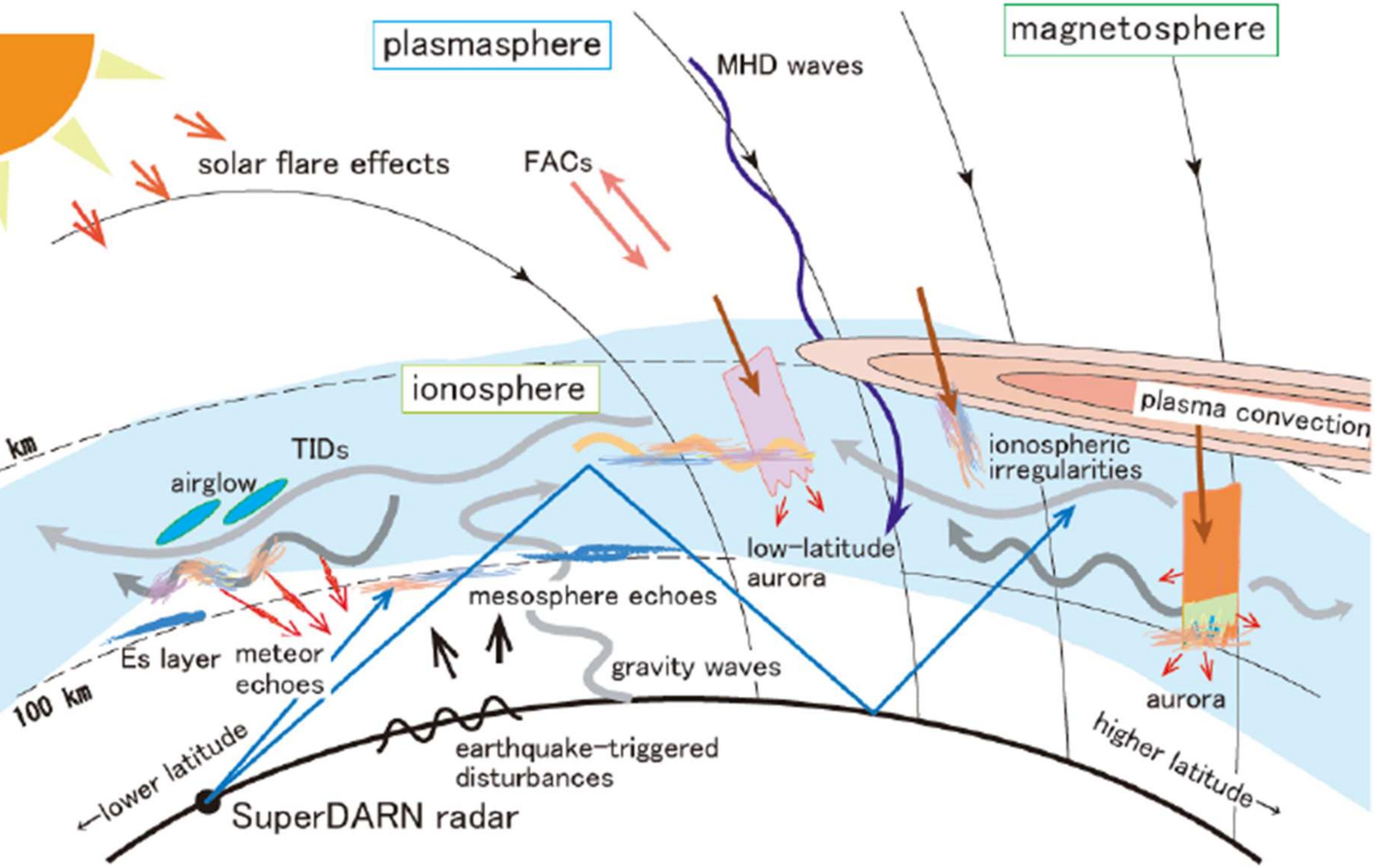


Radar for Ionospheric Space Situational Awareness significance
CYRISSA



European Geostationary Navigation Overlay Service (EGNOS) performance over Europe.

Radar for Ionospheric Space Situational Awareness significance
CYRISSA



Motion of ionosphe plasma due to coupli from the solar wi ('Space Weather')

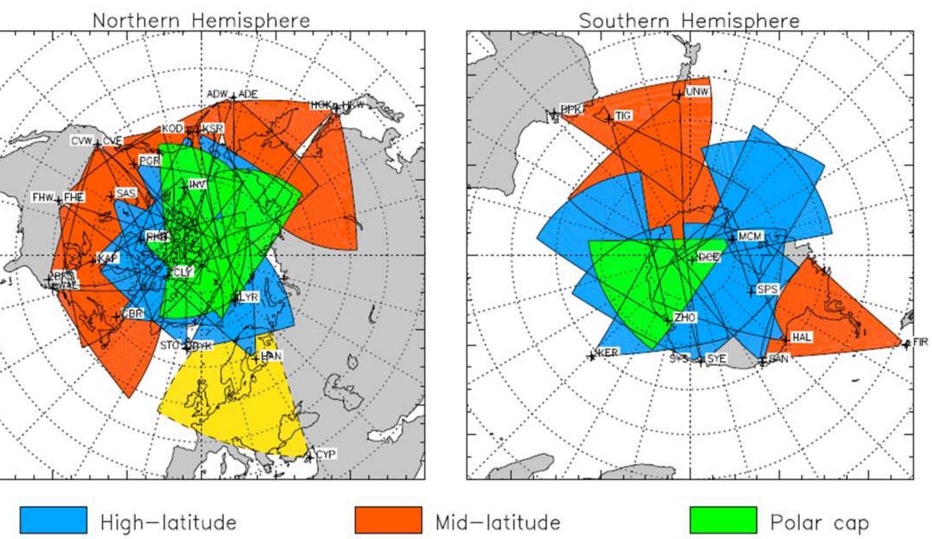
Passage of large-sca waves in the atmosphere

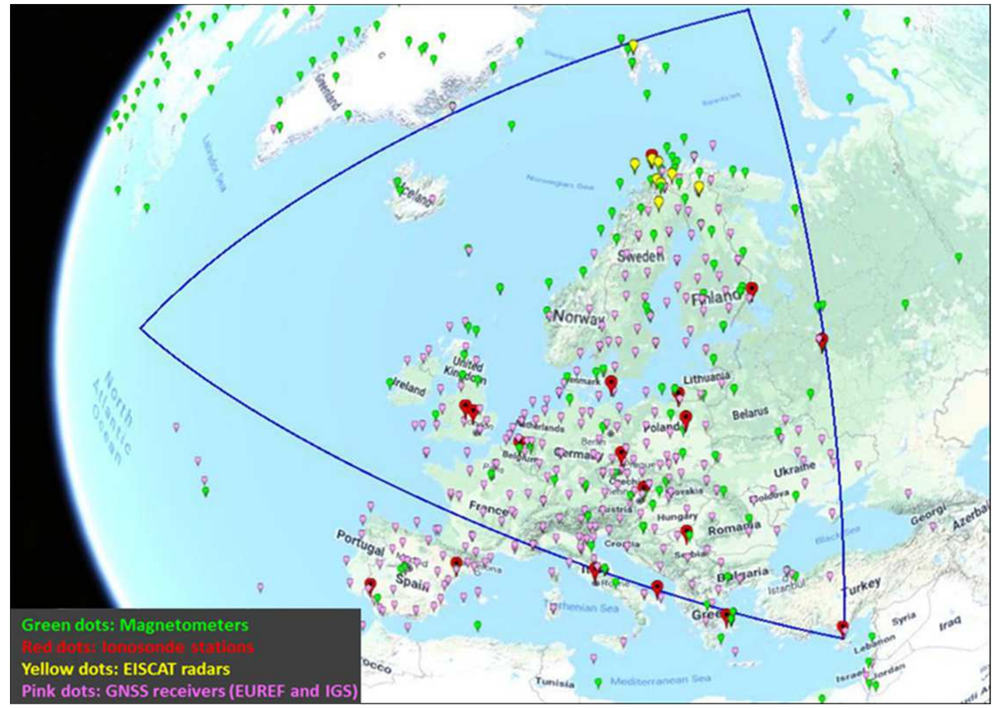
Roughness at the Eart surface including oce waves and ice cover

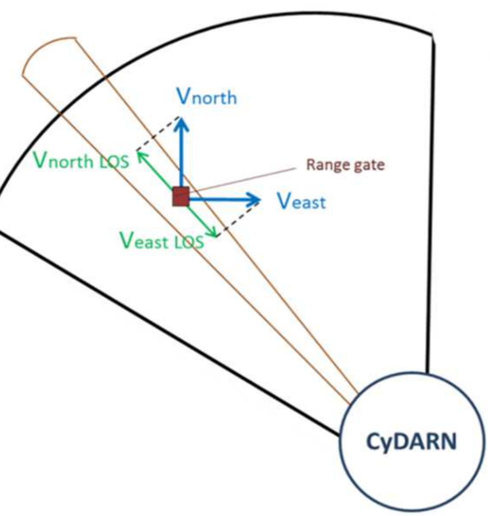
Winds in the atmosphe at 90 km altitude (mete trails)

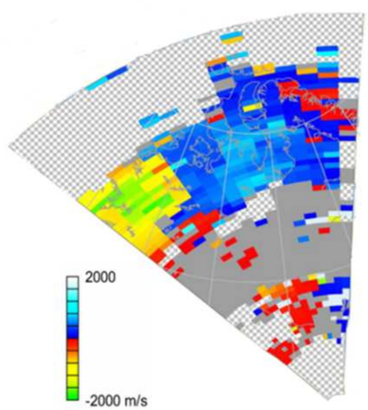
Unusual clouds in t upper atmosphere (Po Mesopheric Clouds)

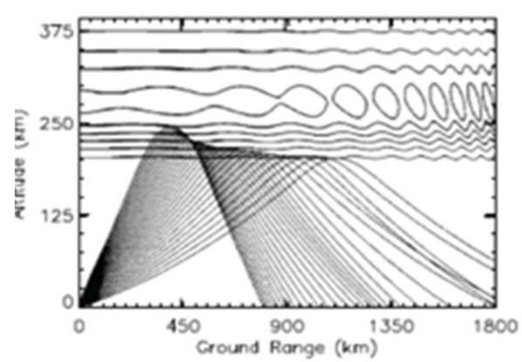
CYprus Radar for Ionospheric Space Situational Awareness
CYRISSA

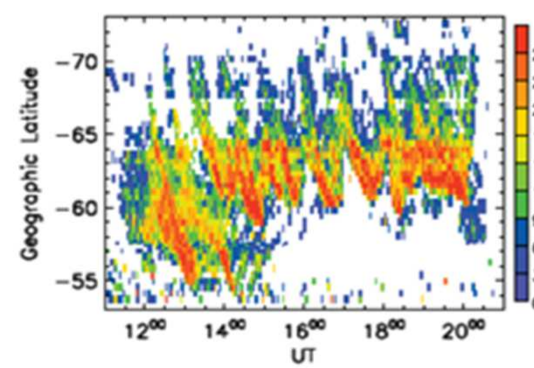




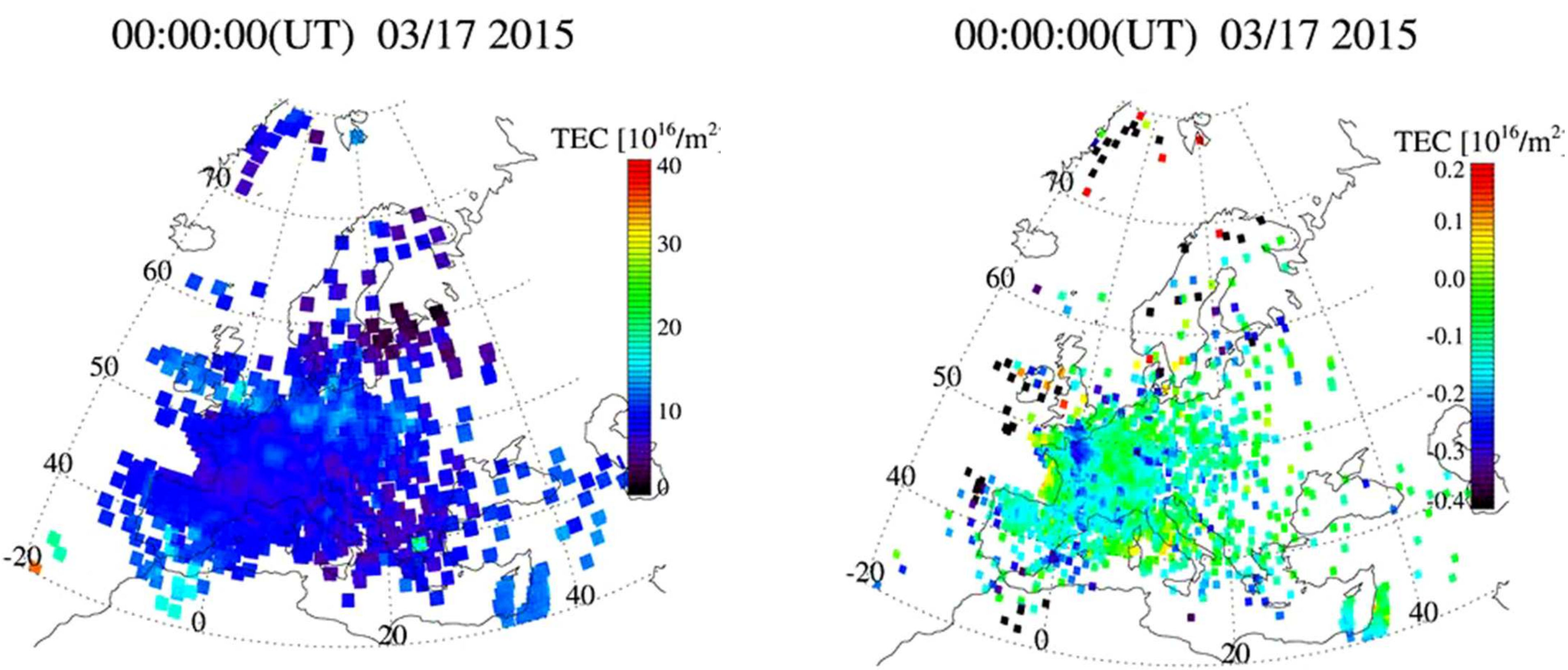








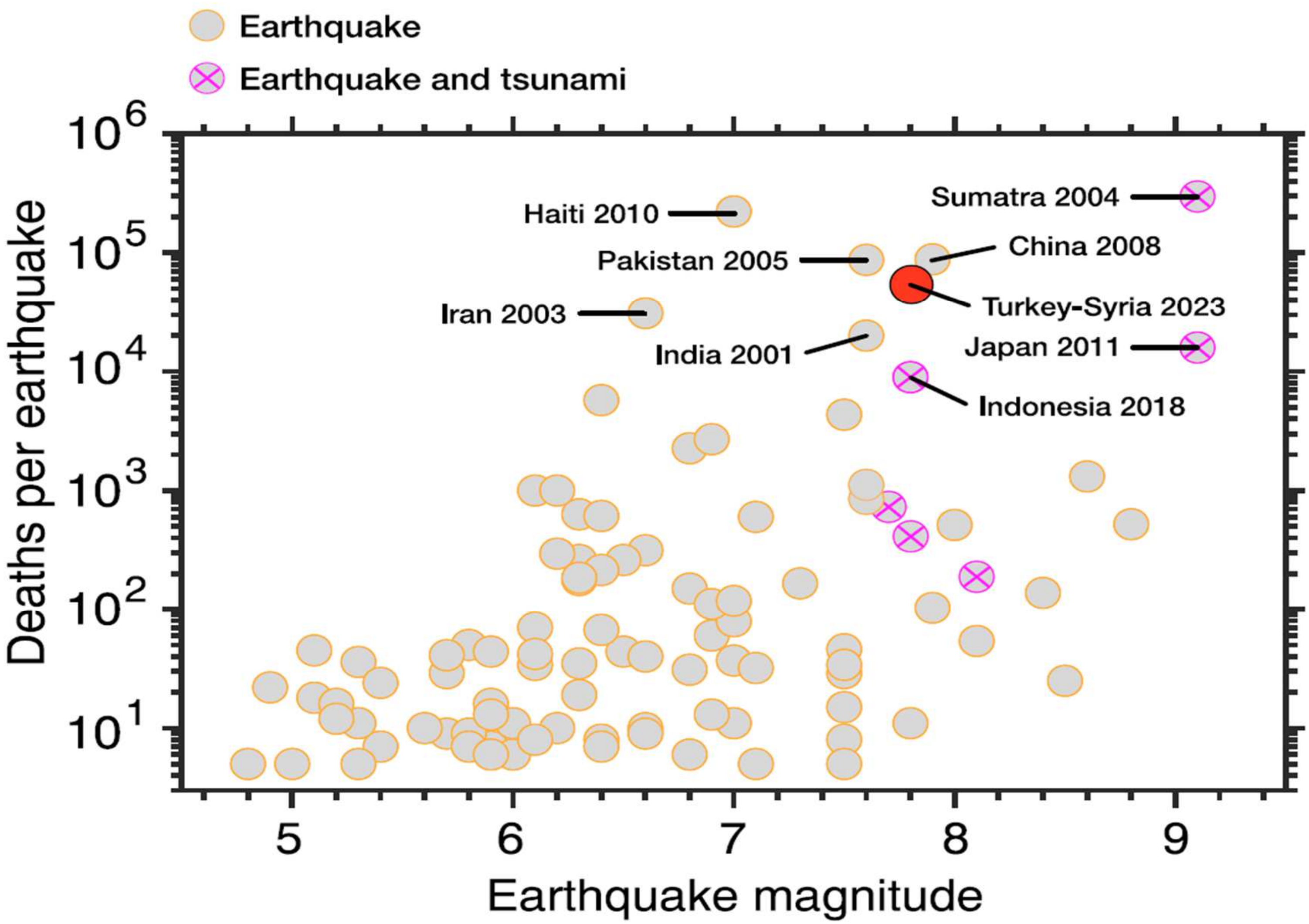
Radar for Ionospheric Space Situational Awareness significance
CYRISSA



Strong equatorward plasma convection on 17 March 2015 (left plot) and Travelling Ionospheric Disturbances (right plot) as shown on Total Electron Content DRAWING maps

Earthquake remote sensing

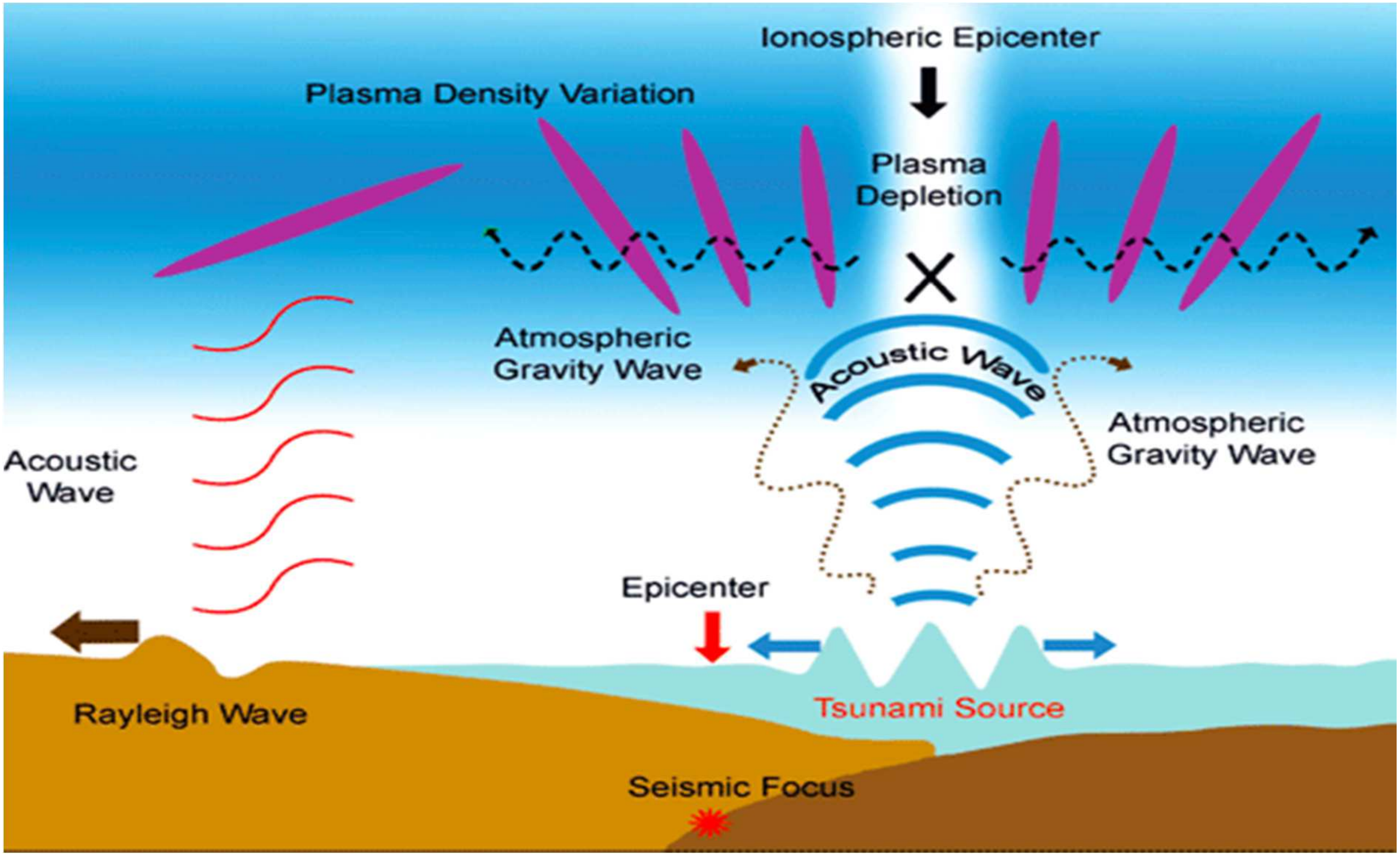
Deaths from earthquakes since 2000



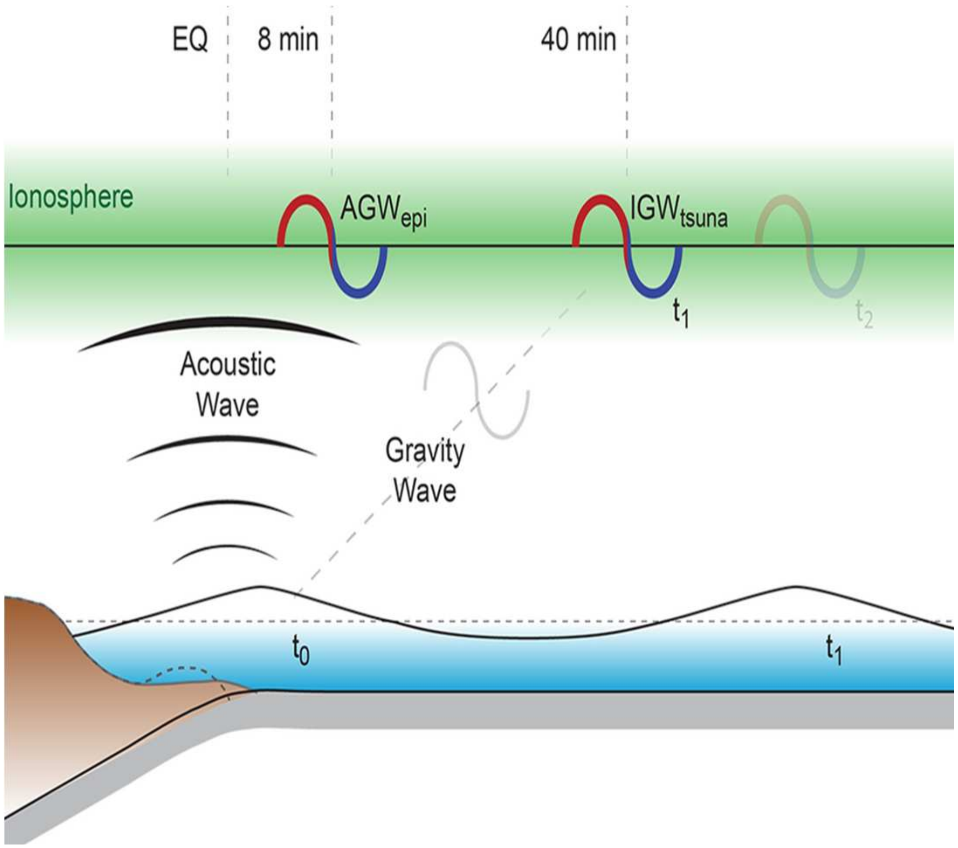
The toll of the Turkey and Syria quakes is one of the highest of any previous magnitude-7.8 event, and **the 5th worst earthquake since 2000**

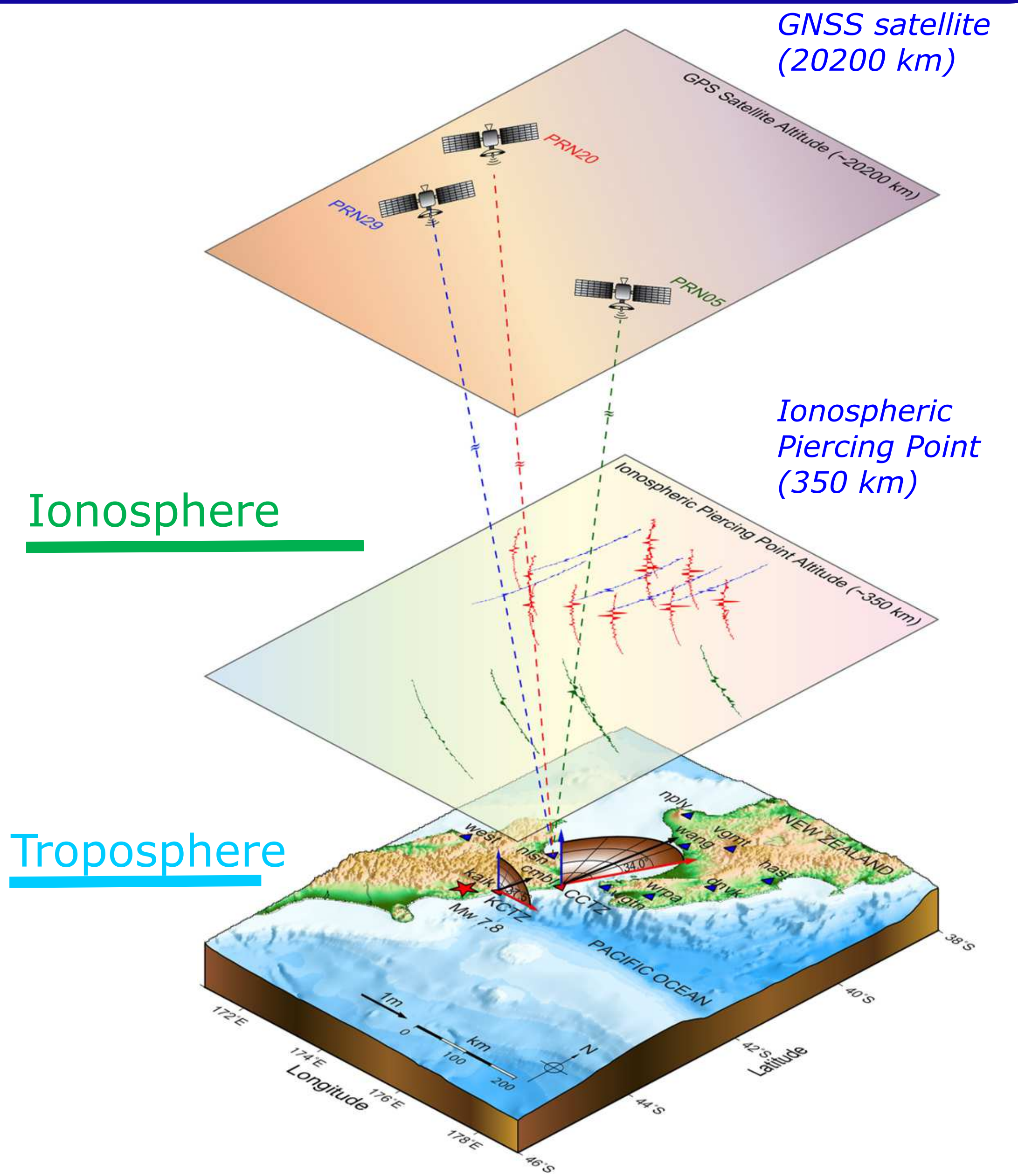
Dal Zilio, L., Ampuero, JP. Earthquake doublet in Turkey and Syria. Commun Earth Environ ***4****, 71 (2023)*
https://doi.org/10.1038/s43247-023-00747-z

Co-seismic ionospheric signatures



Remote sensing of co-seismic ionospheric signatures by GNSS

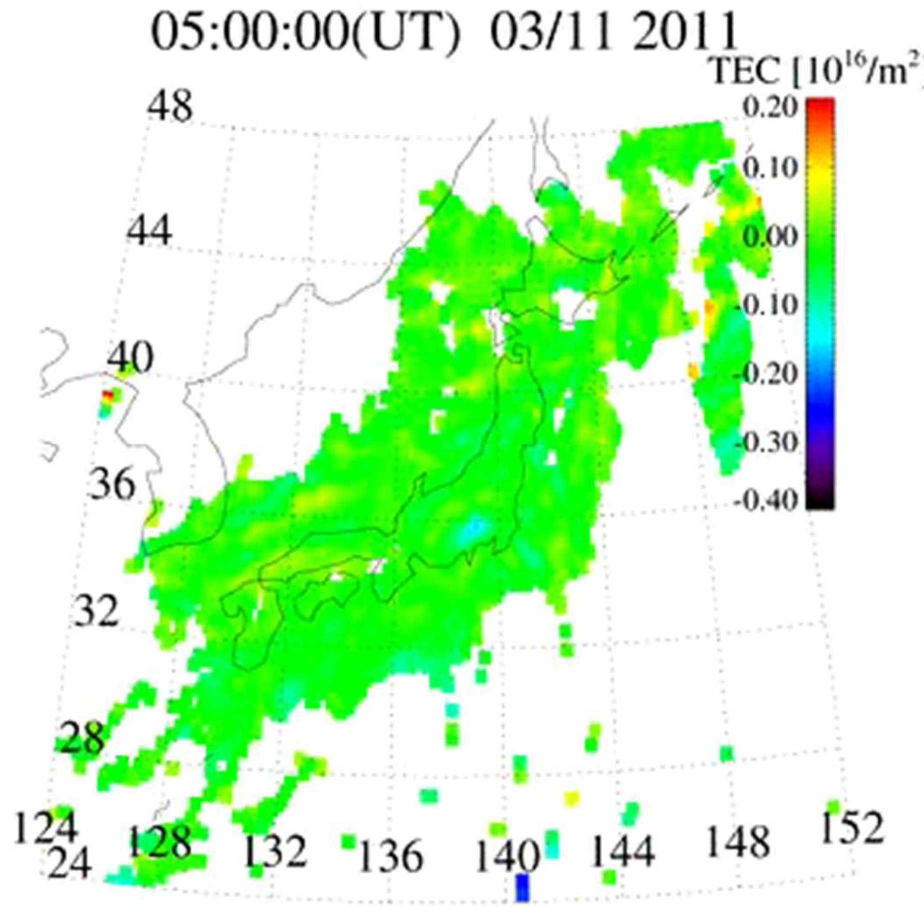




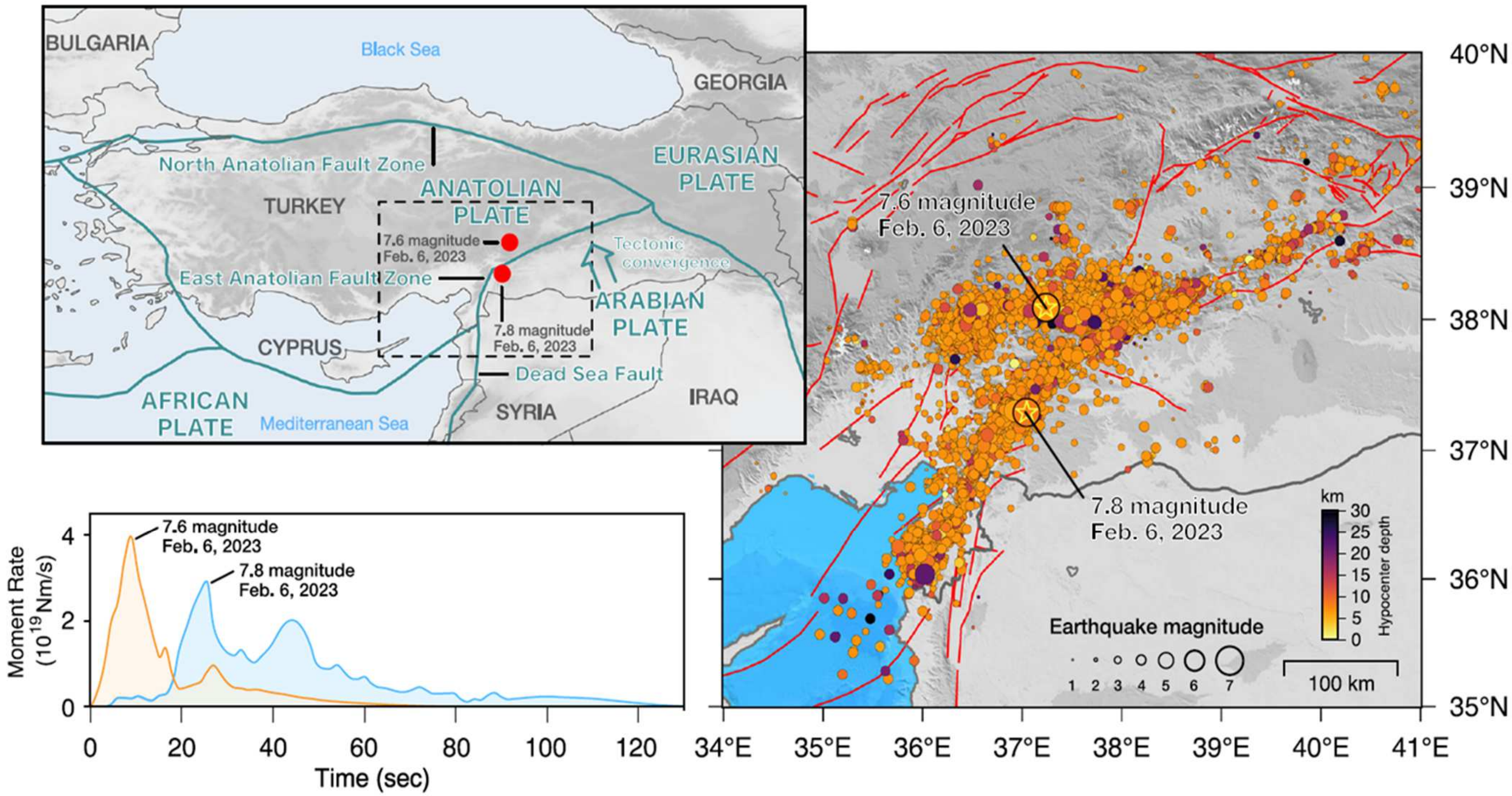
Remote sensing of co-seismic ionospheric signatures by GNSS

Tohoku earthquake and tsunami in ionosphere on 11 March 2011

GEONET GNSS Japanese network

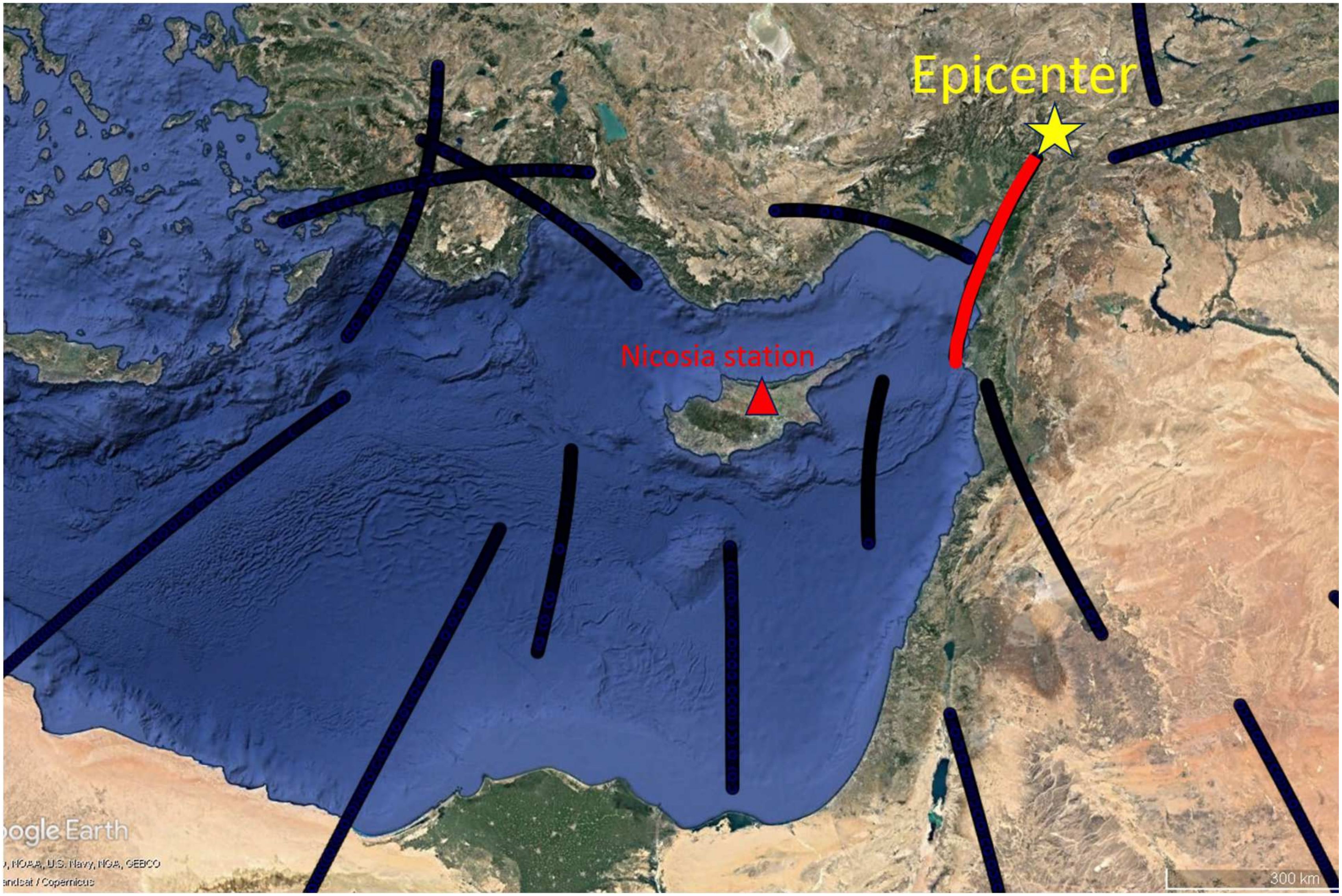


Kahramanmaraș Earthquake Sequence

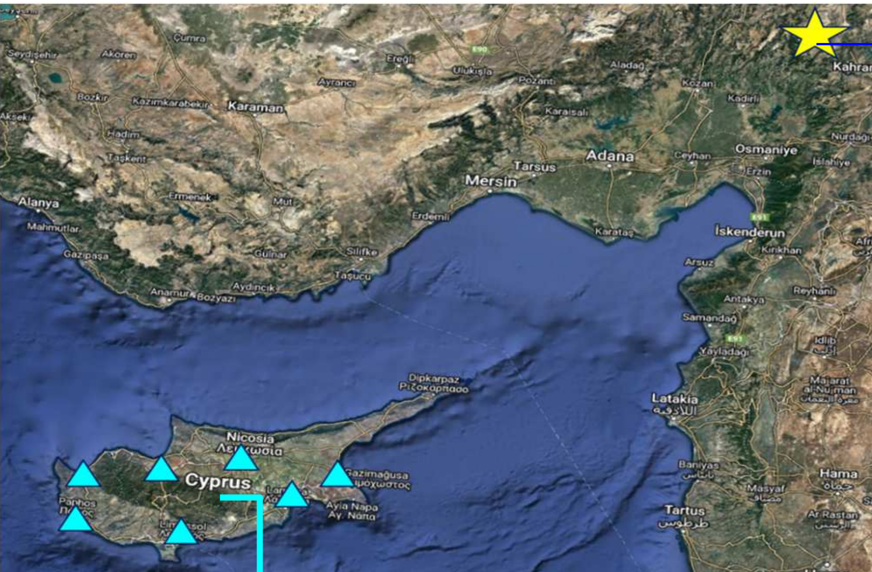


Tectonic setting and seismicity caused by the 2023 Kahramanmaraș Earthquake Sequence

GPS and GLONASS IPP tracks



Ionospheric signatures Cyprus GNSS network

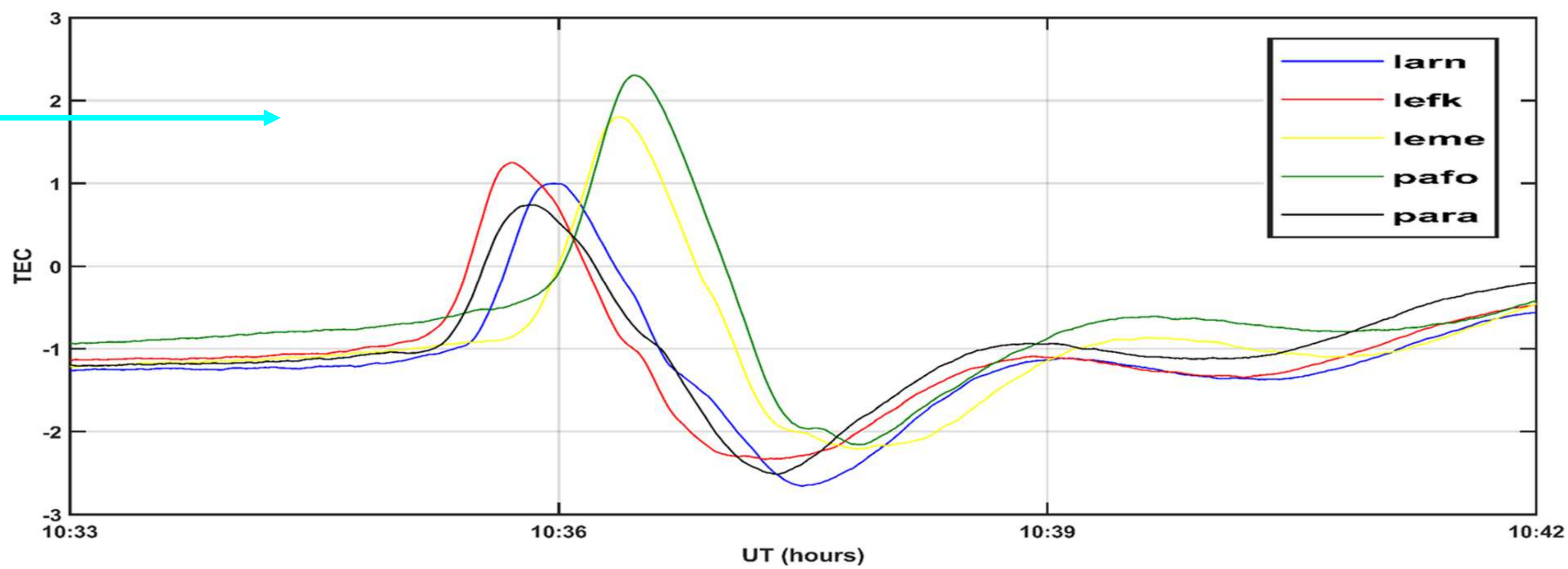


Kahramanmaras earthquake sequence

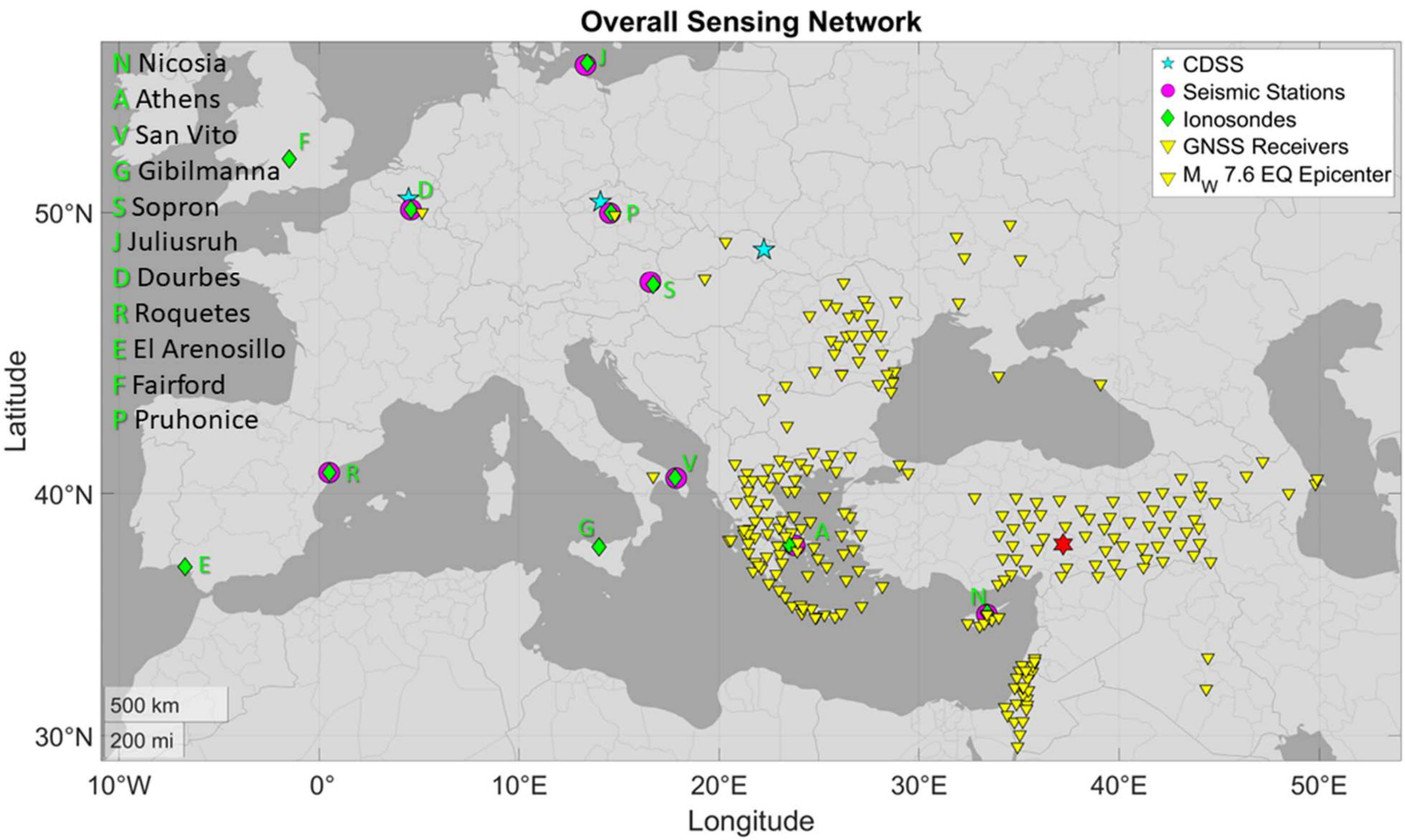
6 Feb 23, 1:17 UTC
M 7.8

6 Feb 23, 1:28 UTC
M 6.7

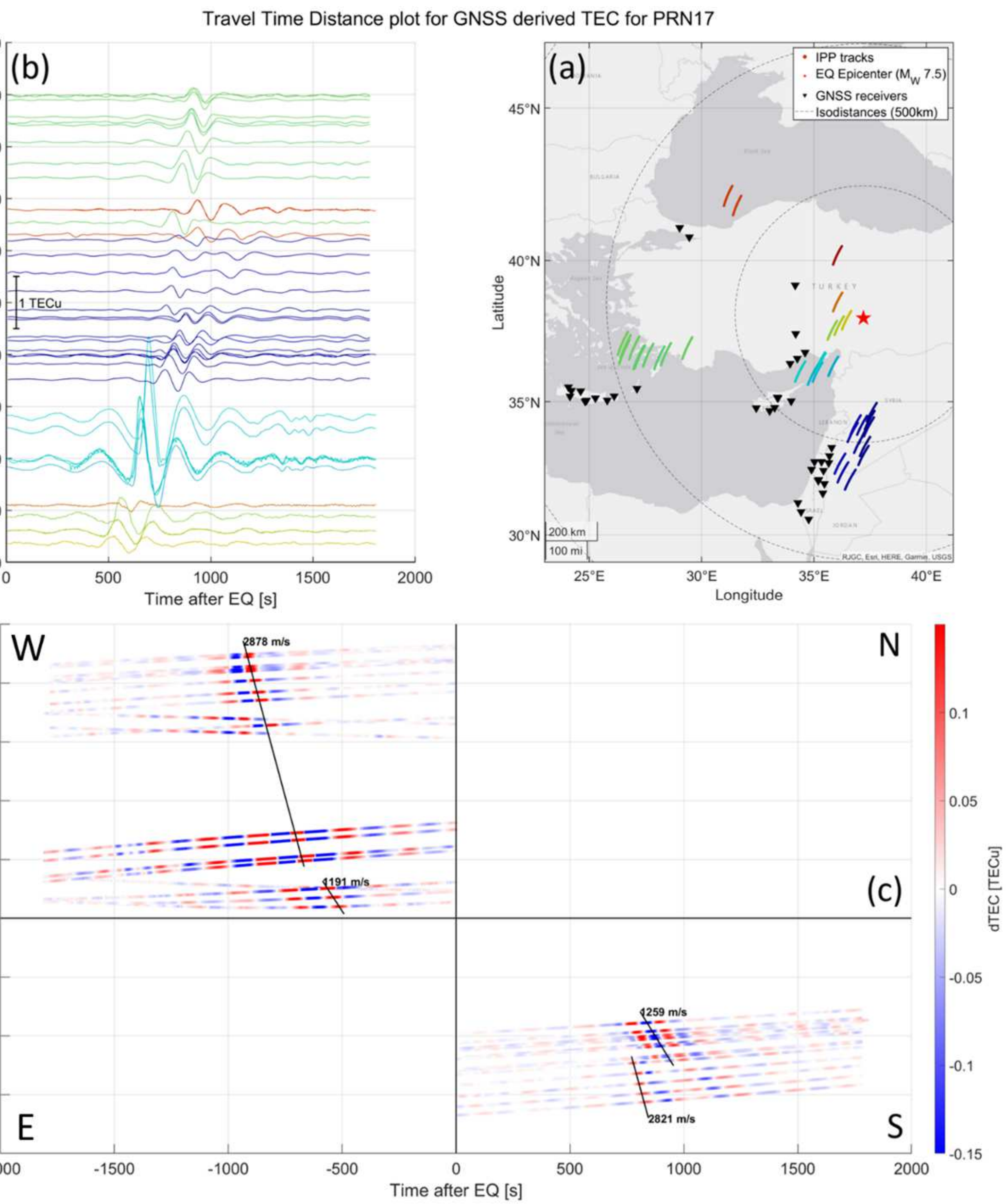
6 Feb 23, 10:24 UTC
M 7.5

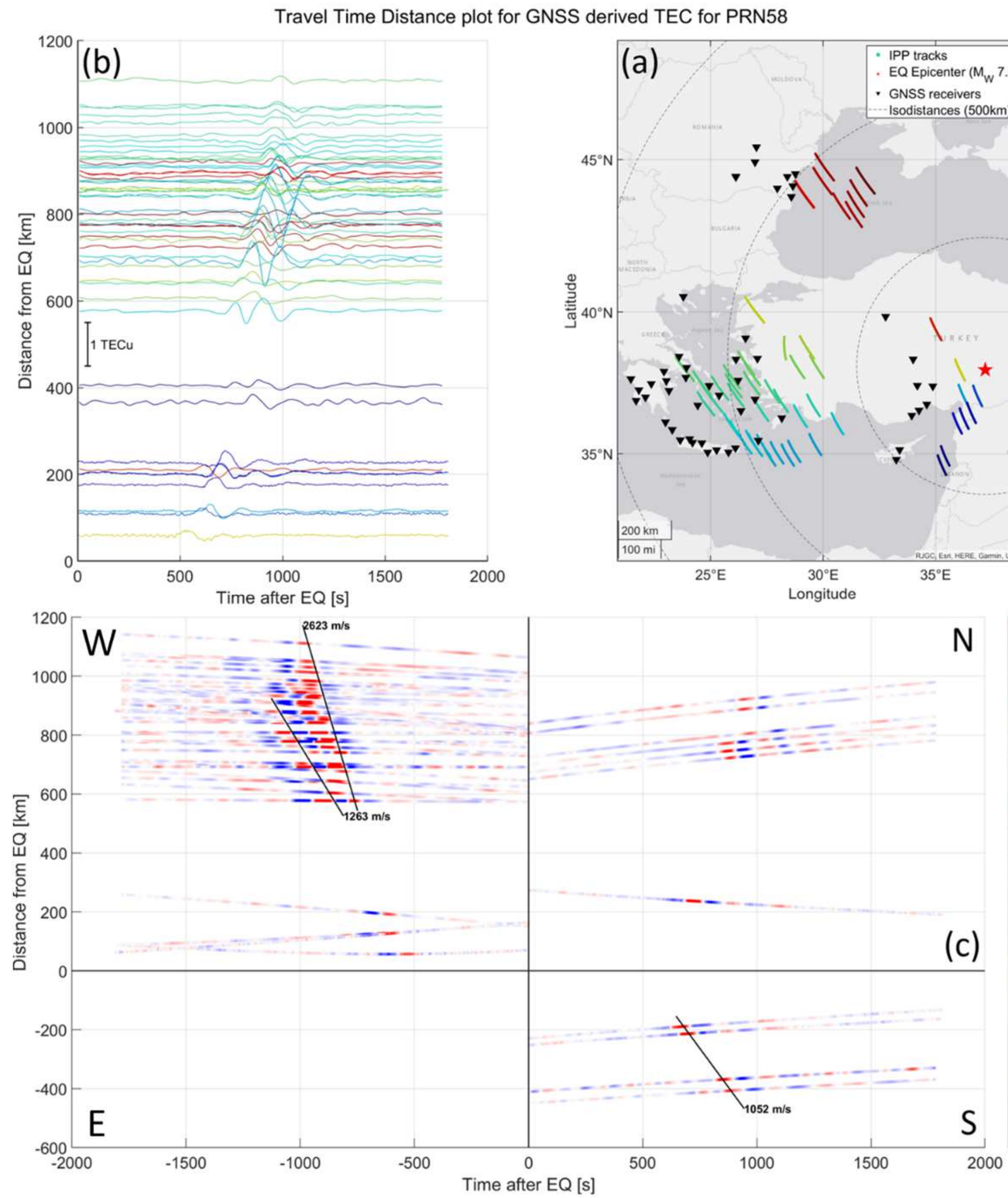


Ionospheric signatures over Europe

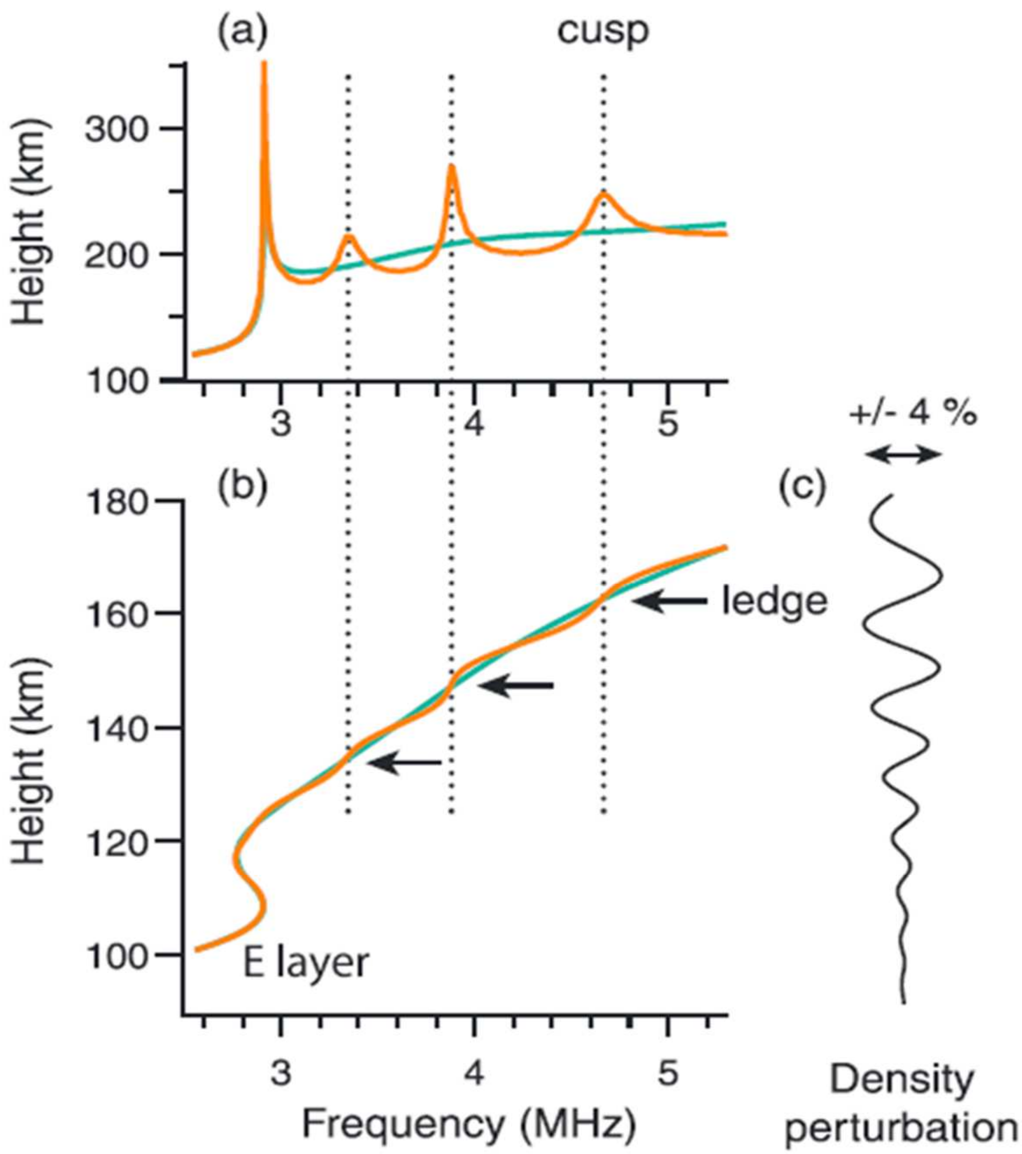


GNSS ionospheric signatures over Europe





Simulating the effect of acoustic waves on ionograms



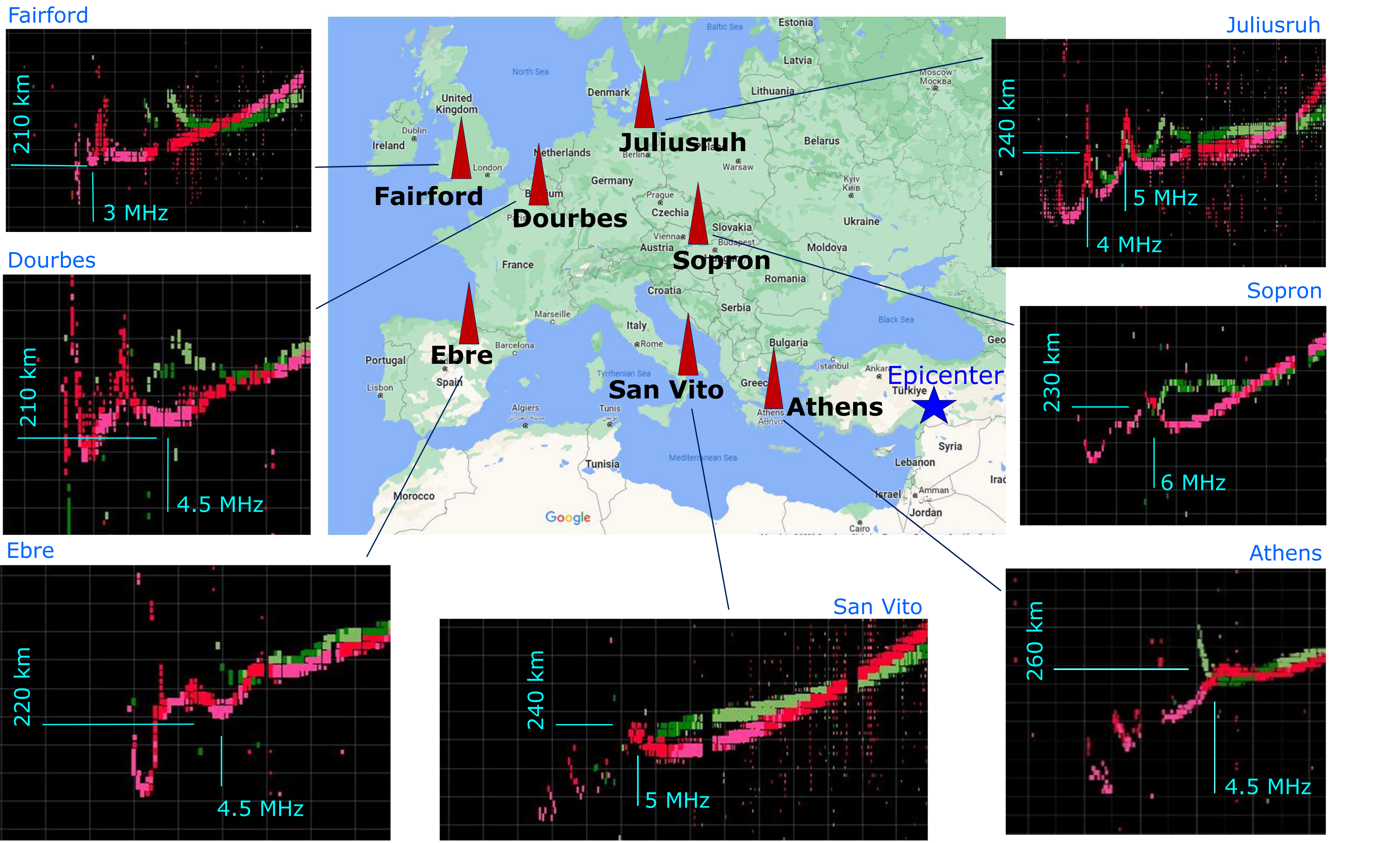
a) Synthesized ionogram traces from undisturbed (green) and modulated (orange) ionospheric plasma layer

b) corresponding undisturbed (green) and modulated (orange) electron density profiles

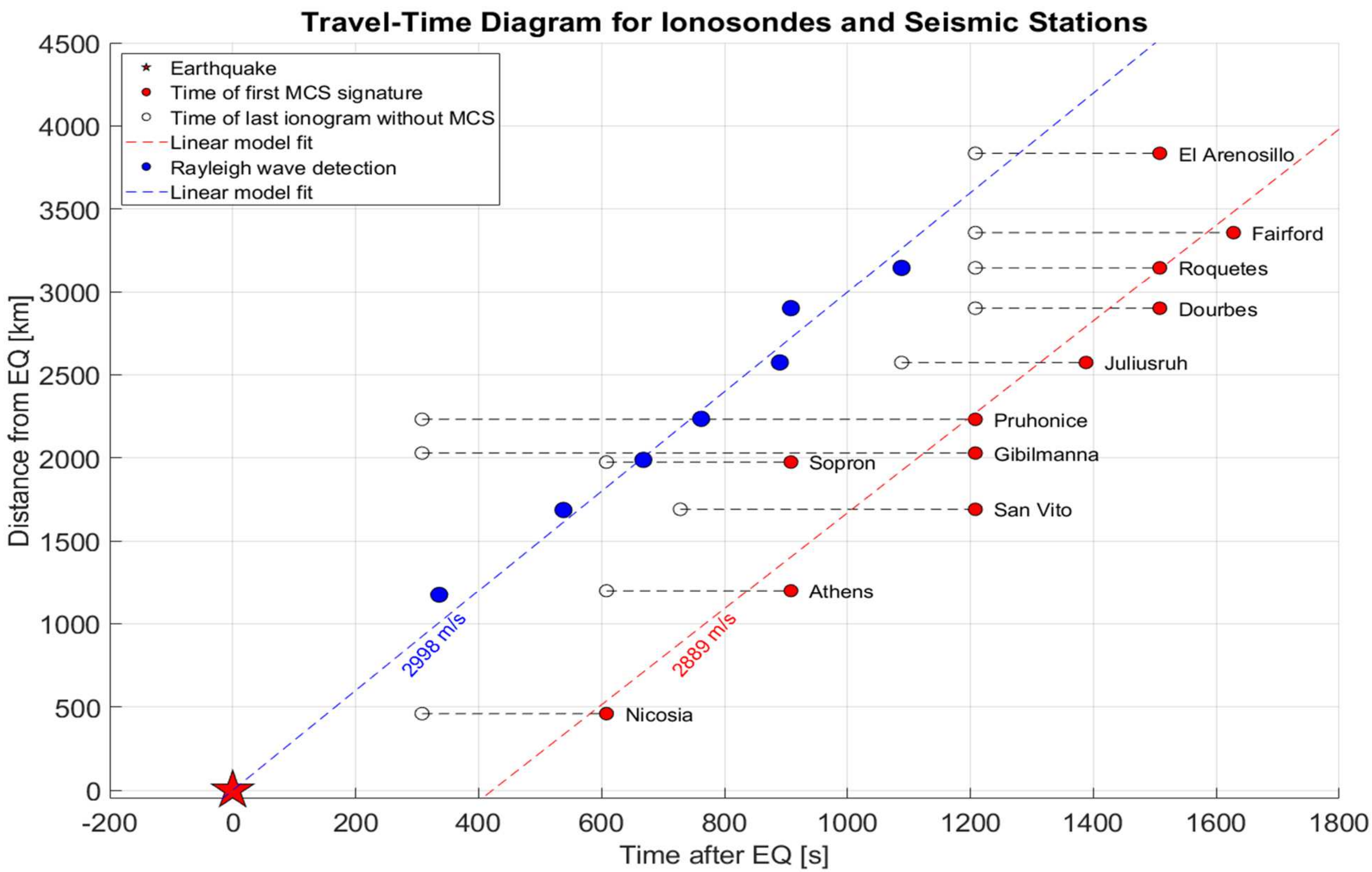
c) quasi-sinusoidal signal yielding the density modulation shown in (b)

Maruyama et al., 2012 JGR Space Physics

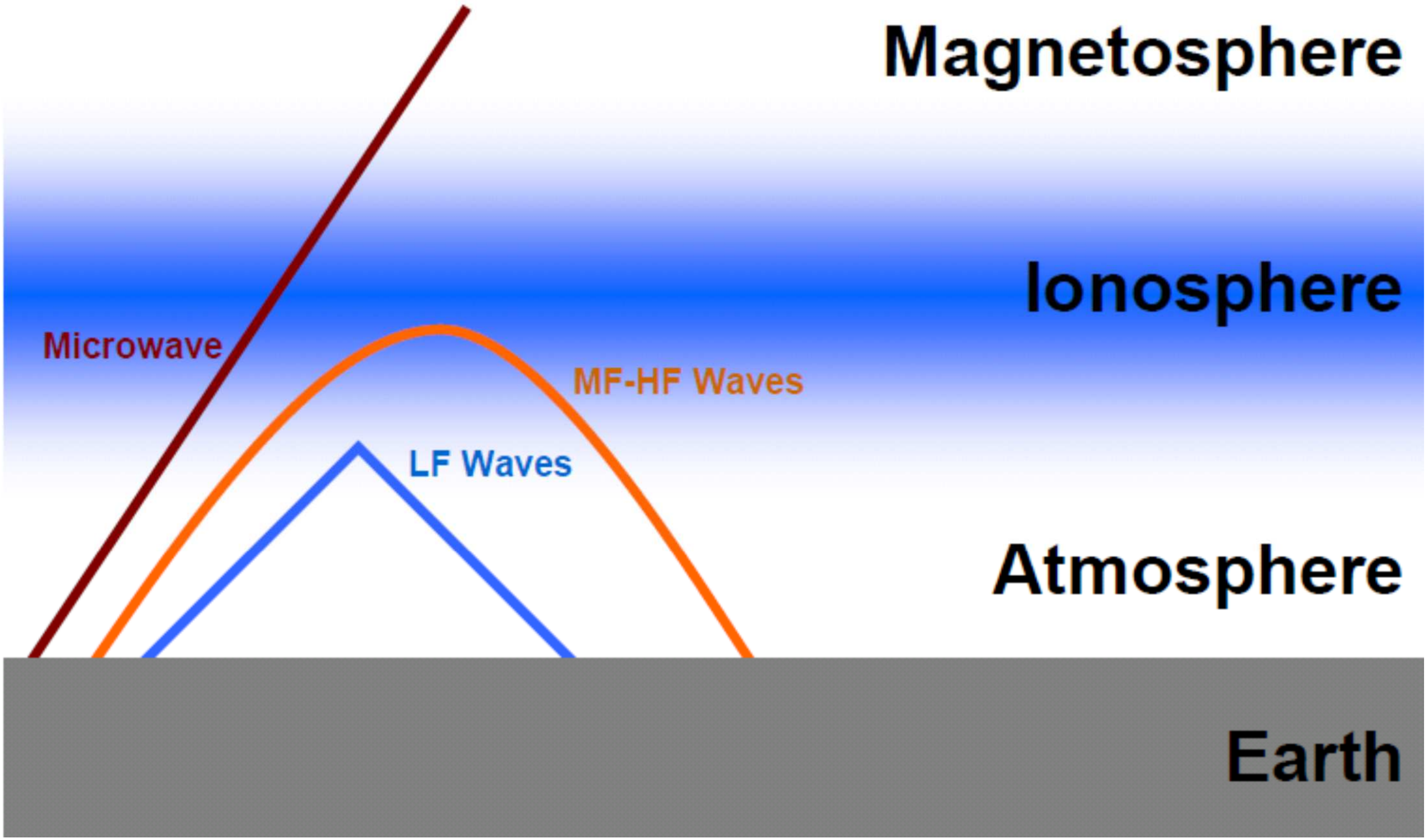
Digisonde ionospheric signatures over Europe



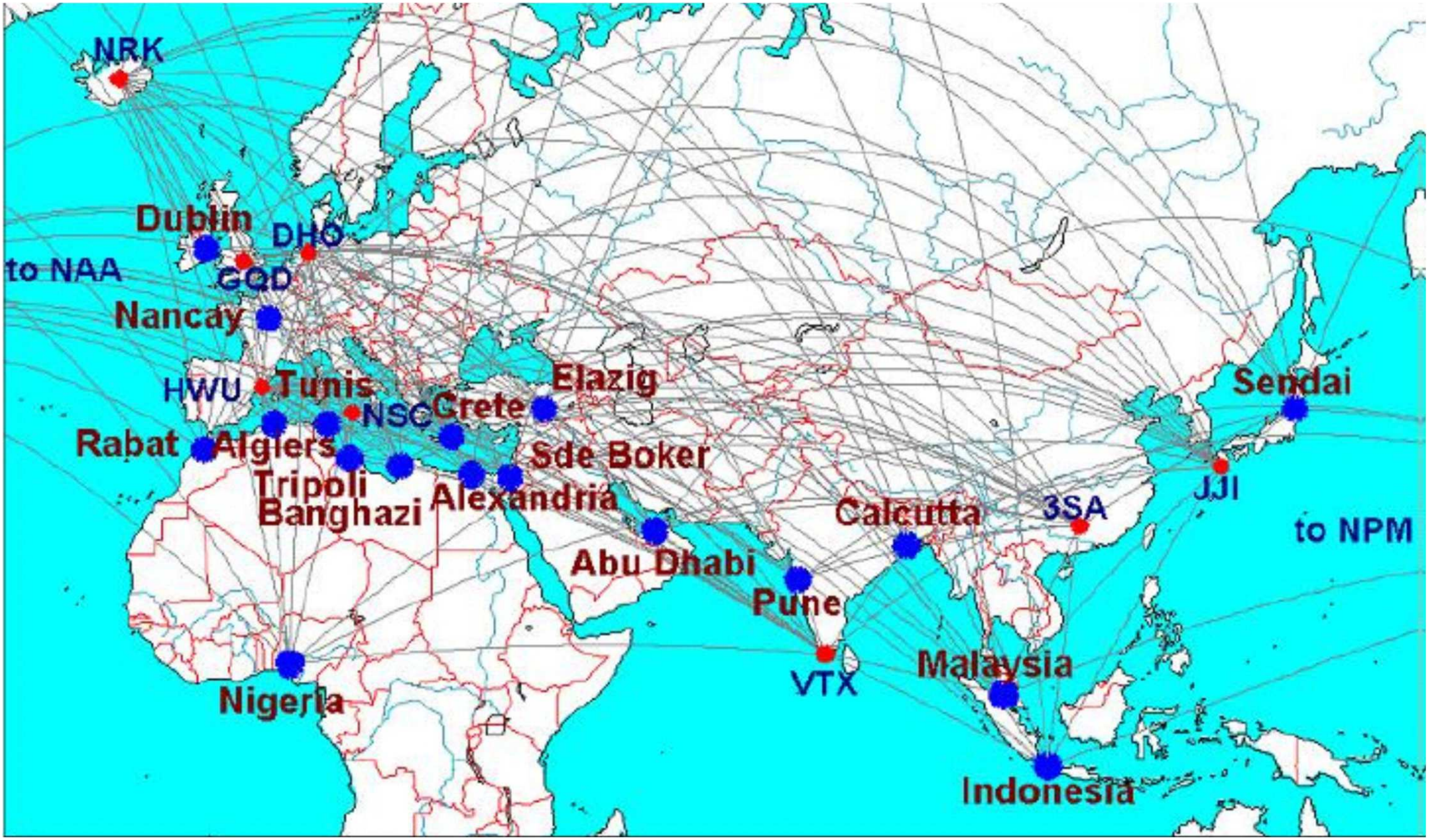
Ionospheric signatures over Europe



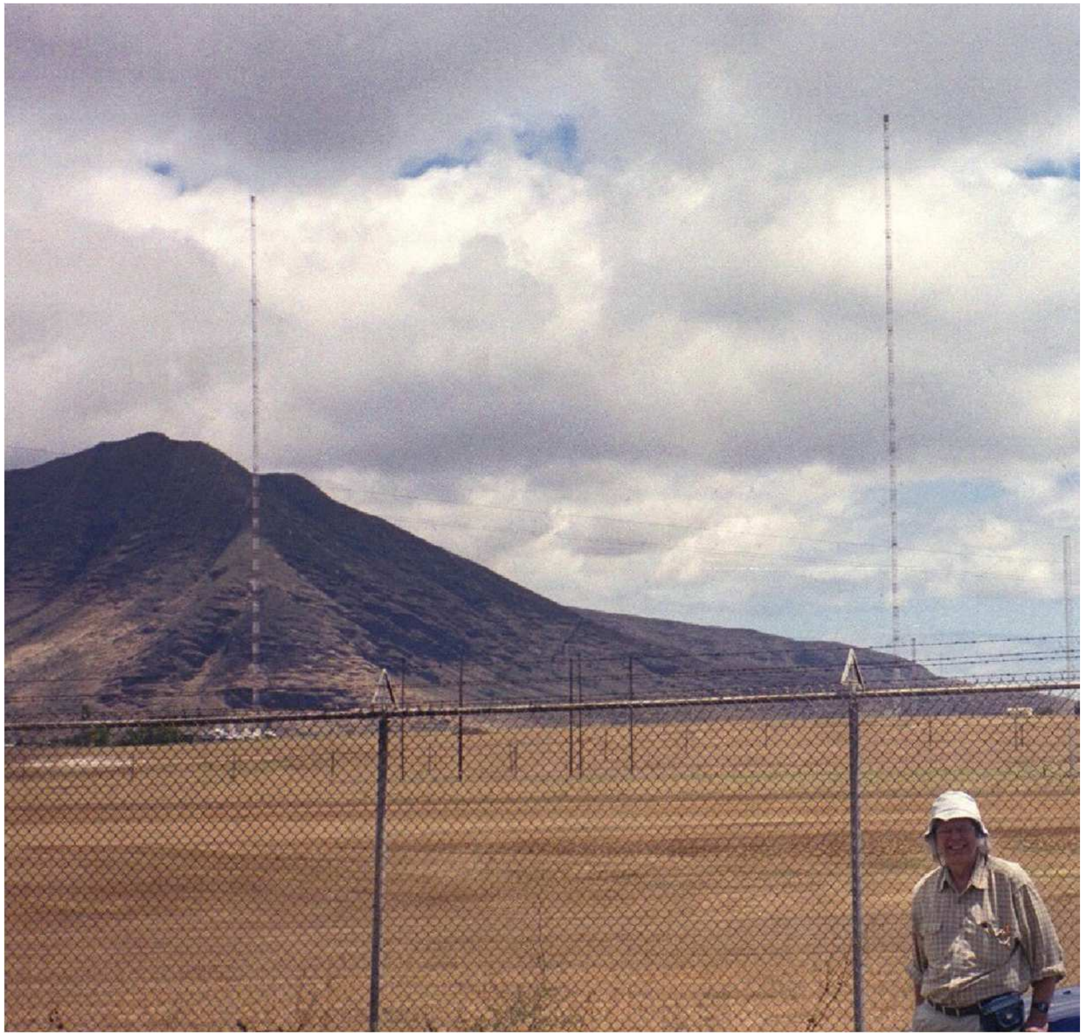
VLF remote sensing



VLF remote sensing

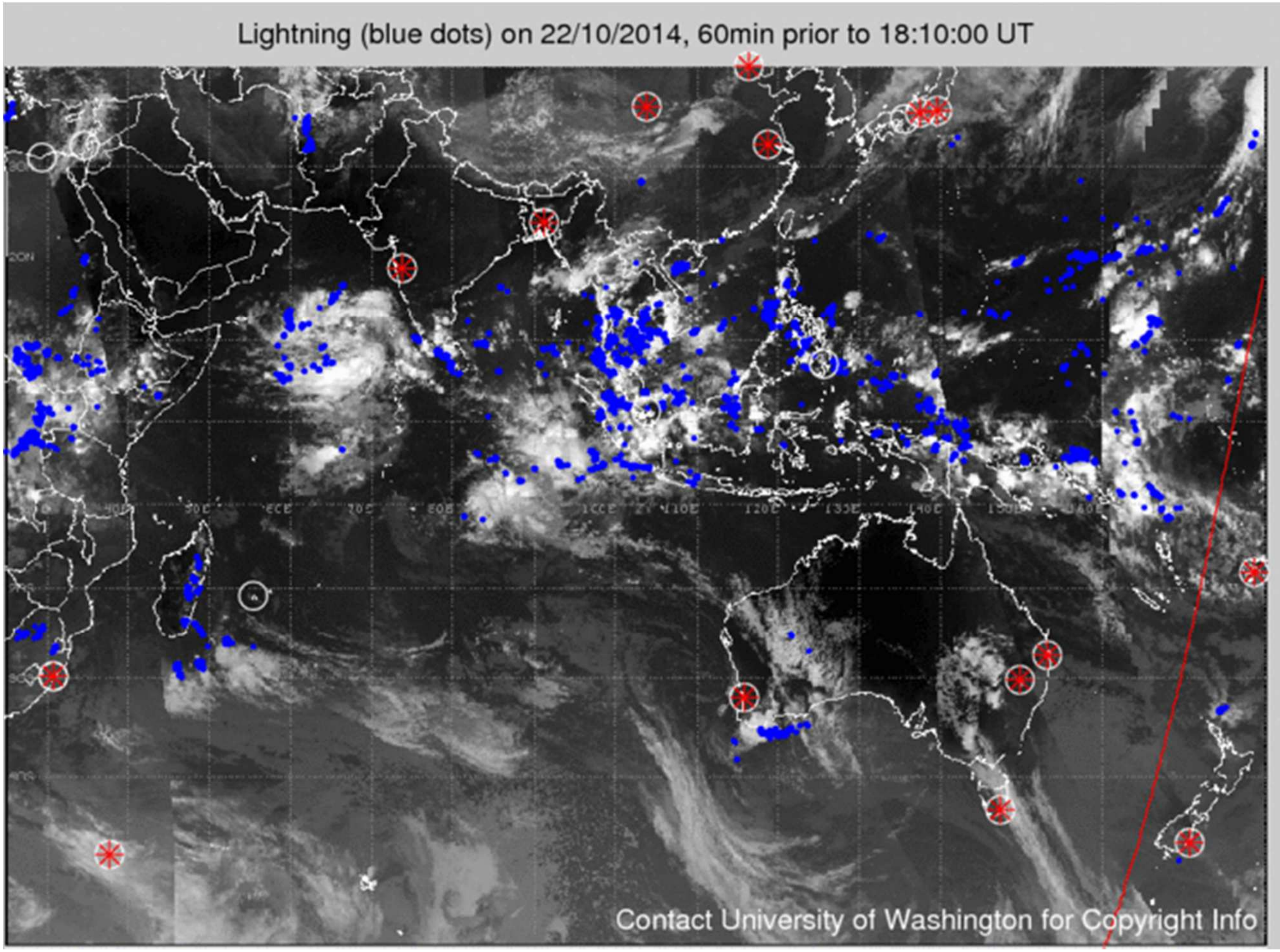


VLF remote sensing



US Navy VLF transmitter, at Lualualei, Hawaii. This transmitter has radiated power of ~500 kW operating at frequency of 21.4 kHz. The towers in the background are ~460 meters high each.

Storm monitoring using VLF signals



THANK YOU!