Radio wave scintillation:
Aspects of interest for ionospheric physics and radio astronomy

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(3) RAL STFC (UK)
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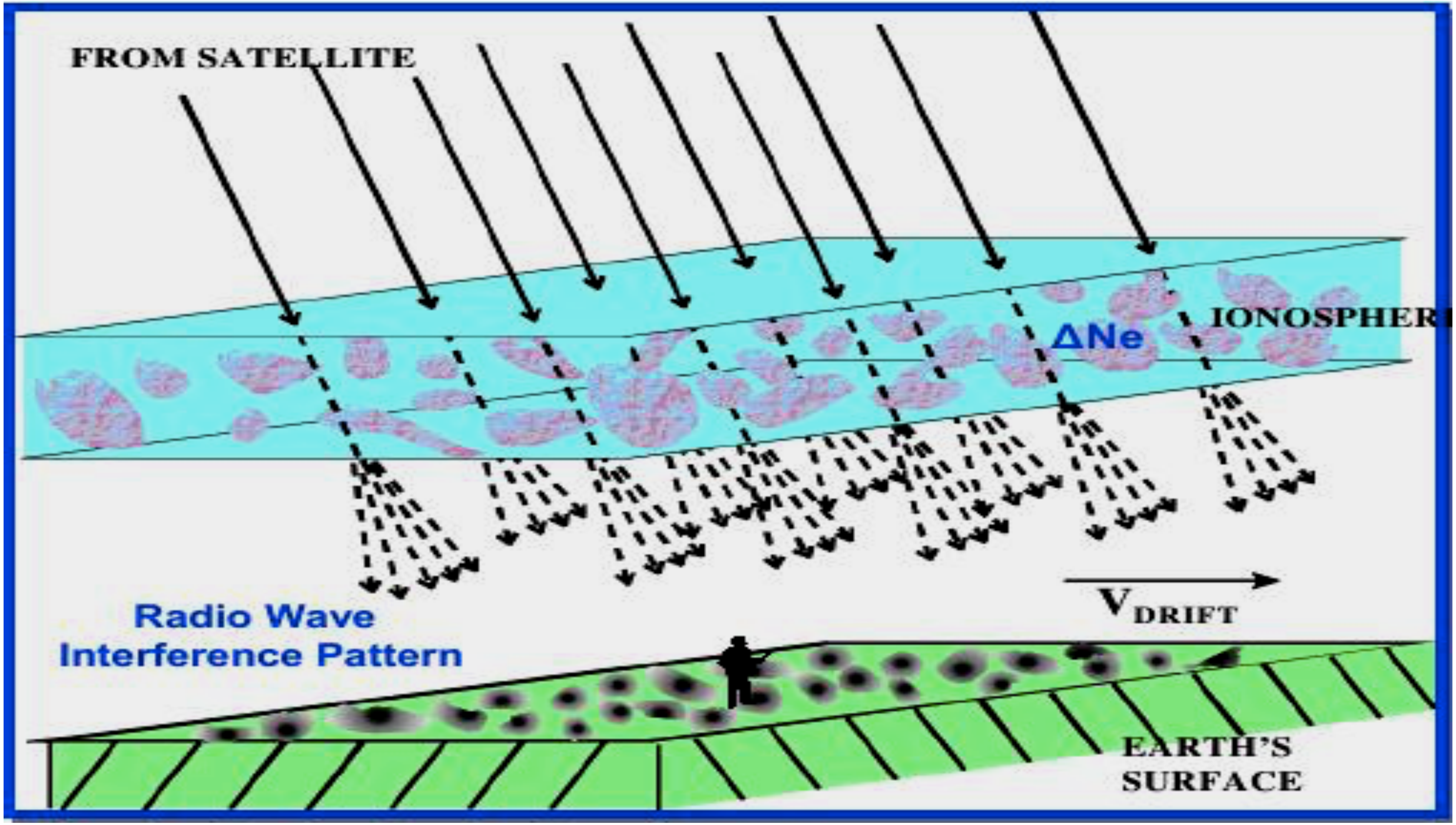
Radio Waves Scintillation – the problem



Methods for handling the problem

1 – Weak scattering (usually occurring with low scintillation)

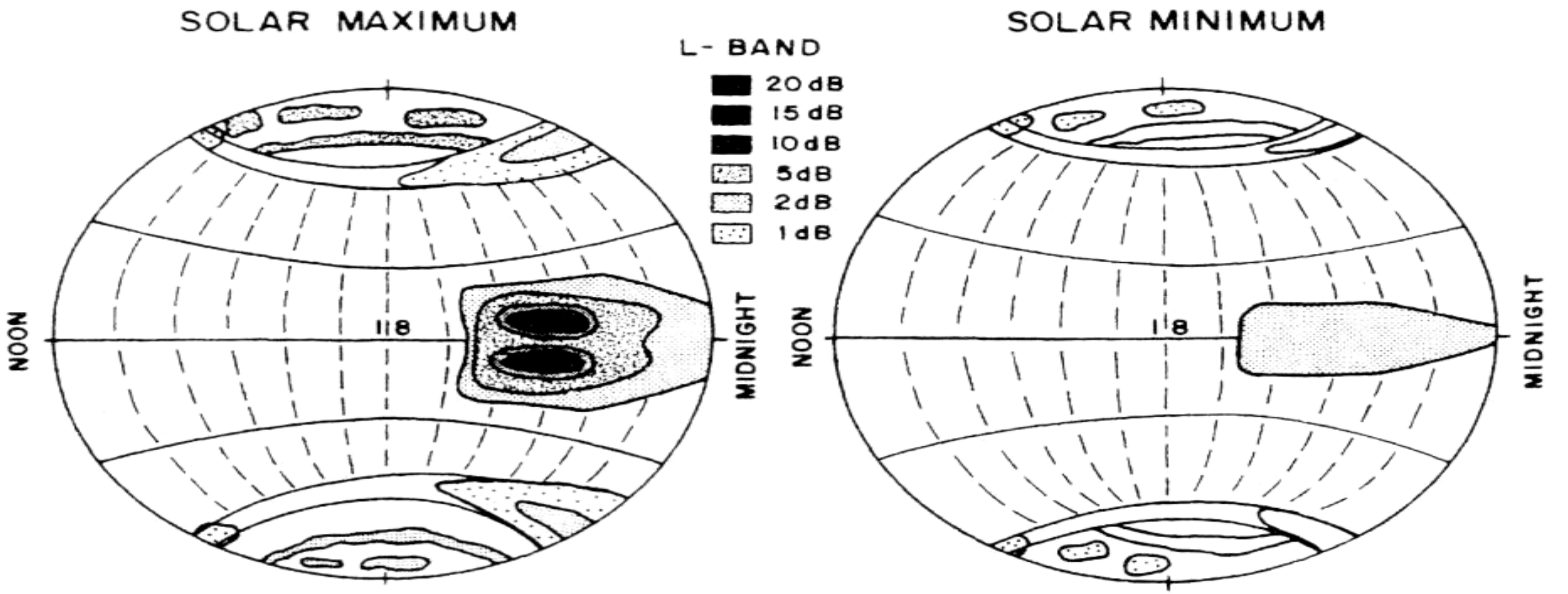
Thin phase screen. Weakly scattering medium. Single scattering. Leading to high scintillation if strong single scattering is assumed. Diffractive scattering. Caused by irregularities smaller than the Fresnel scale.

2 – Multiple scattering (usually occurring with high scintillation)

Thick phase screen. Weakly scattering medium. Multiple scattering. Refractive scattering. Caused by irregularities larger than the Fresnel scale. Focal scale starts to matter.

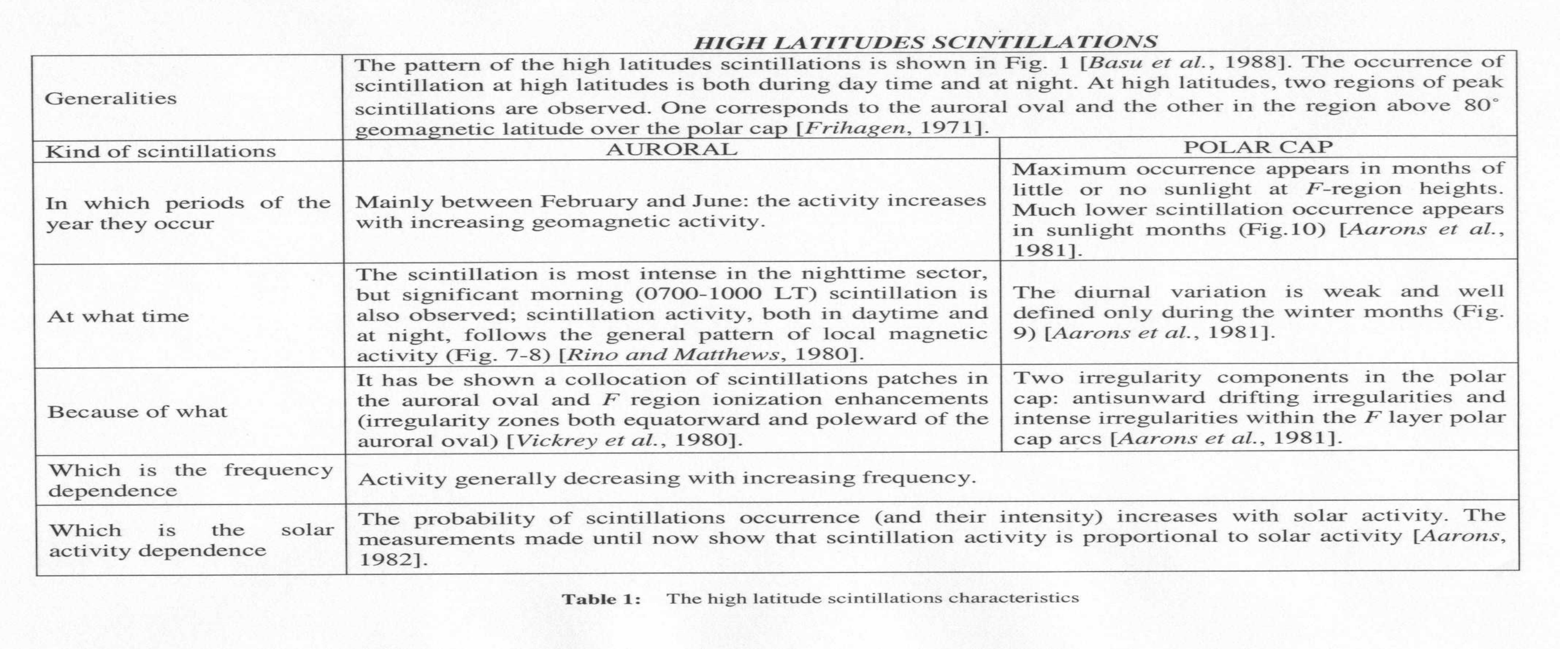
What is known from satellite data

Global morphology of ionospheric scintillations



Basu S., MacKenzie E. and Basu Su., Ionospheric constraints on VHF/UHF communications links during solar maximum and minimum periods, *Radio Sci.*, Vol. 23, N. 3, pp. 363-378, 1998

High Latitudes



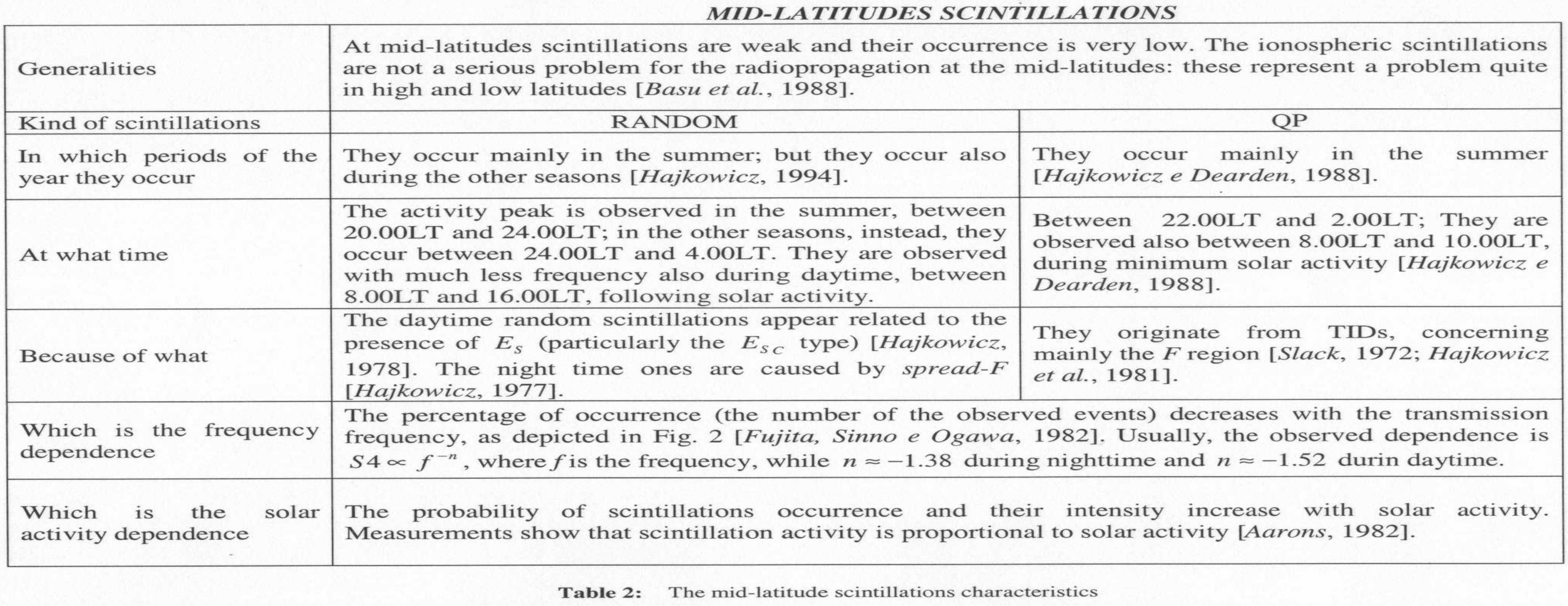
HIGH LATITUDES SCINTILLATIONS

Generalities	The pattern of the high latitudes scintillations is shown in Fig. 1 [*Basu et al.*, 1988]. The occurrence of scintillation at high latitudes is both during day time and at night. At high latitudes, two regions of peak scintillations are observed. One corresponds to the auroral oval and the other in the region above 80° geomagnetic latitude over the polar cap [*Frihagen*, 1971].	
Kind of scintillations	AURORAL	POLAR CAP
In which periods of the year they occur	Mainly between February and June: the activity increases with increasing geomagnetic activity.	Maximum occurrence appears in months of little or no sunlight at *F*-region heights. Much lower scintillation occurrence appears in sunlight months (Fig.10) [*Aarons et al.*, 1981].
At what time	The scintillation is most intense in the nighttime sector, but significant morning (0700-1000 LT) scintillation is also observed; scintillation activity, both in daytime and at night, follows the general pattern of local magnetic activity (Fig. 7-8) [*Rino and Matthews*, 1980].	The diurnal variation is weak and well defined only during the winter months (Fig. 9) [*Aarons et al.*, 1981].
Because of what	It has be shown a collocation of scintillations patches in the auroral oval and *F* region ionization enhancements (irregularity zones both equatorward and poleward of the auroral oval) [*Vickrey et al.*, 1980].	Two irregularity components in the polar cap: antisunward drifting irregularities and intense irregularities within the *F* layer polar cap arcs [*Aarons et al.*, 1981].
Which is the frequency dependence	Activity generally decreasing with increasing frequency.	
Which is the solar activity dependence	The probability of scintillations occurrence (and their intensity) increases with solar activity. The measurements made until now show that scintillation activity is proportional to solar activity [*Aarons*, 1982].	

Table 1: The high latitude scintillations characteristics

Forte et al, 2002

Middle Latitudes



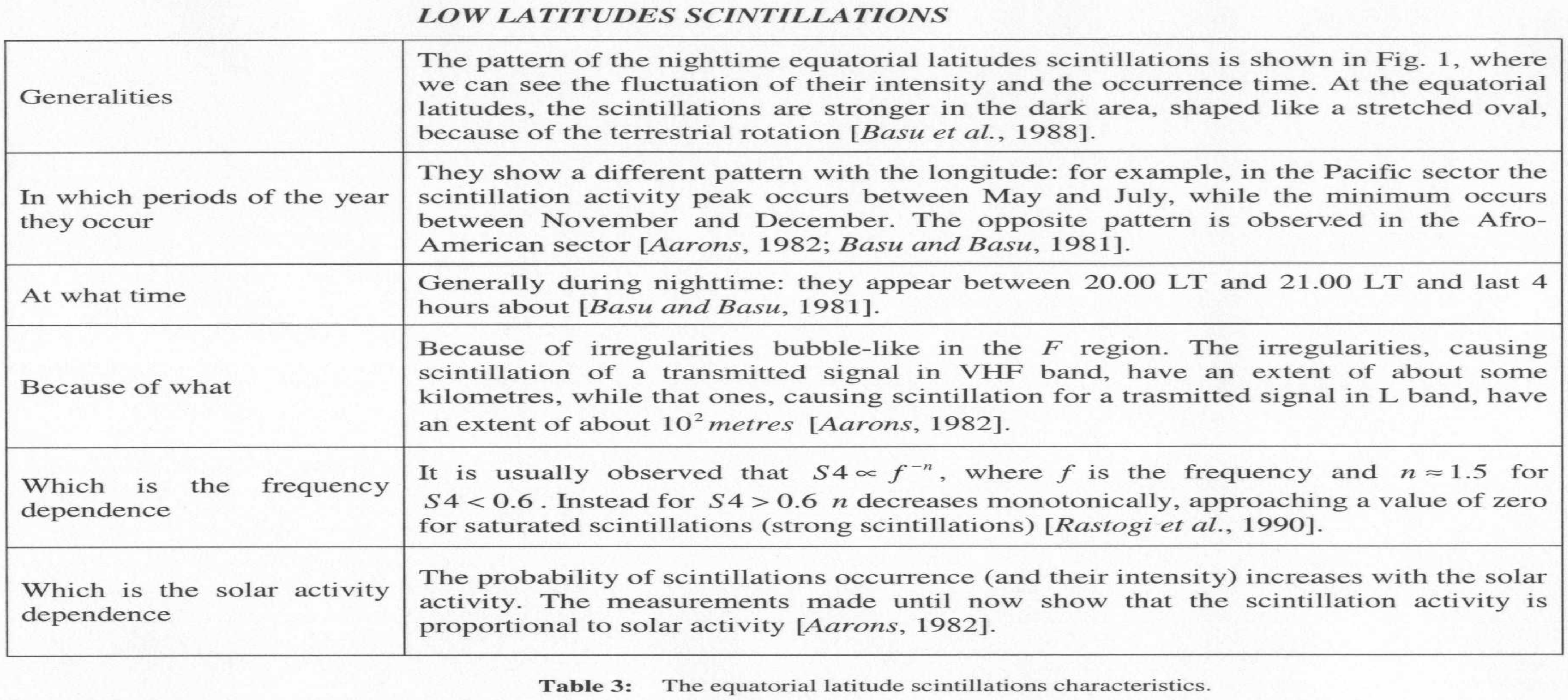
MID-LATITUDES SCINTILLATIONS

Generalities	At mid-latitudes scintillations are weak and their occurrence is very low. The ionospheric scintillations are not a serious problem for the radiopropagation at the mid-latitudes: these represent a problem quite in high and low latitudes [*Basu et al.*, 1988].	
Kind of scintillations	RANDOM	QP
In which periods of the year they occur	They occur mainly in the summer; but they occur also during the other seasons [*Hajkowicz*, 1994].	They occur mainly in the summer [*Hajkowicz e Dearden*, 1988].
At what time	The activity peak is observed in the summer, between 20.00LT and 24.00LT; in the other seasons, instead, they occur between 24.00LT and 4.00LT. They are observed with much less frequency also during daytime, between 8.00LT and 16.00LT, following solar activity.	Between 22.00LT and 2.00LT; They are observed also between 8.00LT and 10.00LT, during minimum solar activity [*Hajkowicz e Dearden*, 1988].
Because of what	The daytime random scintillations appear related to the presence of E_s (particularly the E_{sC} type) [*Hajkowicz*, 1978]. The night time ones are caused by *spread-F* [*Hajkowicz*, 1977].	They originate from TIDs, concerning mainly the *F* region [*Slack*, 1972; *Hajkowicz et al.*, 1981].
Which is the frequency dependence	The percentage of occurrence (the number of the observed events) decreases with the transmission frequency, as depicted in Fig. 2 [*Fujita, Sinno e Ogawa*, 1982]. Usually, the observed dependence is $S4 \propto f^{-n}$, where f is the frequency, while $n \approx -1.38$ during nighttime and $n \approx -1.52$ durin daytime.	
Which is the solar activity dependence	The probability of scintillations occurrence and their intensity increase with solar activity. Measurements show that scintillation activity is proportional to solar activity [*Aarons*, 1982].	

Table 2: The mid-latitude scintillations characteristics

Forte et al, 2002

Low Latitudes



LOW LATITUDES SCINTILLATIONS

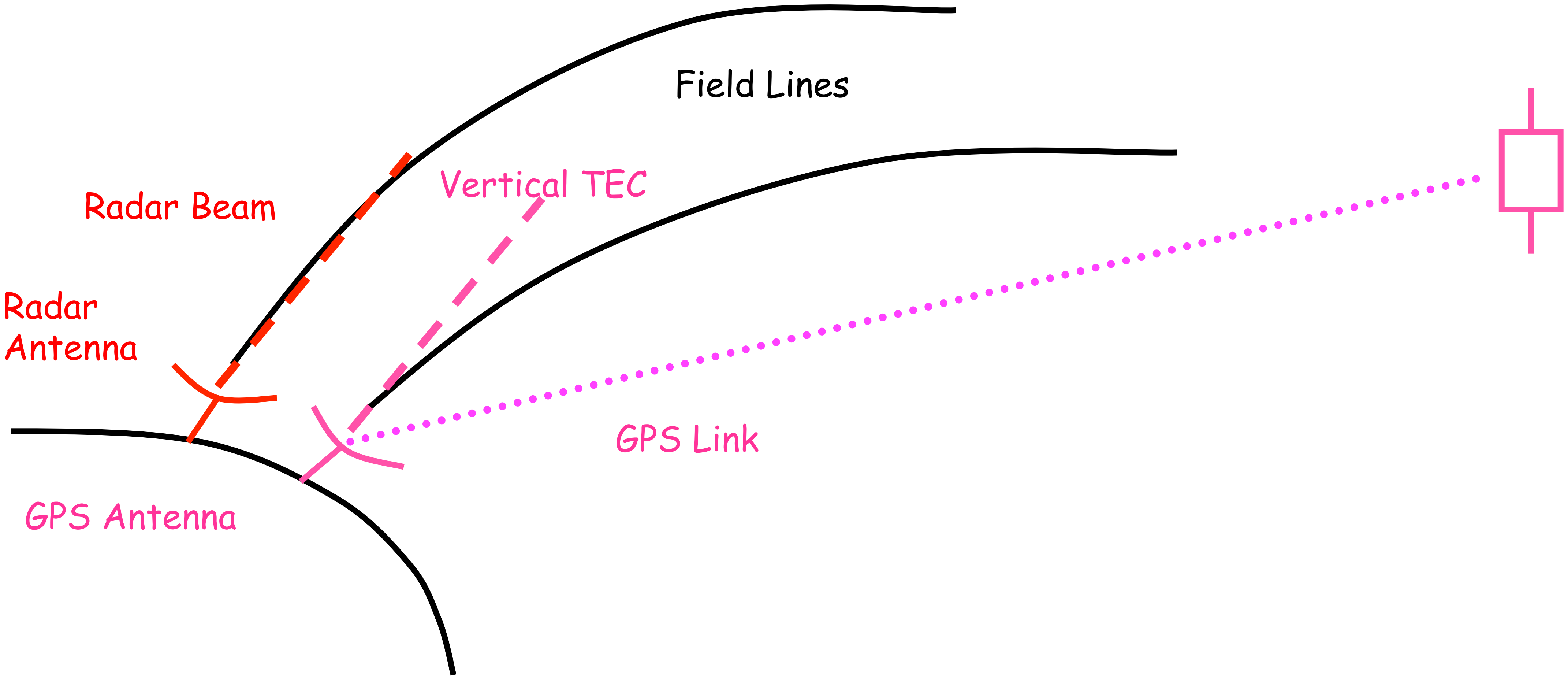
Generalities	The pattern of the nighttime equatorial latitudes scintillations is shown in Fig. 1, where we can see the fluctuation of their intensity and the occurrence time. At the equatorial latitudes, the scintillations are stronger in the dark area, shaped like a stretched oval, because of the terrestrial rotation [*Basu et al.*, 1988].
In which periods of the year they occur	They show a different pattern with the longitude: for example, in the Pacific sector the scintillation activity peak occurs between May and July, while the minimum occurs between November and December. The opposite pattern is observed in the Afro-American sector [*Aarons*, 1982; *Basu and Basu*, 1981].
At what time	Generally during nighttime: they appear between 20.00 LT and 21.00 LT and last 4 hours about [*Basu and Basu*, 1981].
Because of what	Because of irregularities bubble-like in the F region. The irregularities, causing scintillation of a transmitted signal in VHF band, have an extent of about some kilometres, while that ones, causing scintillation for a trasmitted signal in L band, have an extent of about 10^2 *metres* [*Aarons*, 1982].
Which is the frequency dependence	It is usually observed that $S4 \propto f^{-n}$, where f is the frequency and $n \approx 1.5$ for $S4 < 0.6$. Instead for $S4 > 0.6$ n decreases monotonically, approaching a value of zero for saturated scintillations (strong scintillations) [*Rastogi et al.*, 1990].
Which is the solar activity dependence	The probability of scintillations occurrence (and their intensity) increases with the solar activity. The measurements made until now show that the scintillation activity is proportional to solar activity [*Aarons*, 1982].

Table 3: The equatorial latitude scintillations characteristics.

Forte et al, 2002

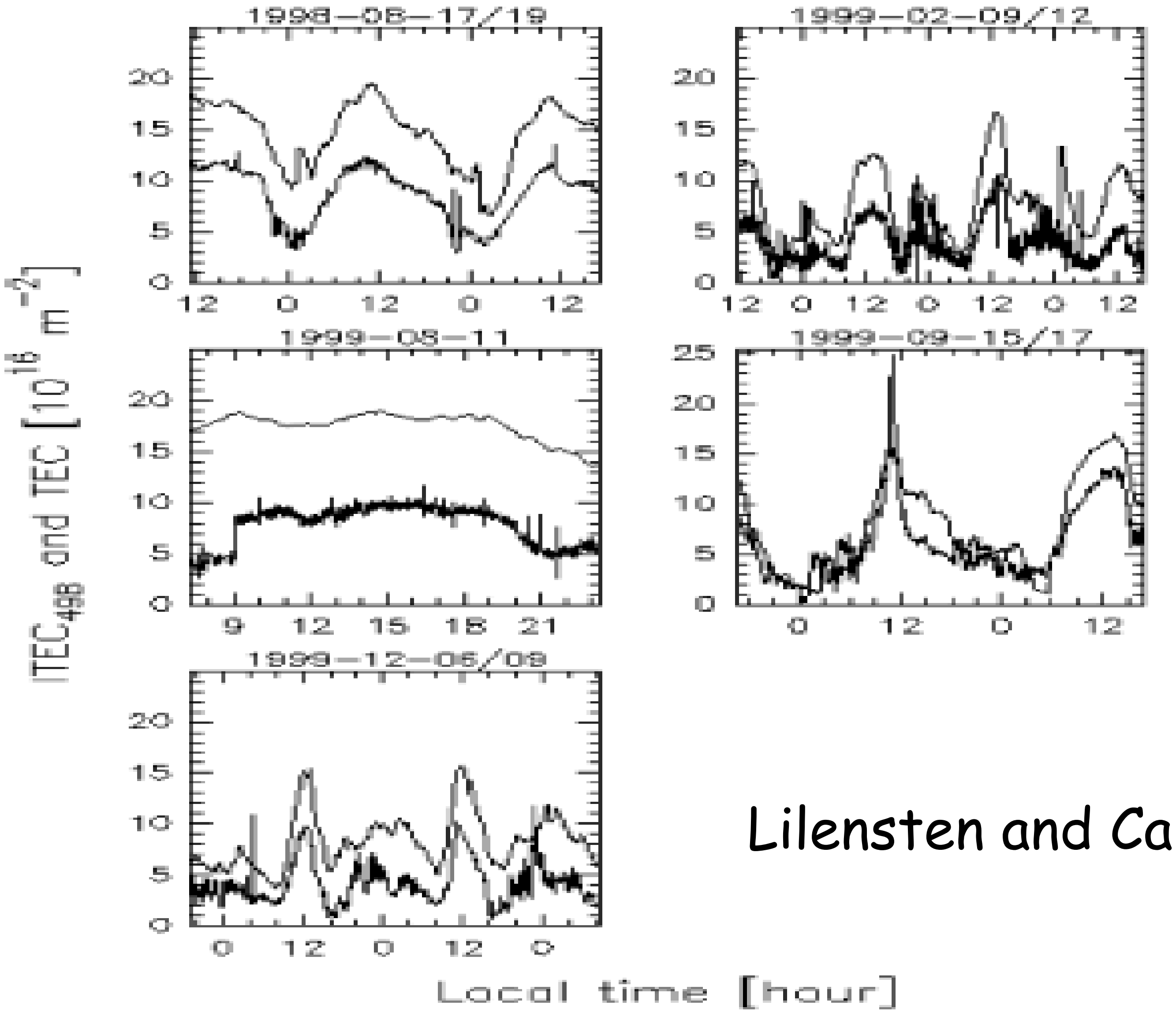
TEC Estimates from different instruments:
EISCAT vs GPS

Previous studies



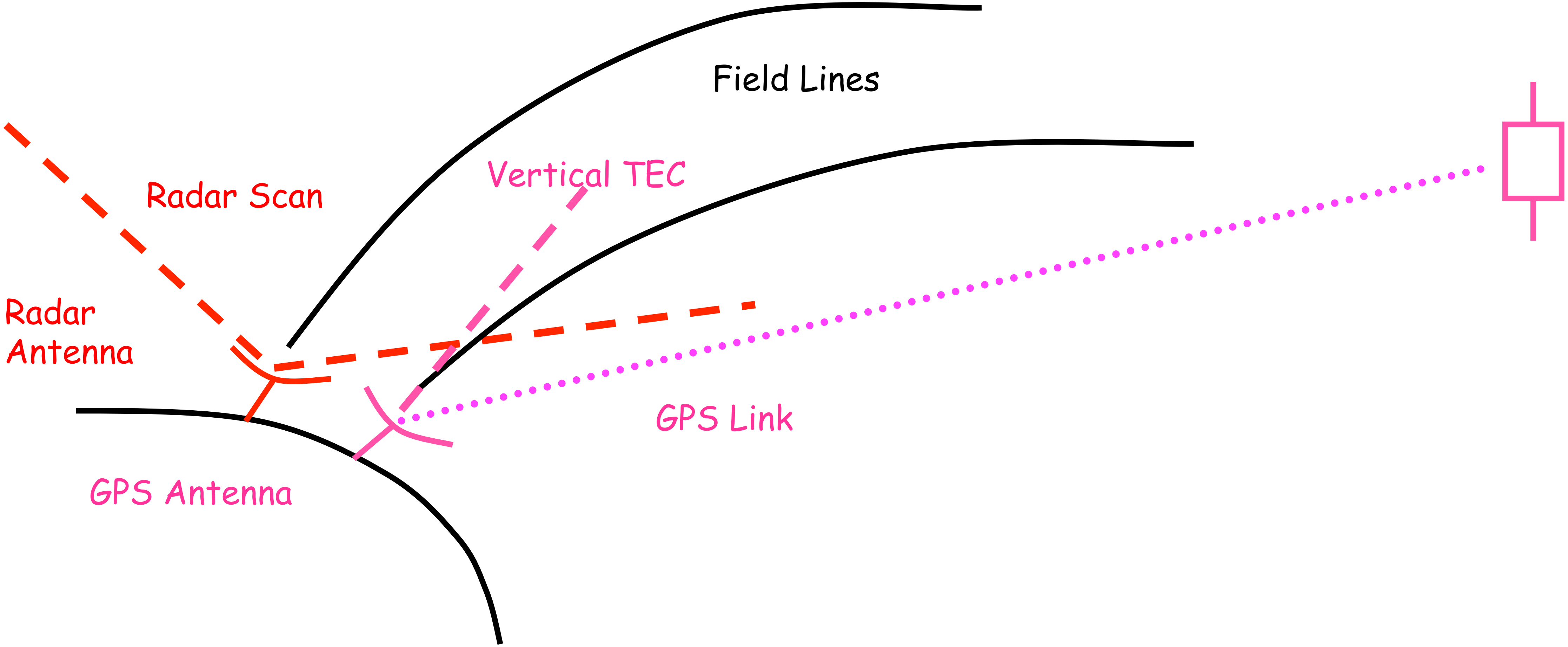
Lilensten and Cander, 2003

Previous studies



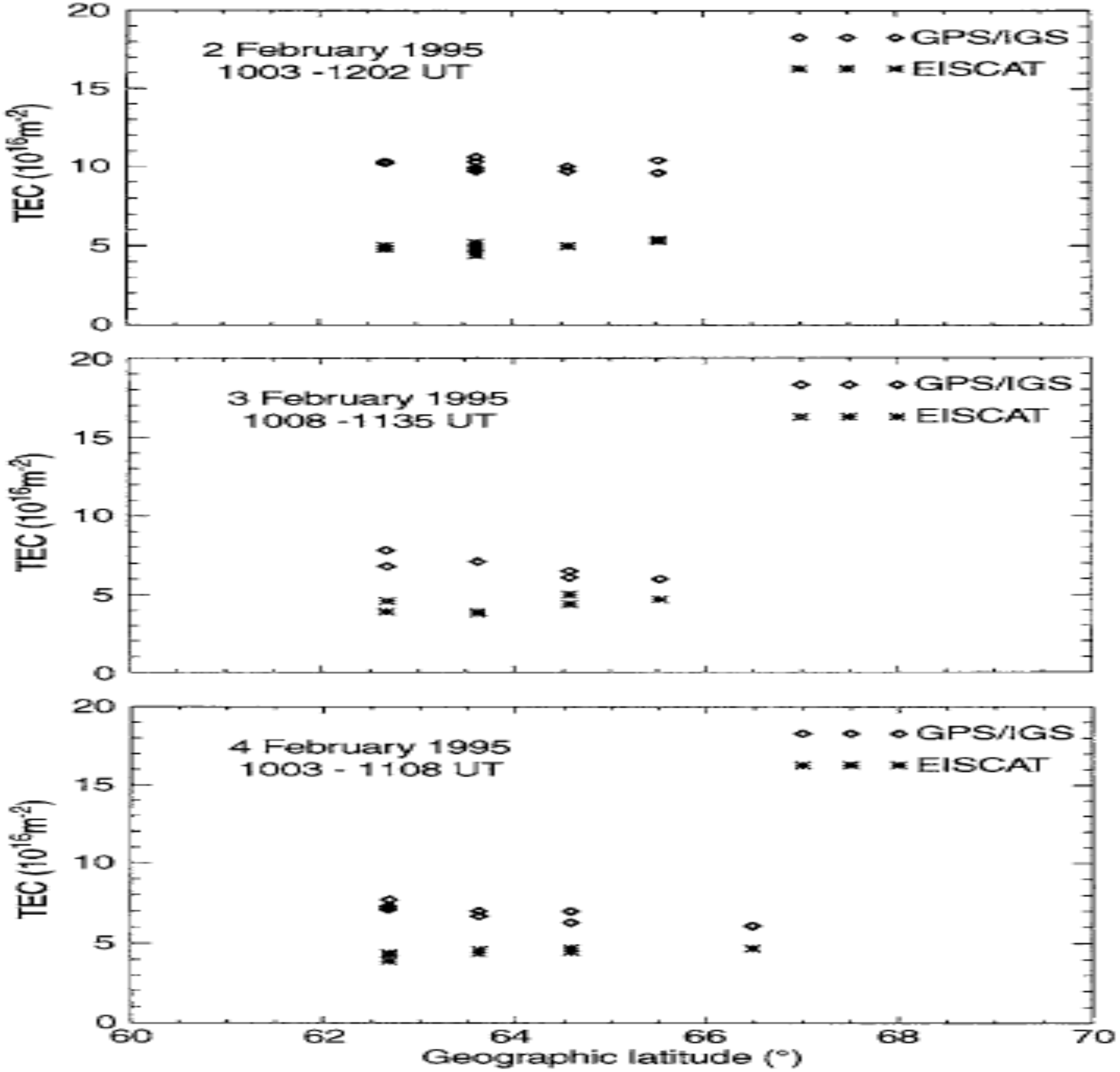
Lilensten and Cander, 2003

Previous studies



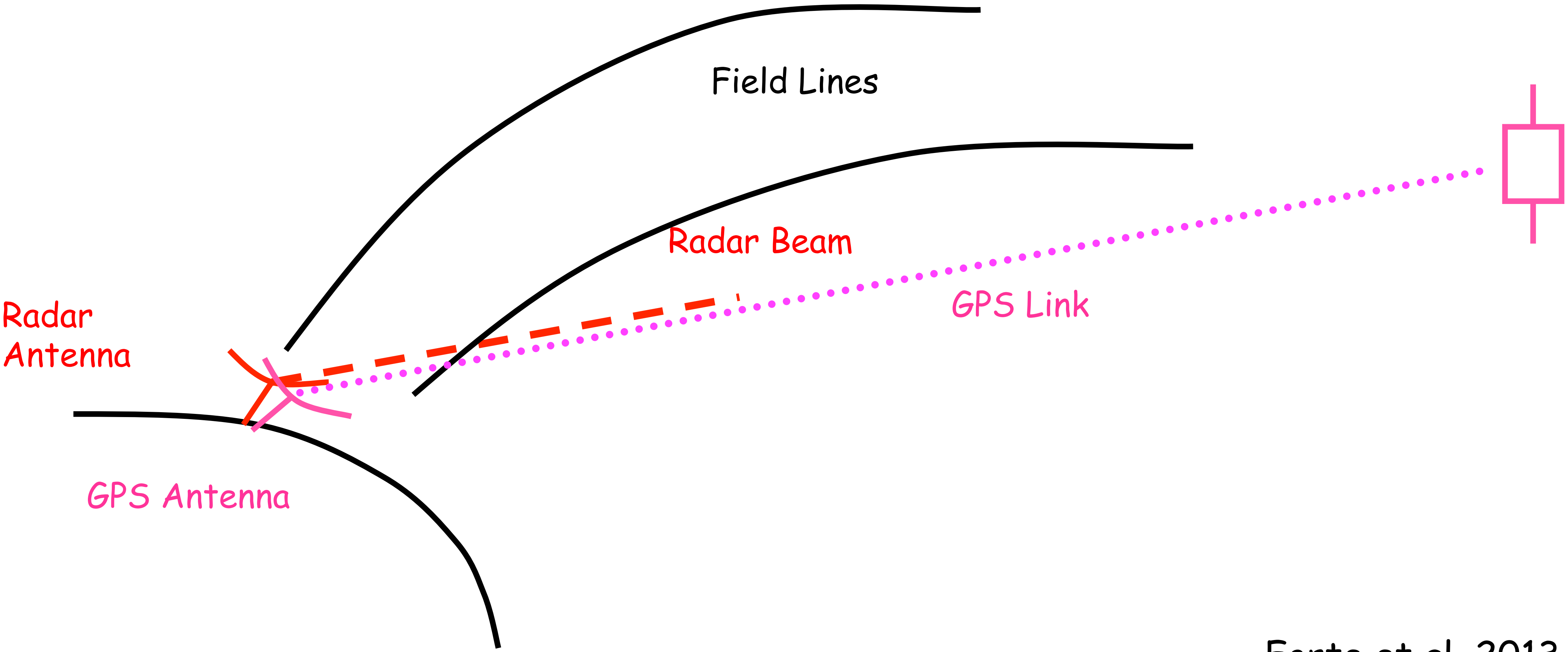
Jakowski et al, 1996

Previous studies



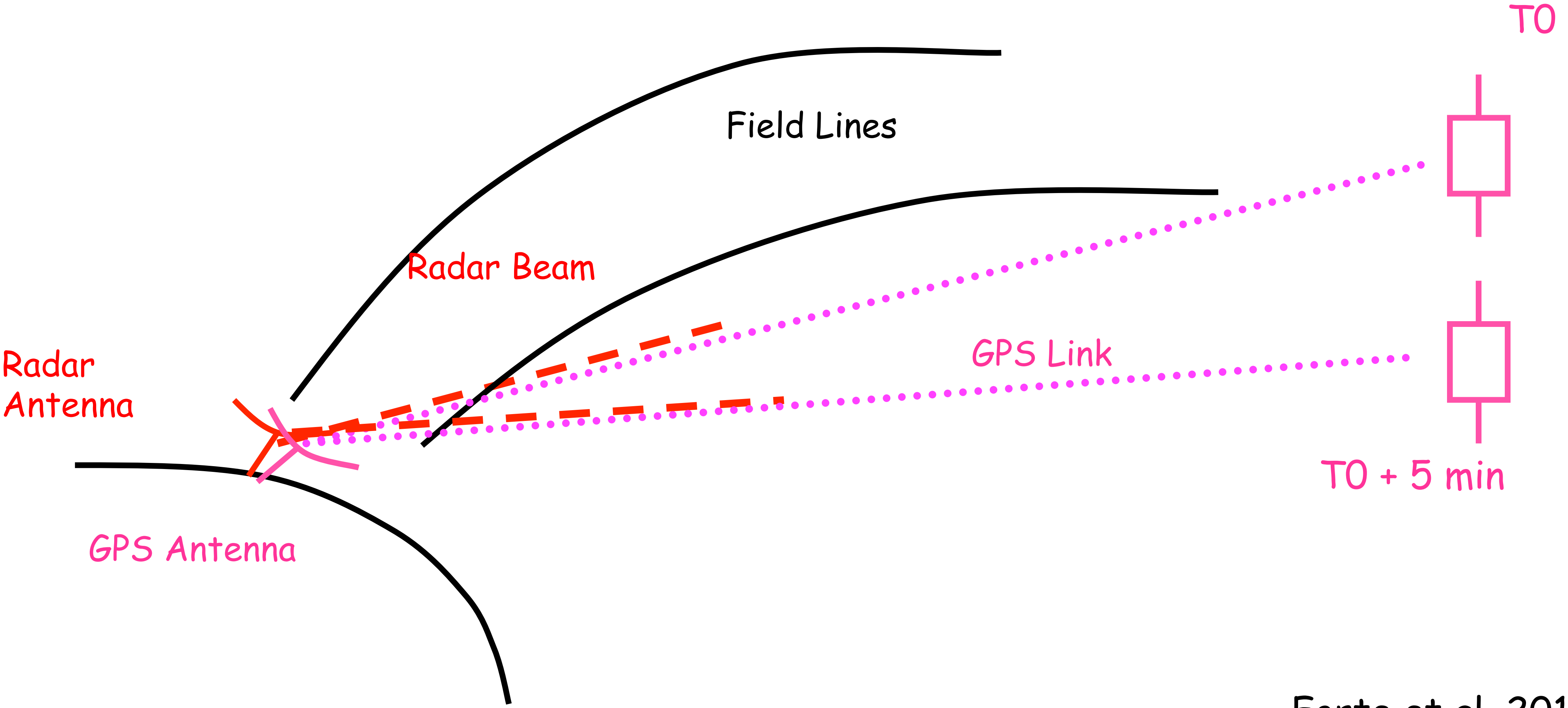
Jakowski et al, 1996

EISCAT measurement geometry – new experiment



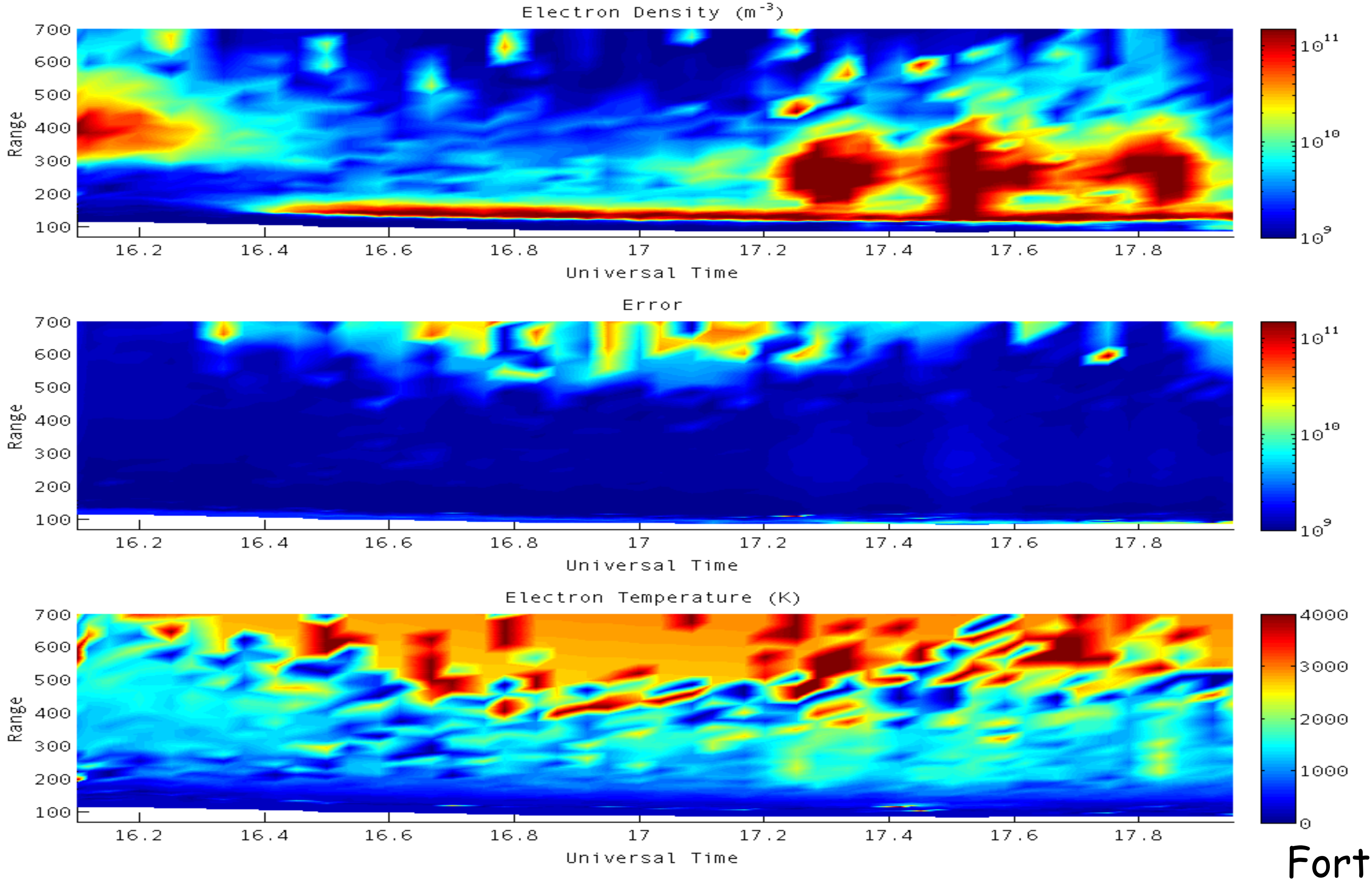
Forte et al, 2013

EISCAT measurement geometry – new experiment



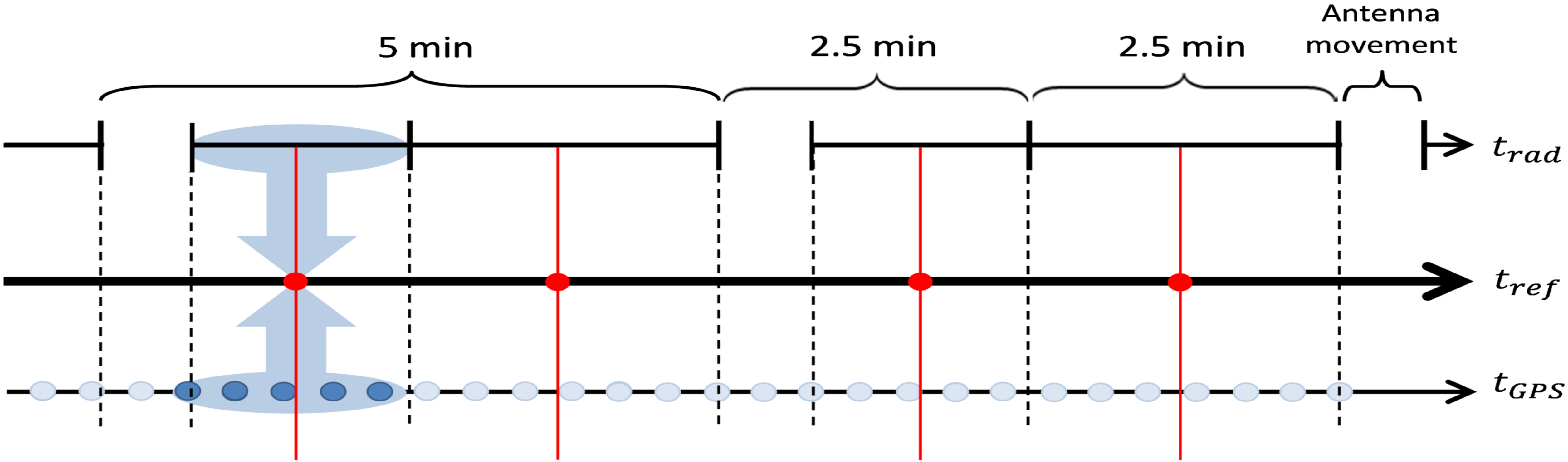
Forte et al, 2013

Electron density profiles – 150 sec average



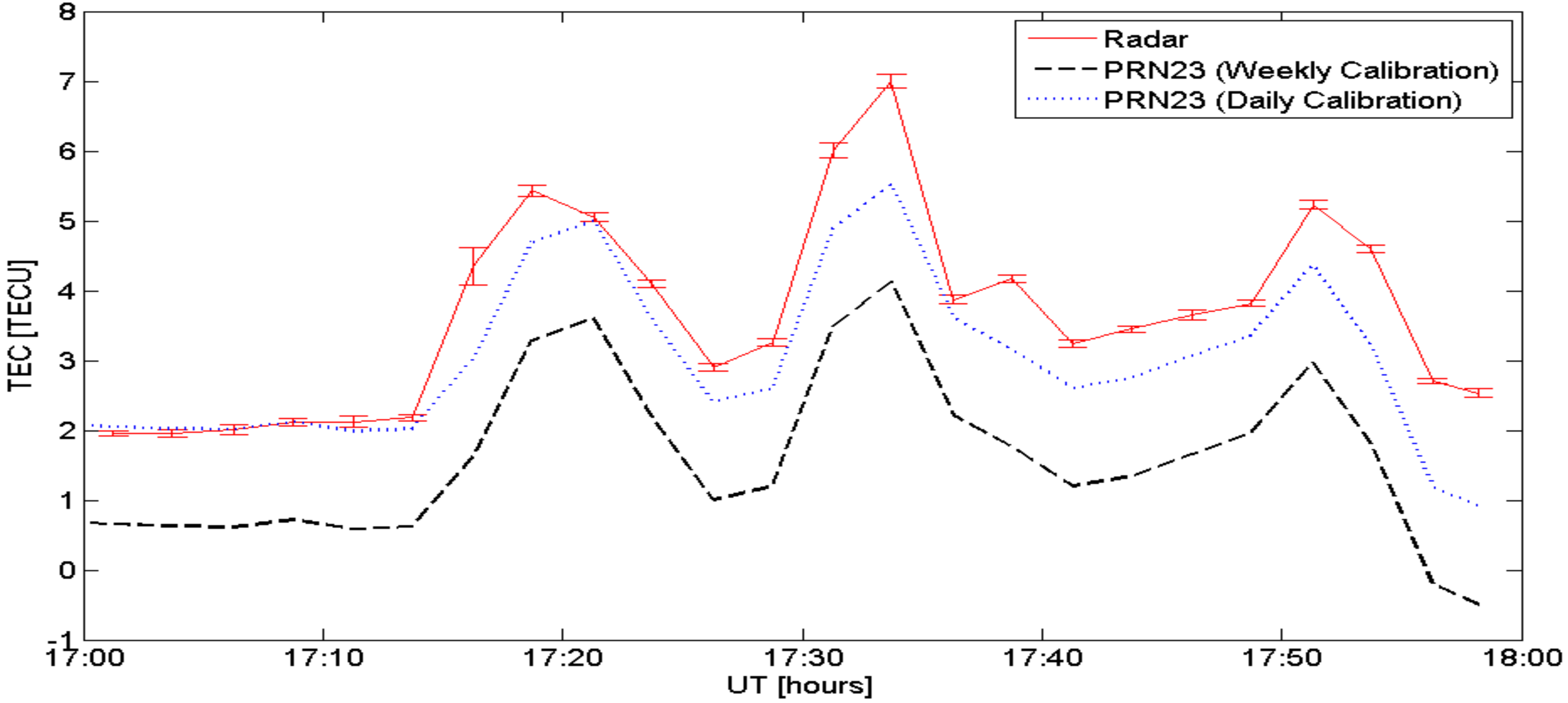
Forte et al, 2013

Time alignment



Forte et al, 2013

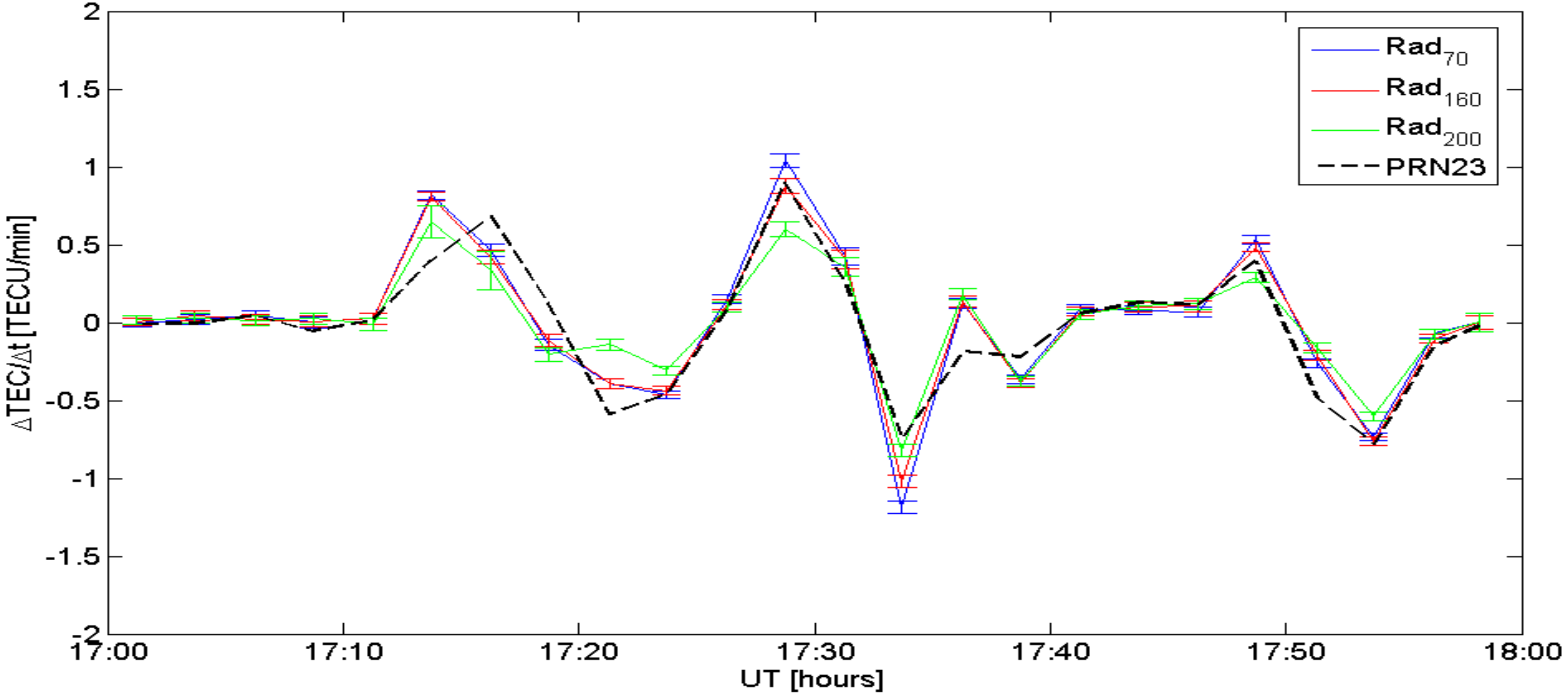
TEC: EISCAT vs GPS



Tromso, 12 December 2011

Forte et al, 2013

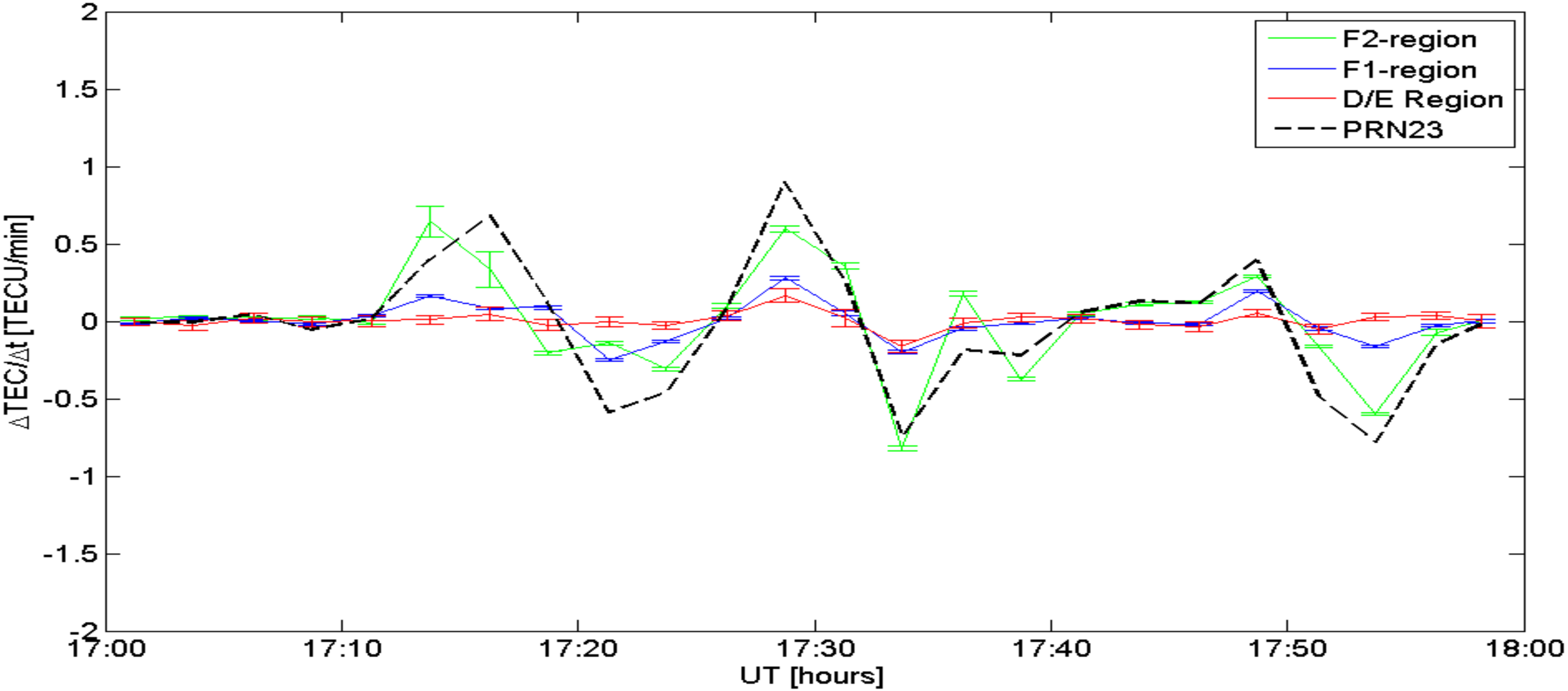
TEC Fluctuations: EISCAT vs GPS



Tromso, 12 December 2011

Forte et al, 2013

TEC Fluctuations: EISCAT vs GPS



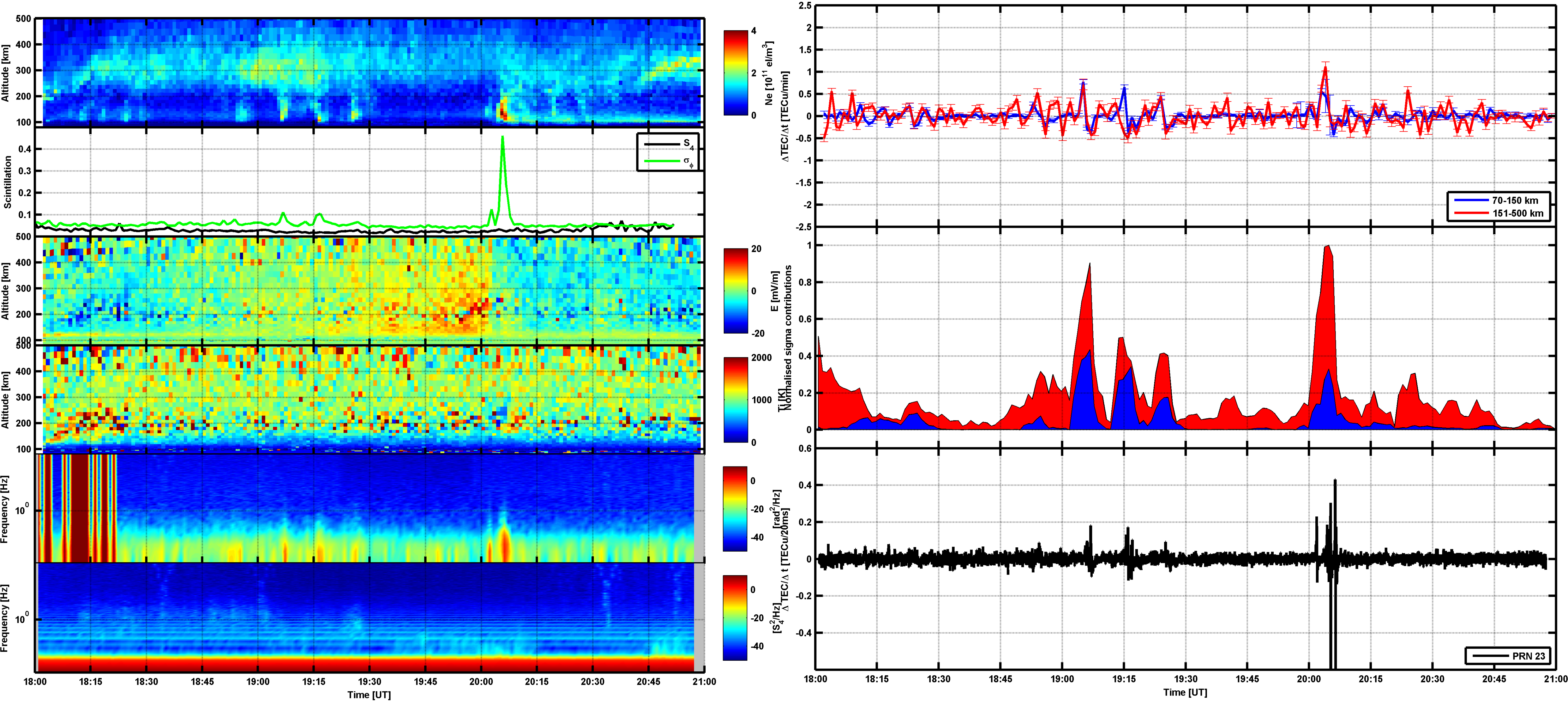
Tromso, 12 December 2011

Forte et al, 2013

Origin of L-band scintillation:
EISCAT and GPS

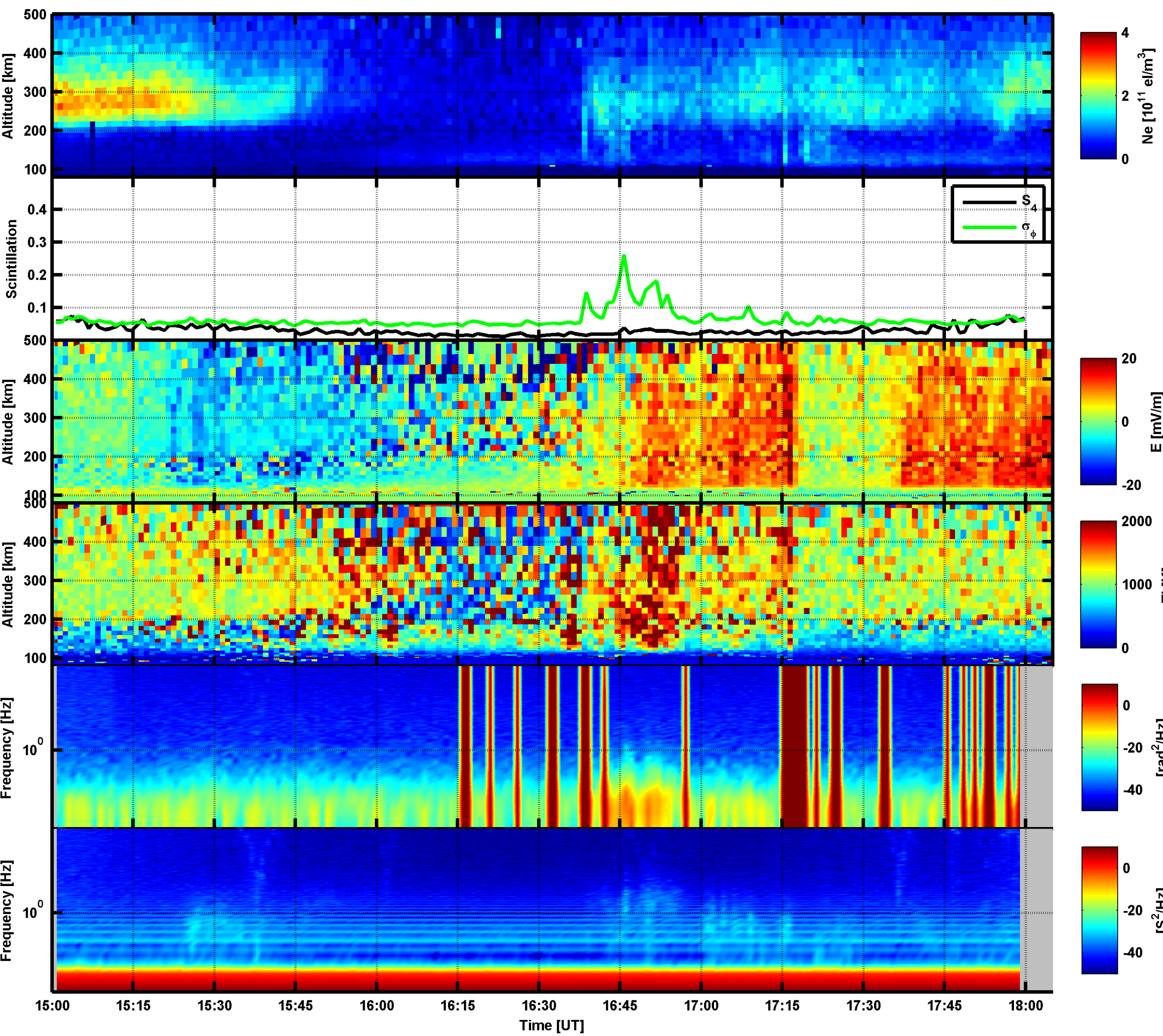
17 October 2013

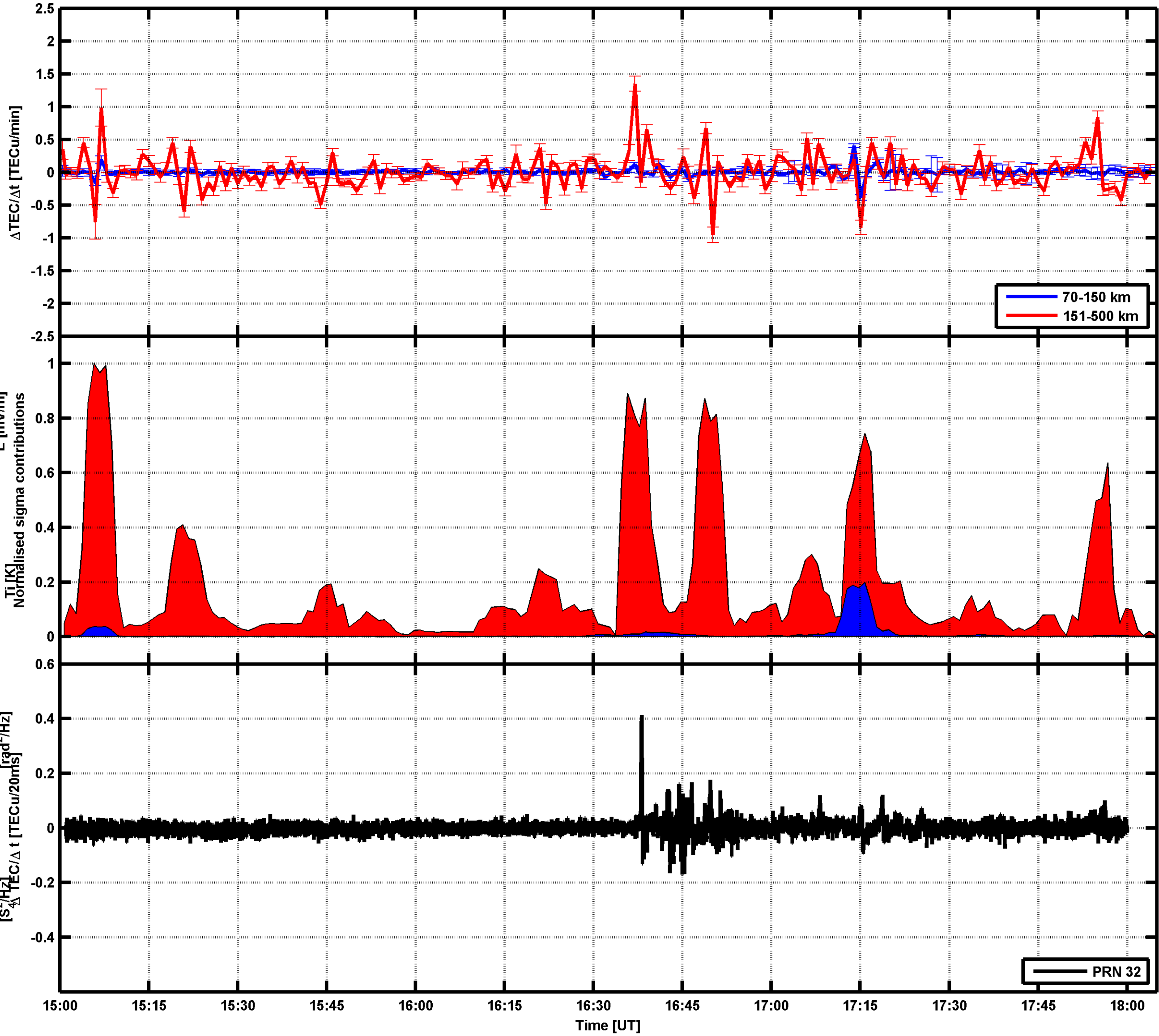
Forte et al, 2016
under final review



16 October 2013

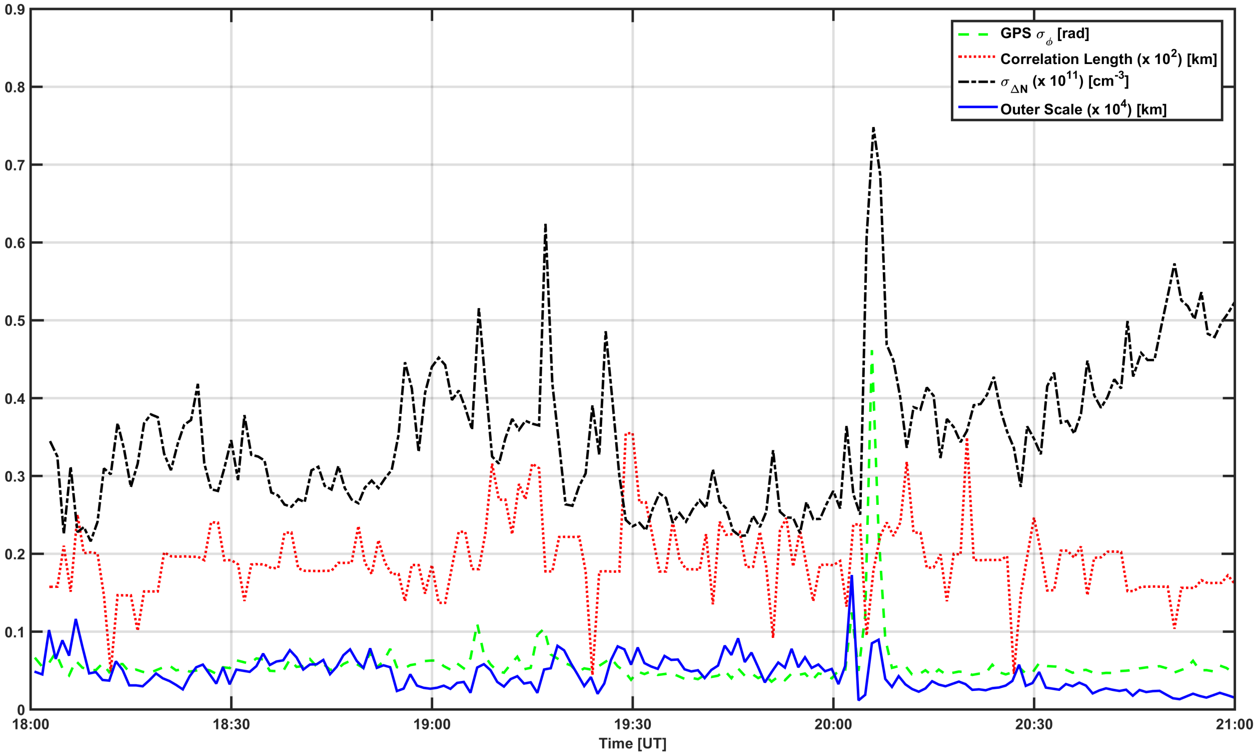
Forte et al, 2016
under final review

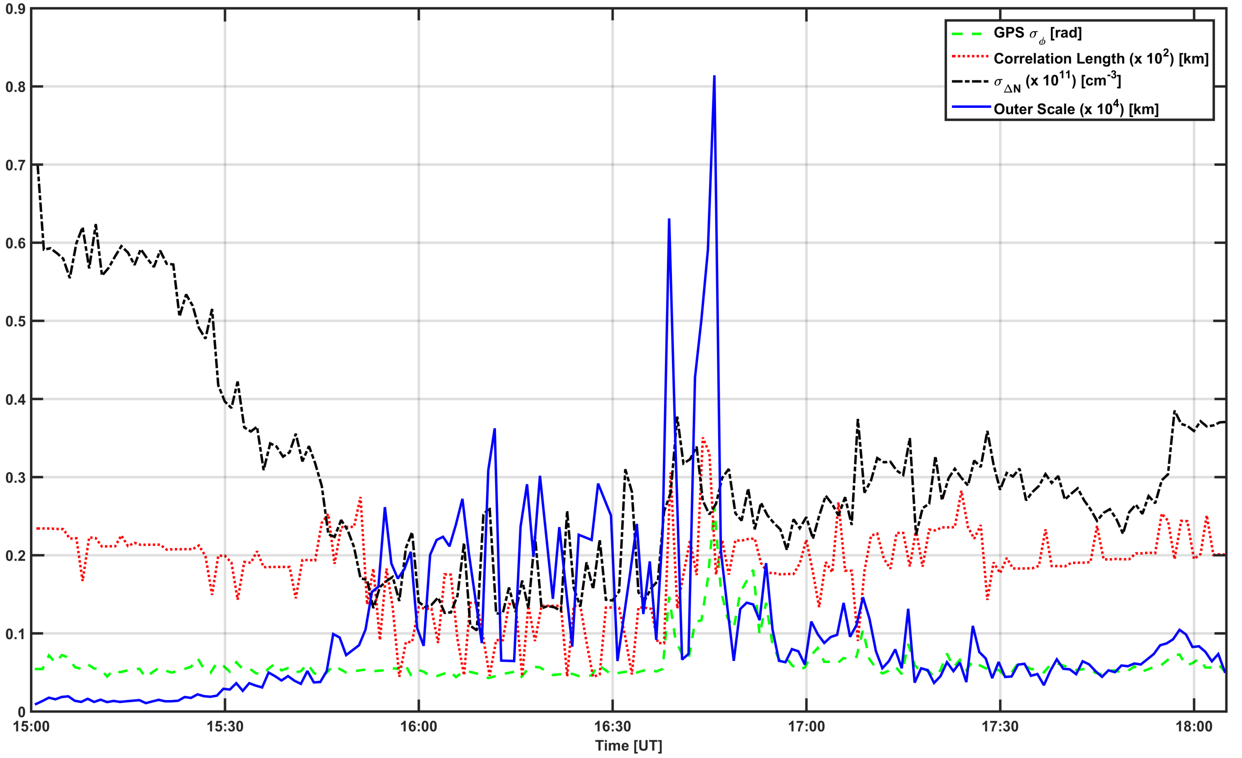




Structure function

Forte et al, 2016
under final review





17 October 2013

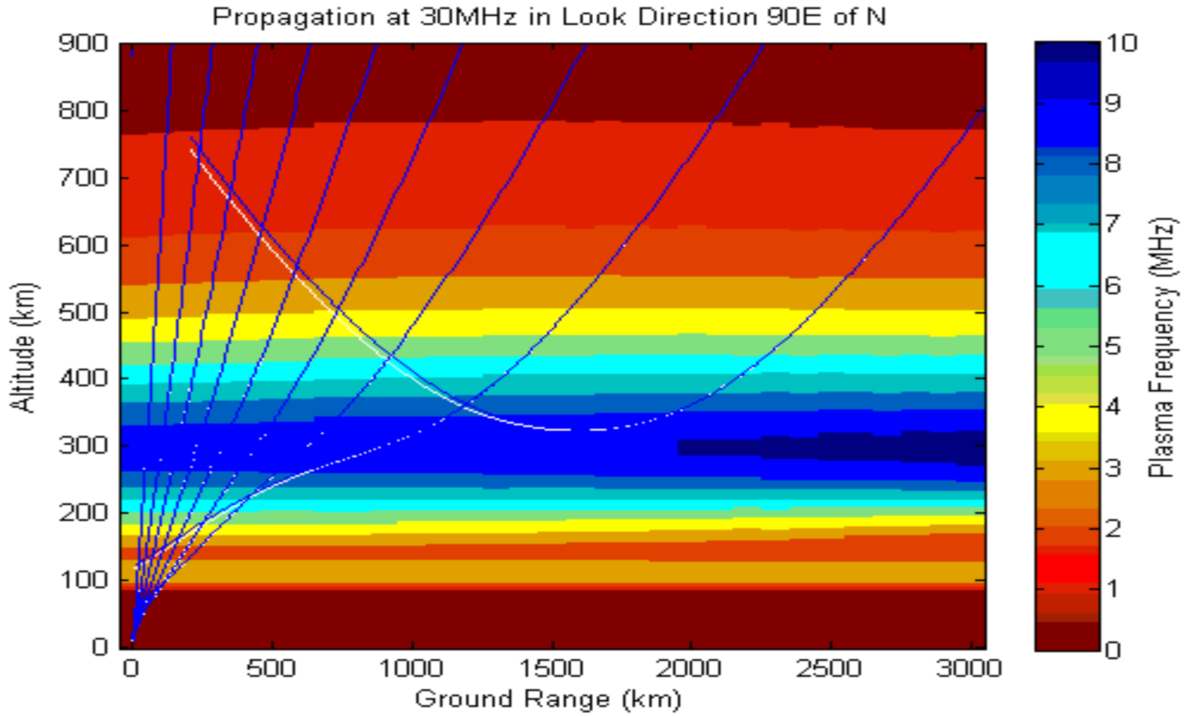
16 October 2013

Examples of the effects of the ionosphere on LOFAR

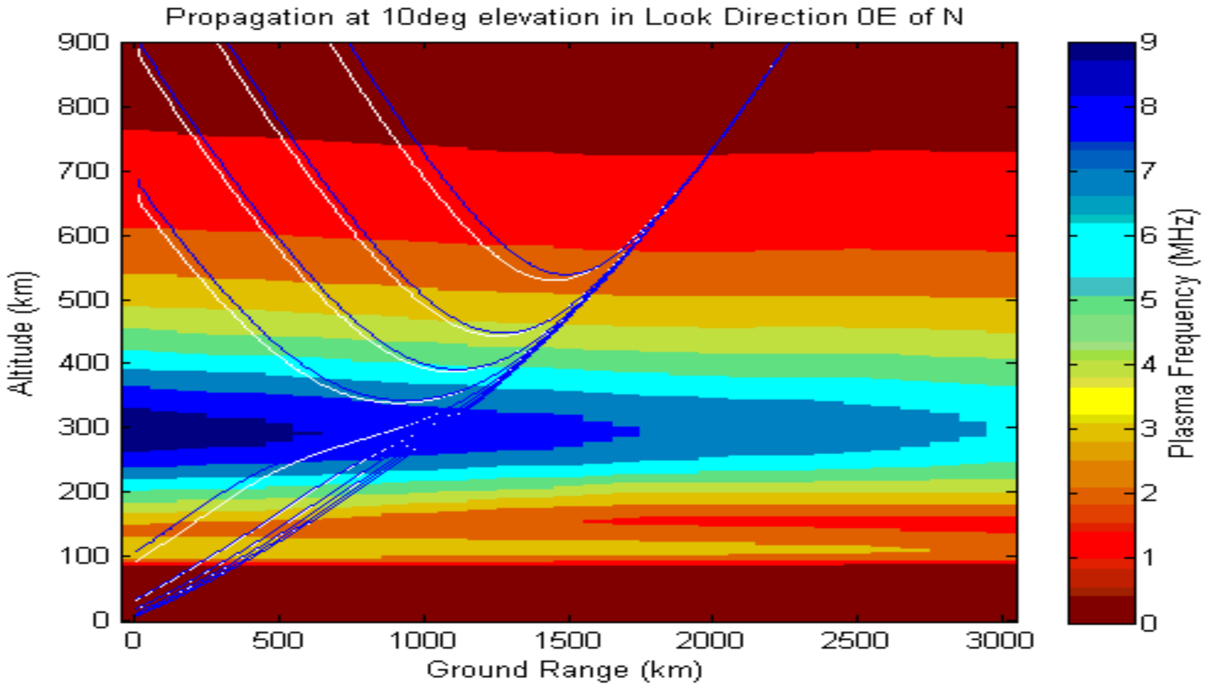
The Effect of the Ionsphere on LOFAR

Coleman, Forte et al, 2016 under preparation

- Ionosphere can severely affect radio signals at low frequencies.
- Below are signal paths that would land at origin without ionosphere.



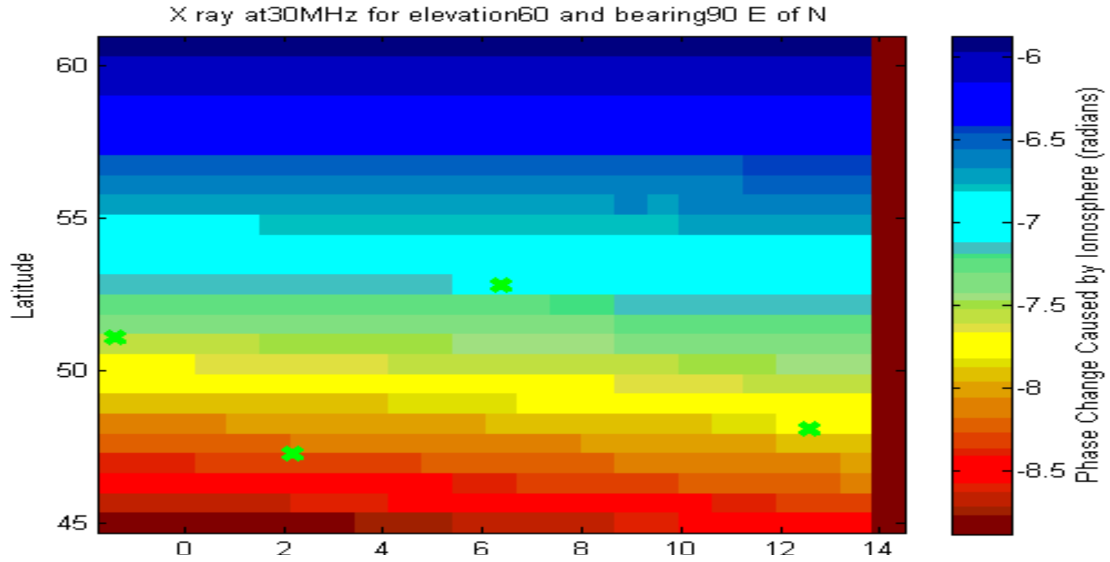
- In particular, if frequency too low, signals cannot penetrate ionsophere.
- Below are low angle paths from 5MHz to 50Mhz (no penetration below 20MHz).

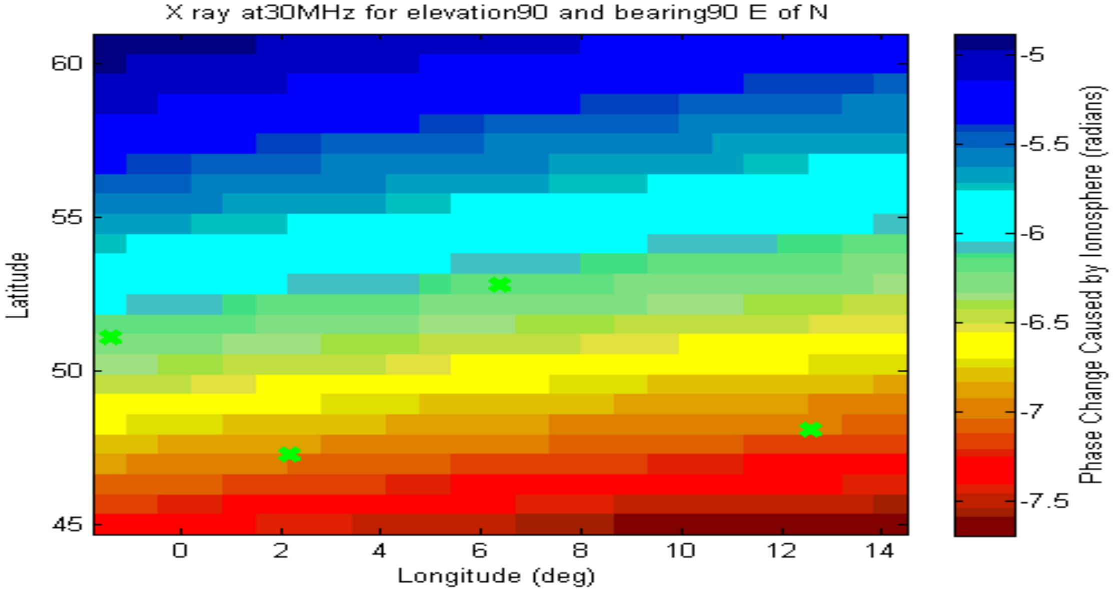


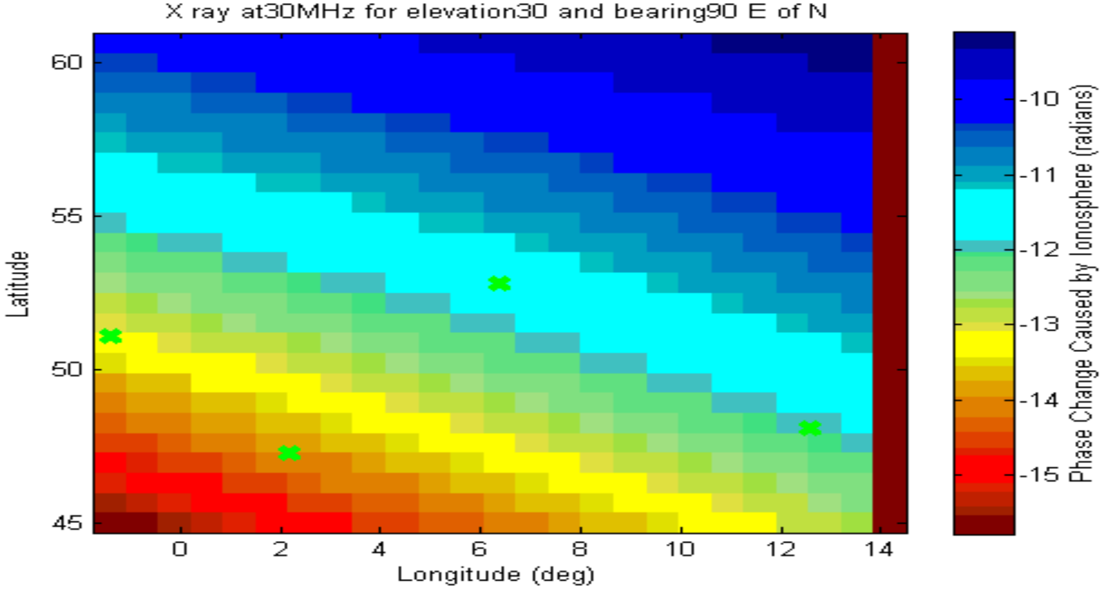
The Effect of the Ionosphere on Phase

Coleman, Forte et al,
2016 under preparation

- Figures show the phase corrections for angles of 0°, 30° and 60° from vertical.
- Major LOFAR sites marked as crosses. Considerable variation across array.


X ray at30MHz for elevation60 and bearing90 E of N

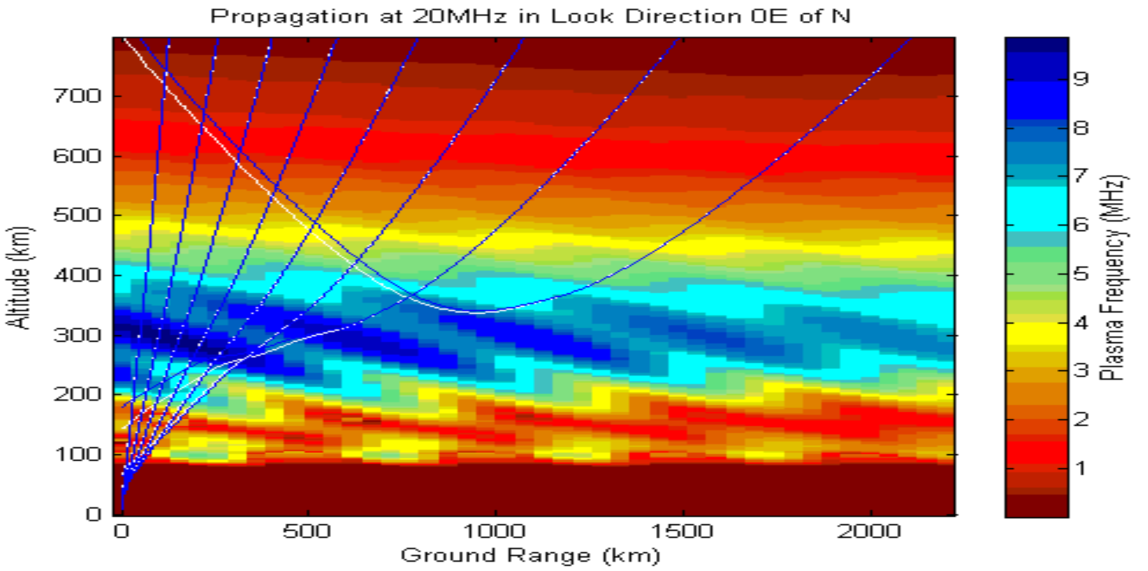

X ray at30MHz for elevation90 and bearing90 E of N

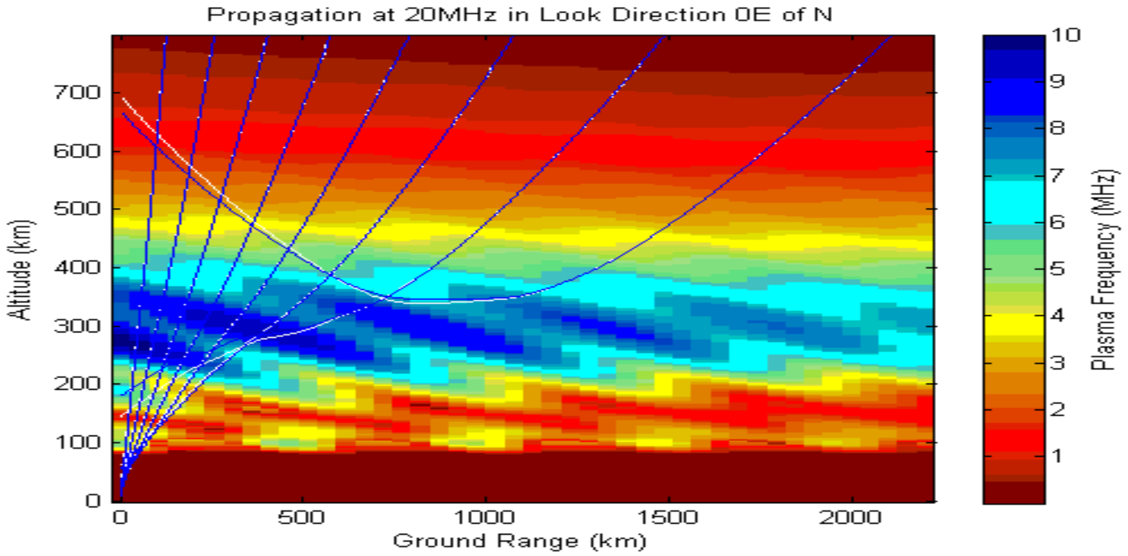

X ray at30MHz for elevation30 and bearing90 E of N

Effect of Disturbances on Propagation

Coleman, Forte et al, 2016 under preparation

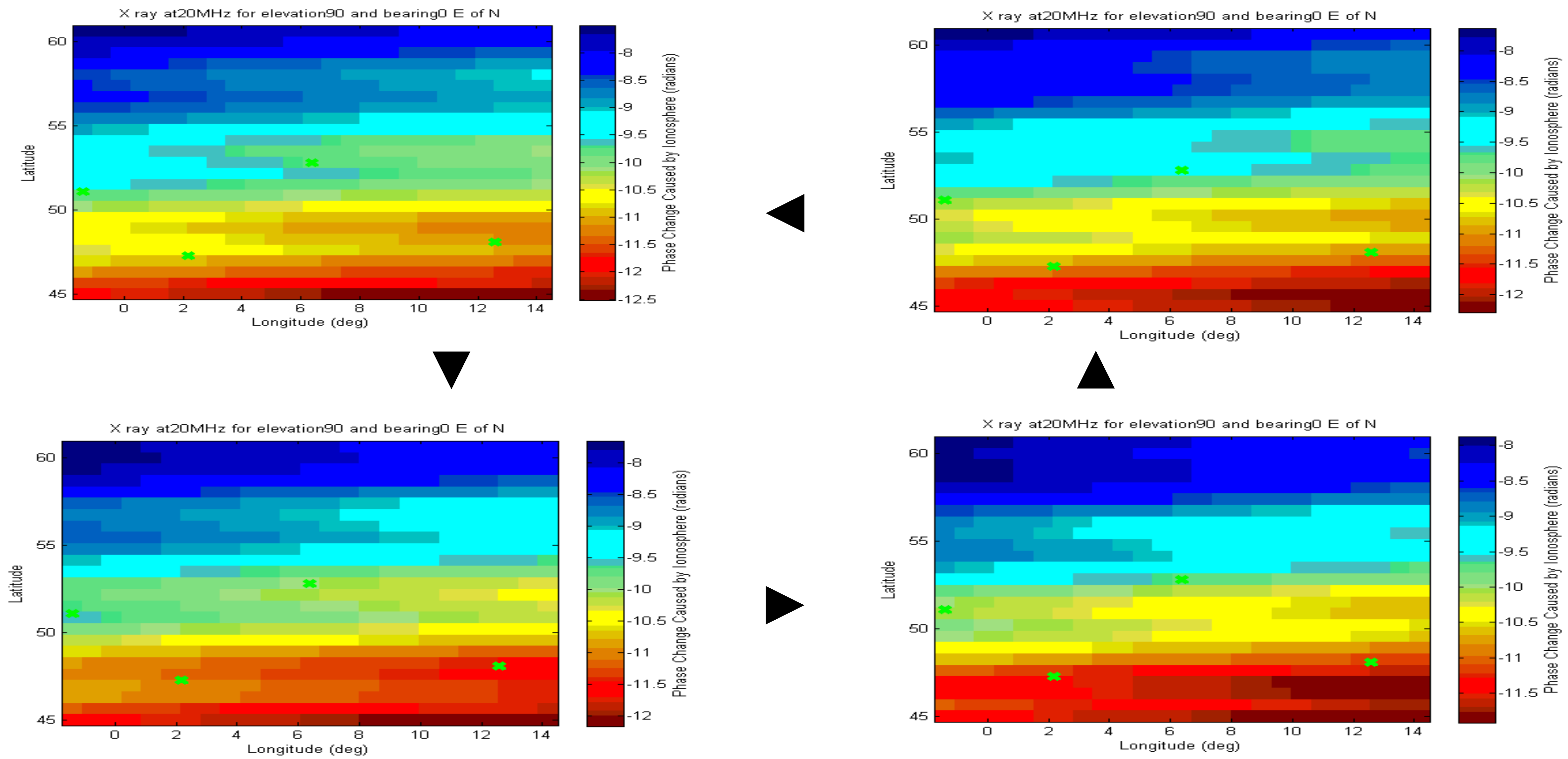
- Gravity waves in the neutral atmosphere cause TIDs, fluctuations in ionospheric plasma (Hooke, 1968)
- Fluctuations in plasma cause fluctuations in signal path geometry
- In addition, they cause significant fluctuations in phase corrections
- Fluctuations depend on inclination of incoming paths





Variation in Phase Correction Over a Cycle

Coleman, Forte et al, 2016 under preparation



Mitigation of space weather threats to GNSS services

THEME [SPA.2013.2.3-01]

Recent developments on the estension of EGNOS into Africa

The research leading to these results has received funding from the European Community's Seventh Framework Programme ([FP7/2007-2013]) under grant agreement n° 607081.

http://misw.info/

SEVENTH FRAMEWORK PROGRAMME

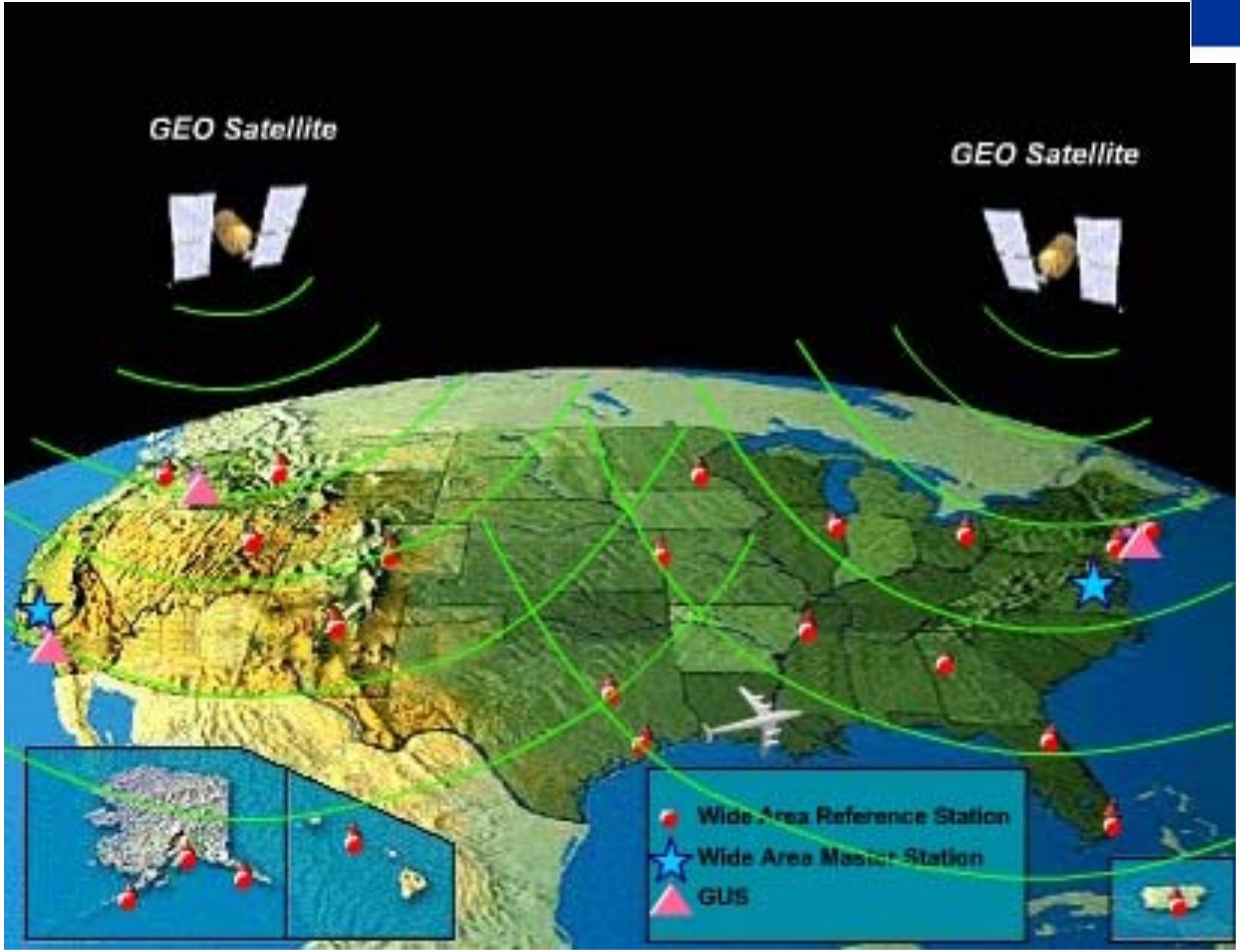
Beneficiaries

SEVENTH FRAMEWORK
PROGRAMME

1. UNIVERSITY OF BATH (UK)
2. THALES ALENIA SPACE ITALIA SPA
3. THALES ALENIA SPACE FRANCE
4. THE UNIVERSITY OF NOTTINGHAM (UK)
5. POLITECNICO DI TORINO POLITO (Italy)
6. ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA (Italy)
7. EISCAT SCIENTIFIC ASSOCIATION (Sweden)
8. JRC JOINT RESEARCH CENTRE - EUROPEAN COMMISSION (Belgium)
9. DANISH TECHNOLOGICAL UNIVERISTY (Denmark)
10. CENTRUM BADAN KOSMICZNYCH POLSKIEJ AKADEMII NAUK (Poland)
11. SVEUCILISTE U ZAGREBU FAKULTET ELEKTROTEHNIKE RACUNARSTVA UNIZG-FER (Croatia)
12. MET OFFICE (UK)

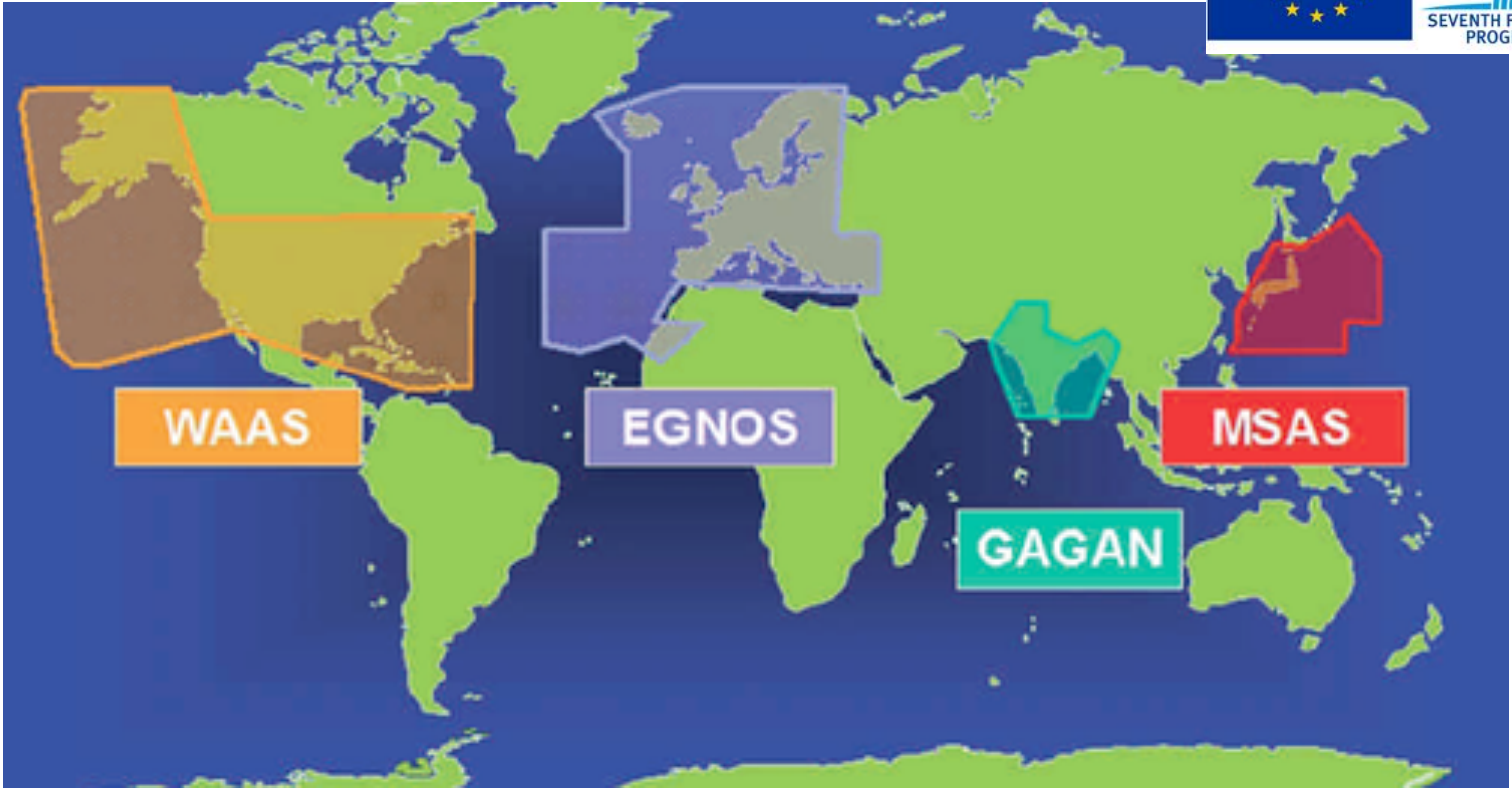
The concept of SBAS

WAAS CONUS



Credit: FAA

SBAS coverage



The limitations to the extension of SBAS into low latitudes

1. Mapping techniques do not accommodate strong gradients
2. The ground network of reference receivers are not robust in tracking through scintillation events,
3. Accurate fore-warning of significant space weather events is not available

SEVENTH FRAMEWORK PROGRAMME

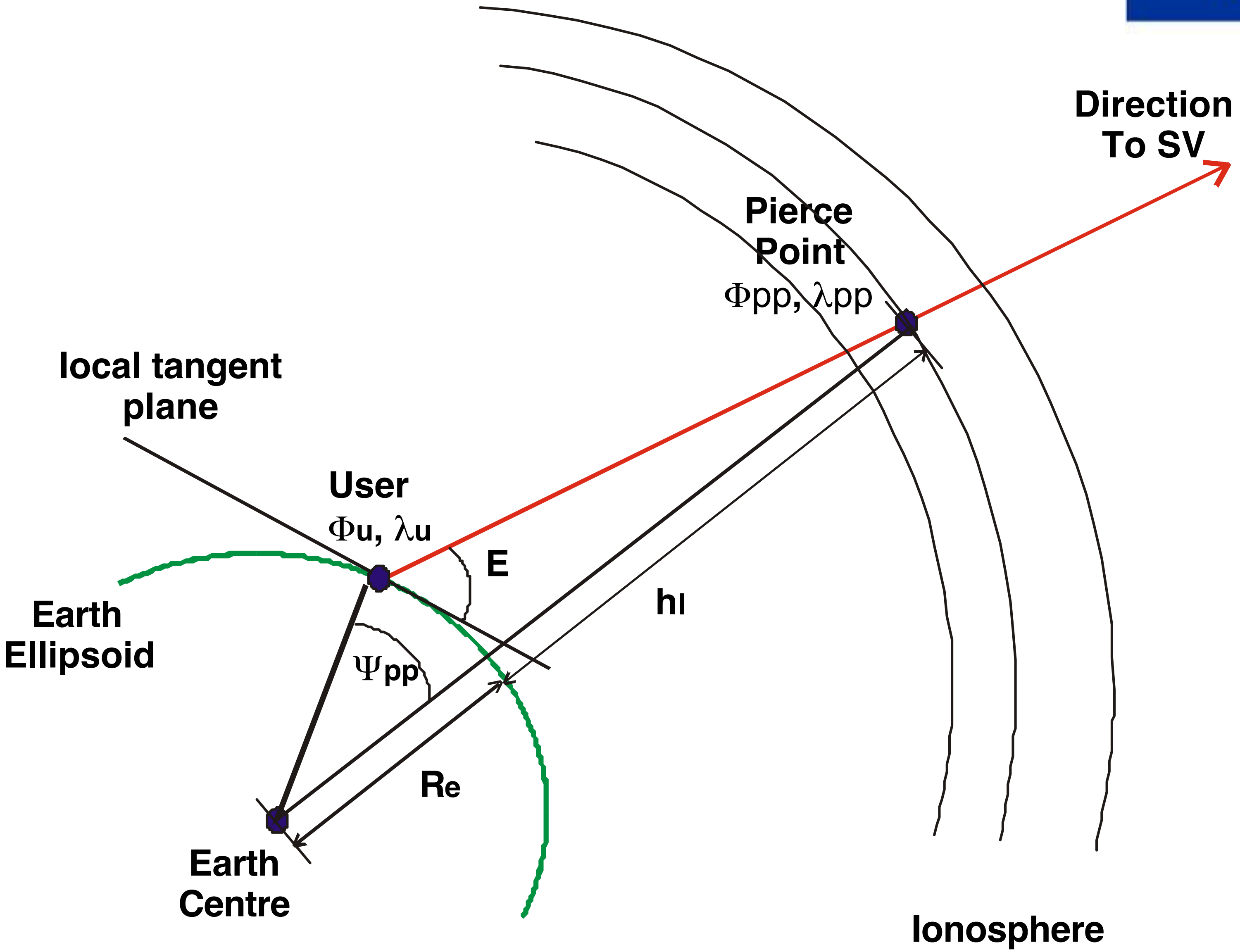
Objectives

SEVENTH FRAMEWORK PROGRAMME

1. To monitor and characterise ionospheric gradients and scintillation at low, high and middle latitudes
1. To quantify the impact of ionospheric gradients and scintillation on satellite navigation signals, receivers, and overall satellite navigation systems.
2. To develop innovative algorithms to mitigate against space weather vulnerabilities (i.e. scintillation) at receiver level (including Galileo signals).
3. To develop innovative algorithms to mitigate against space weather vulnerabilities (i.e. ionisation gradients and scintillation) at service level, e.g. SBAS.
4. To devise recommendations on best practices for GNSS future services with reference to space weather.

The problem of ionisation gradients

How to calculate corrections to ionopheric delays



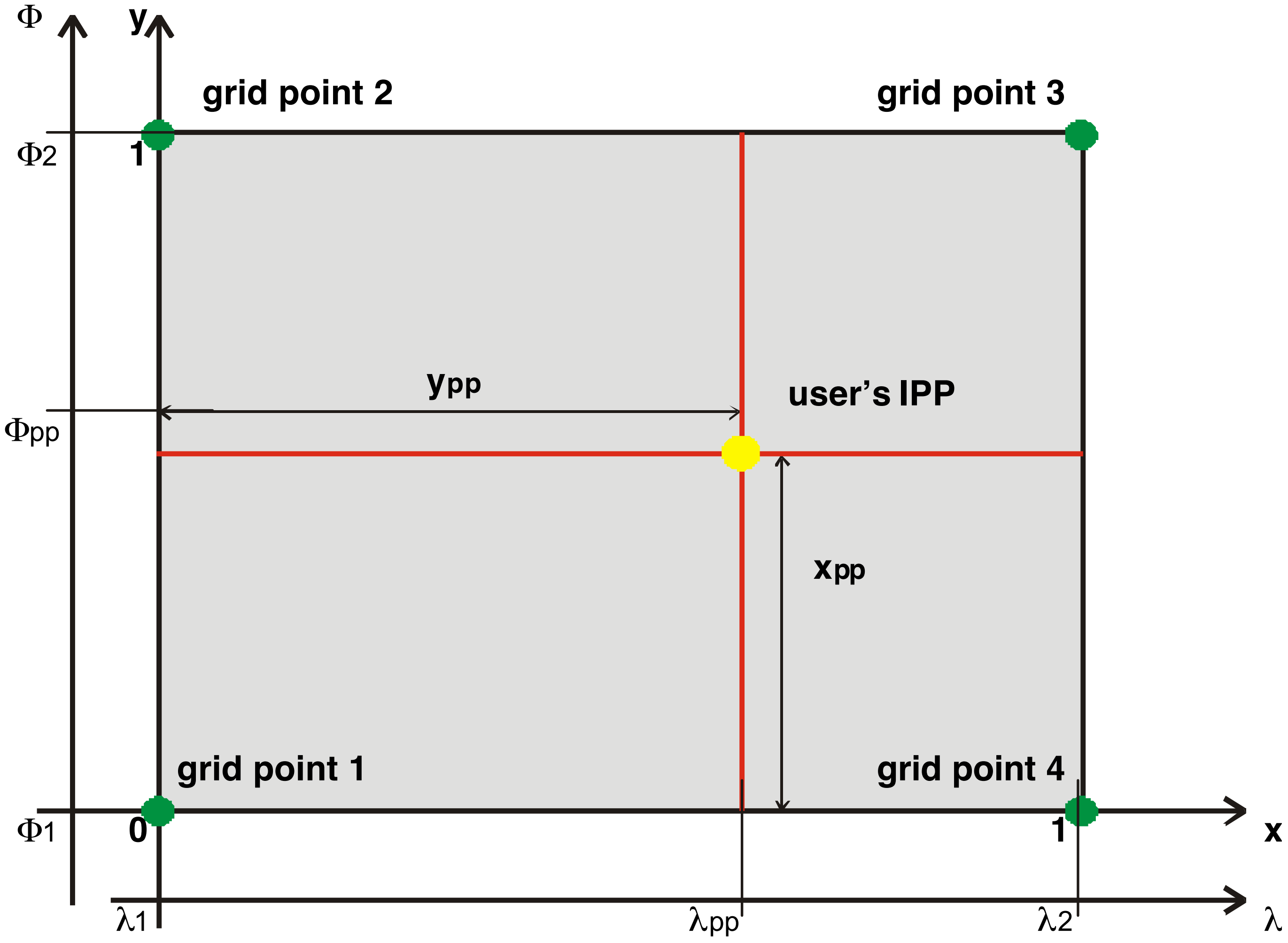
Credit: RTCA

How to calculate corrections to ionopheric delays

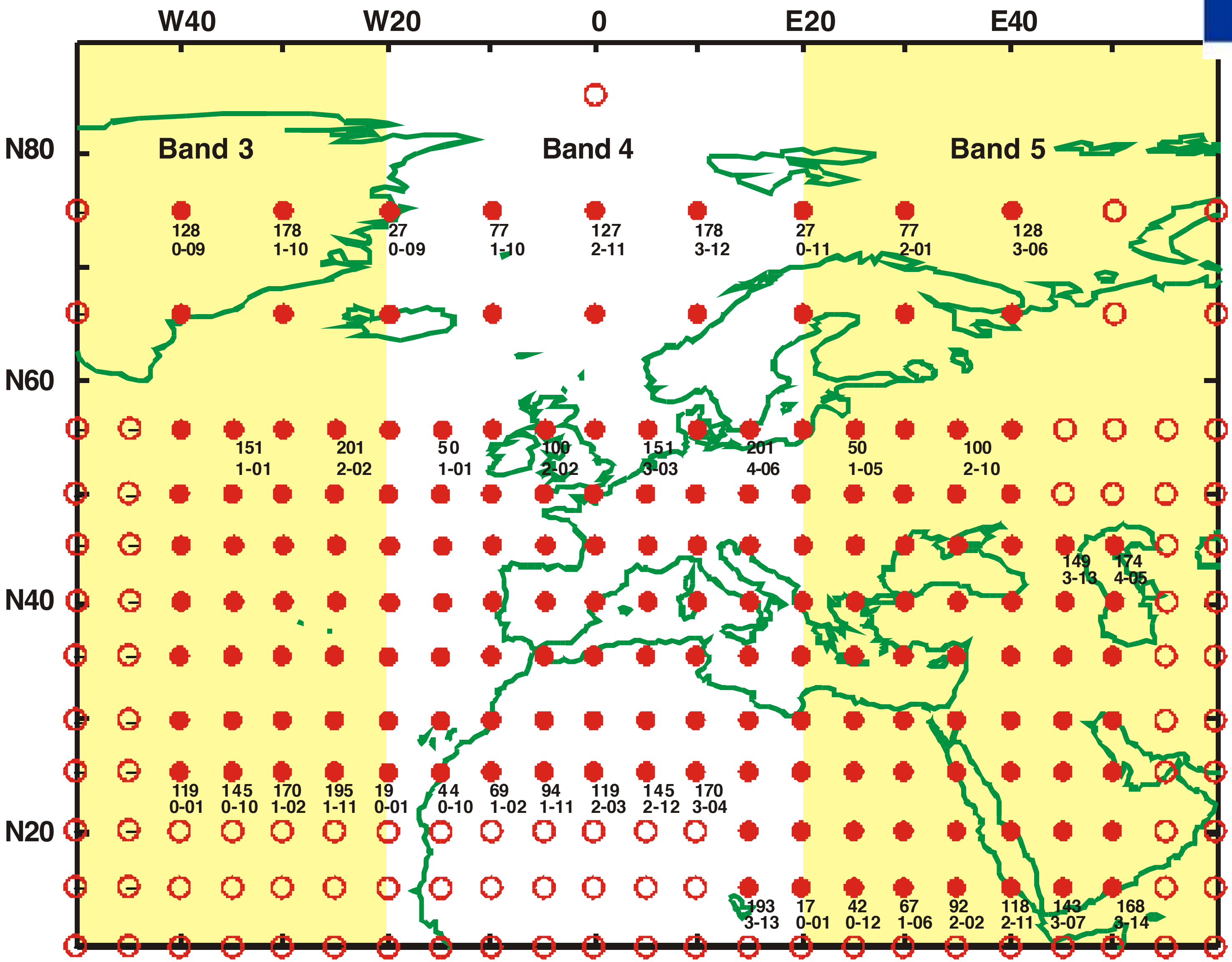
$$\tau_{vpp}(\Phi_{pp},\lambda_{pp}) = \sum_{i=1}^{4} W_i(x_{pp}, y_{pp})\,\tau_{vi}$$

with		
	τ_{vpp}	vertical ionospheric delay at pierce point
	τ_{vi}	vertical ionospheric delay at grid points
	W_i	weighting function

Credit: RTCA



Example of ionispheric grid points



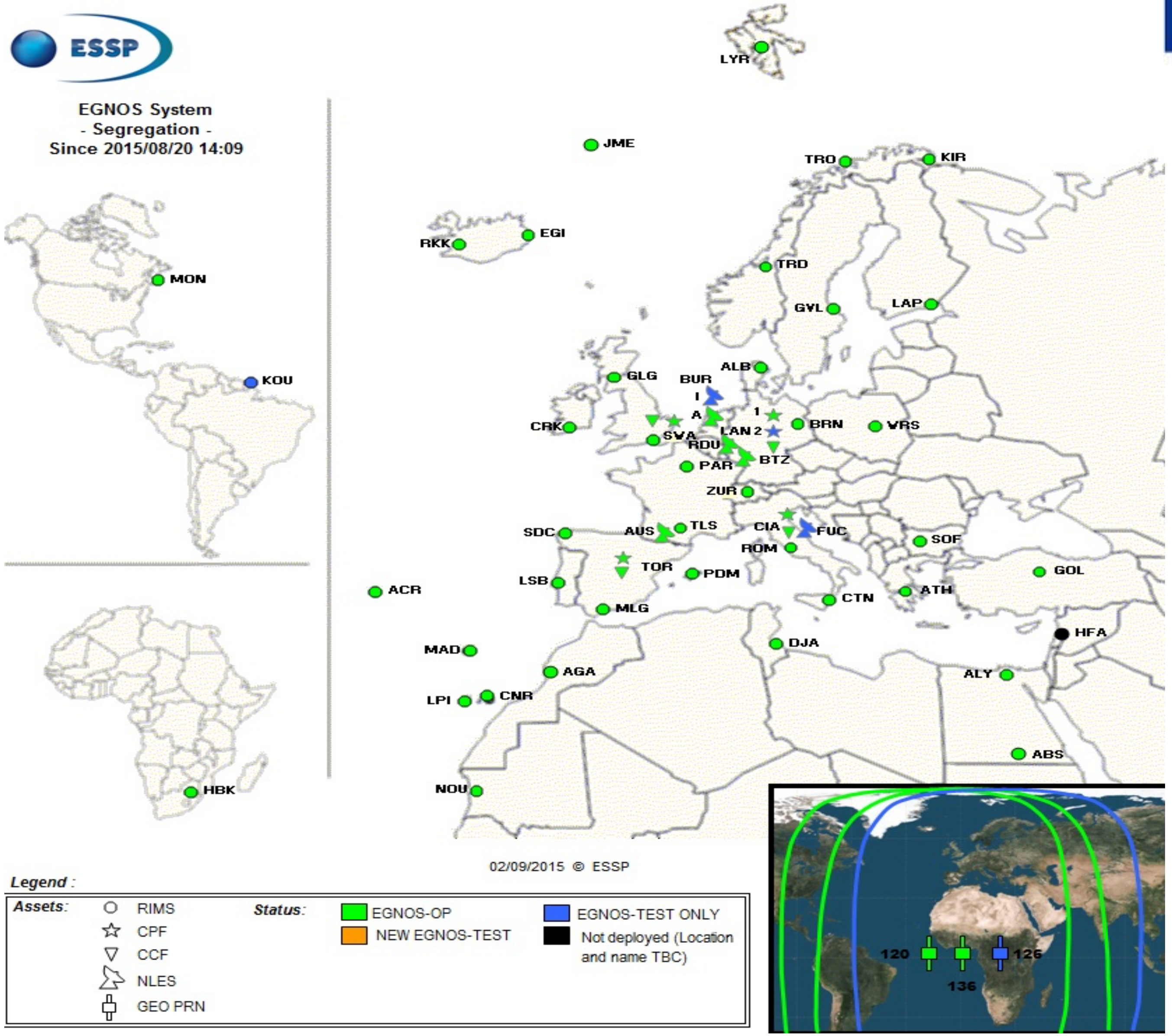
● IGP supported by ESTB together with IGP grid number, MT 26 block id and delay number

○ IGP not suppor- ted ted by ESTB

Credit: RTCA

EGNOS monitoring stations – courtesy ESSP

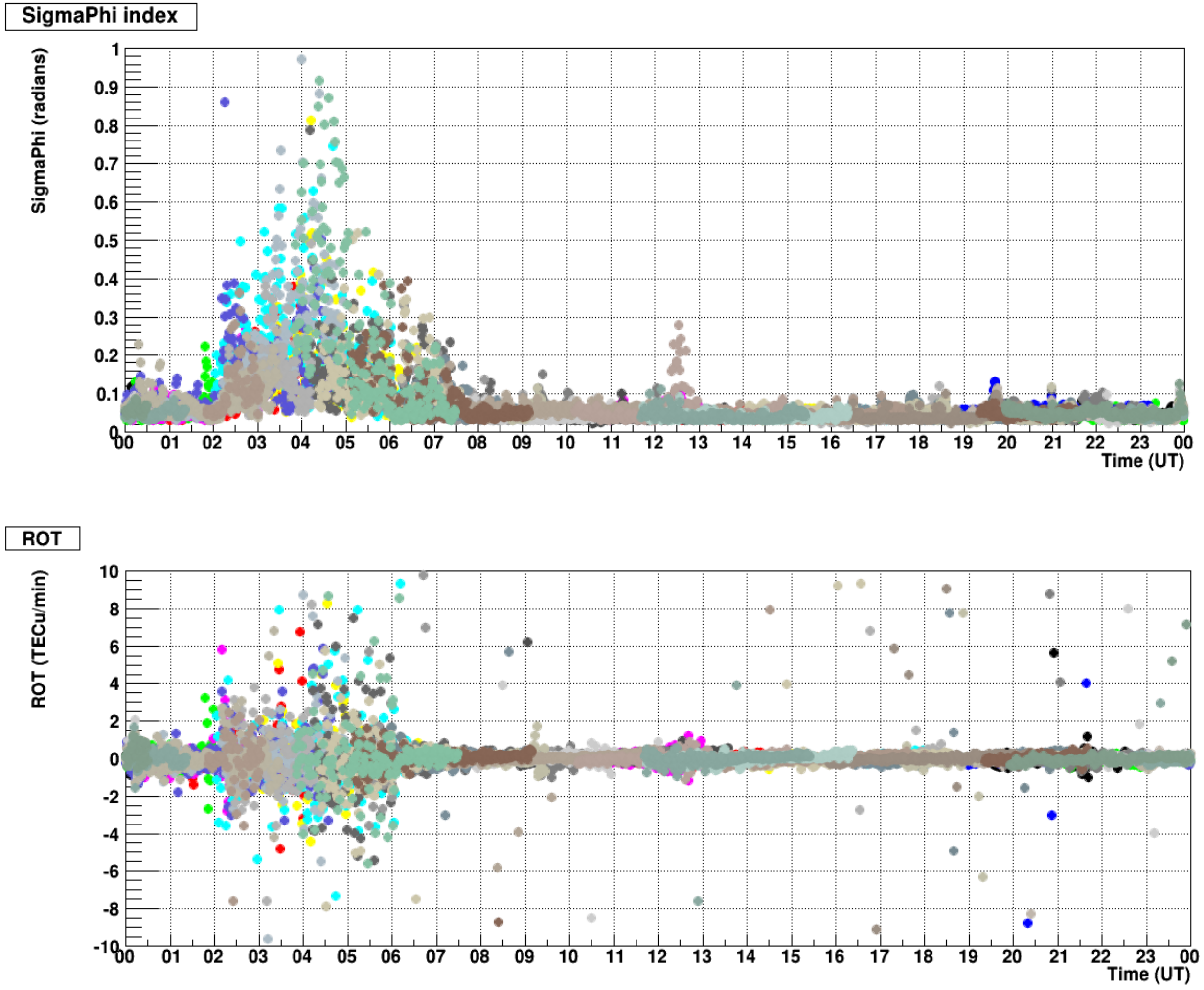
SEVENTH FRAMEWORK PROGRAMME



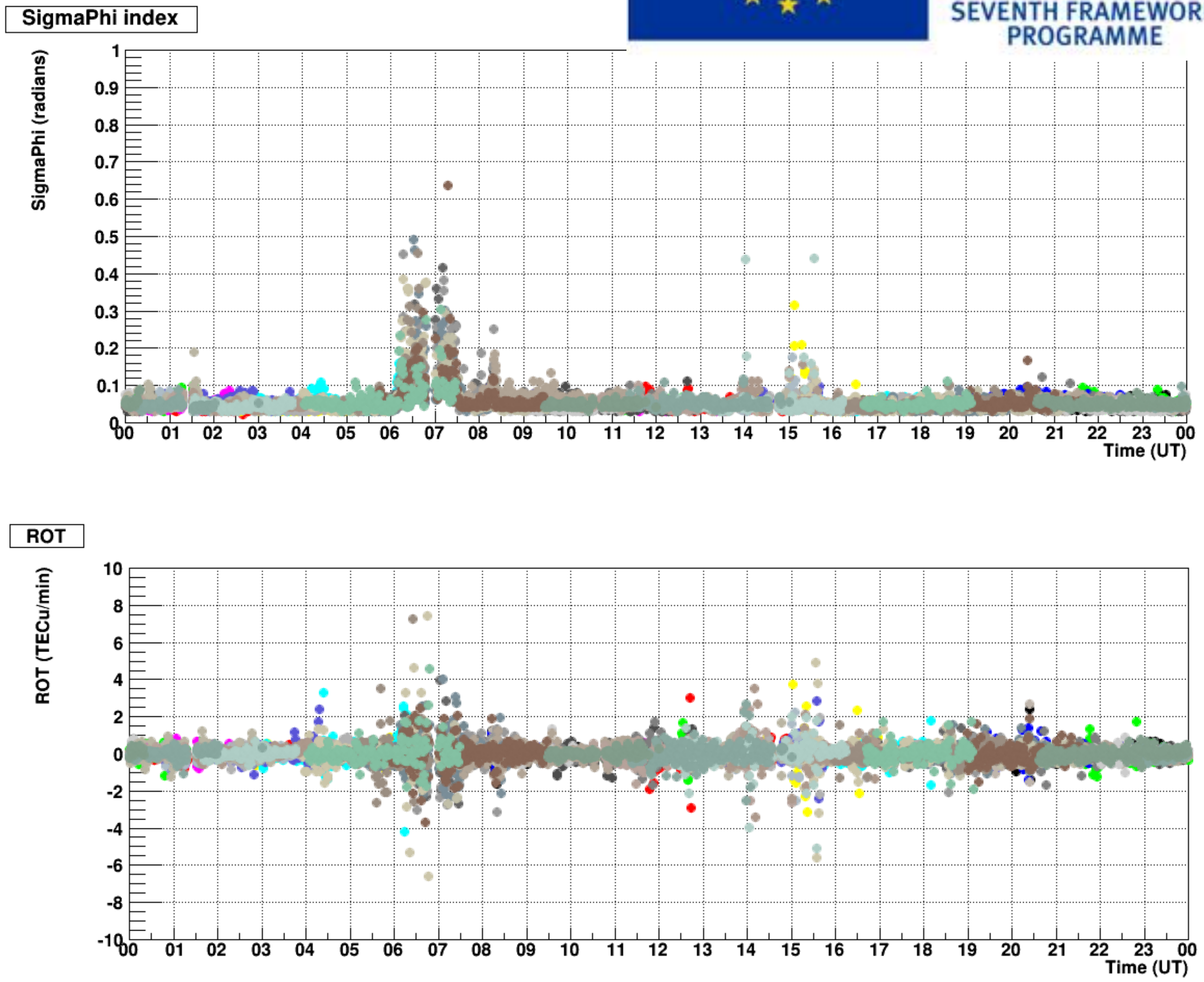
Credit: ESSP

Examples of ionisation structures
Scenarios in the Euro-African sector

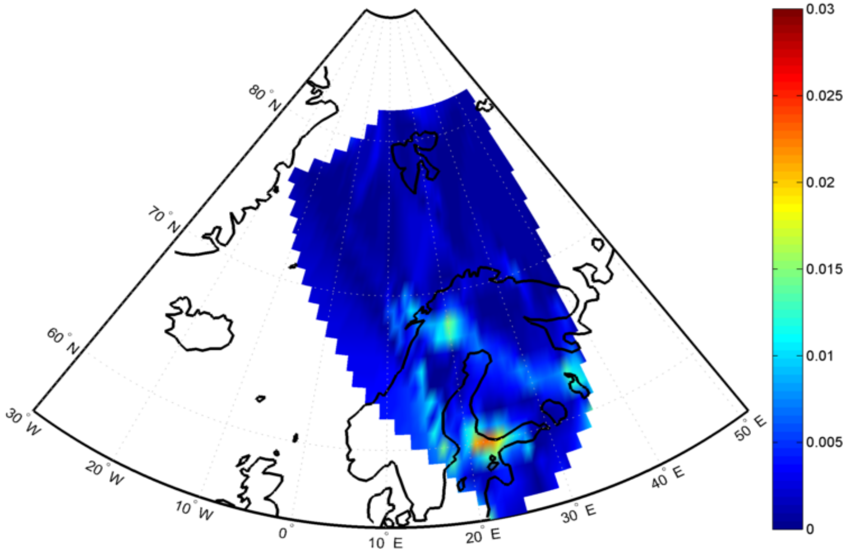
Rate of Change of TEC and Scintillation



23 June 2015
Trondheim (63.42 N, 10.41 E)



23 June 2015
Ny Alesund (78.93 N, 11.06 E)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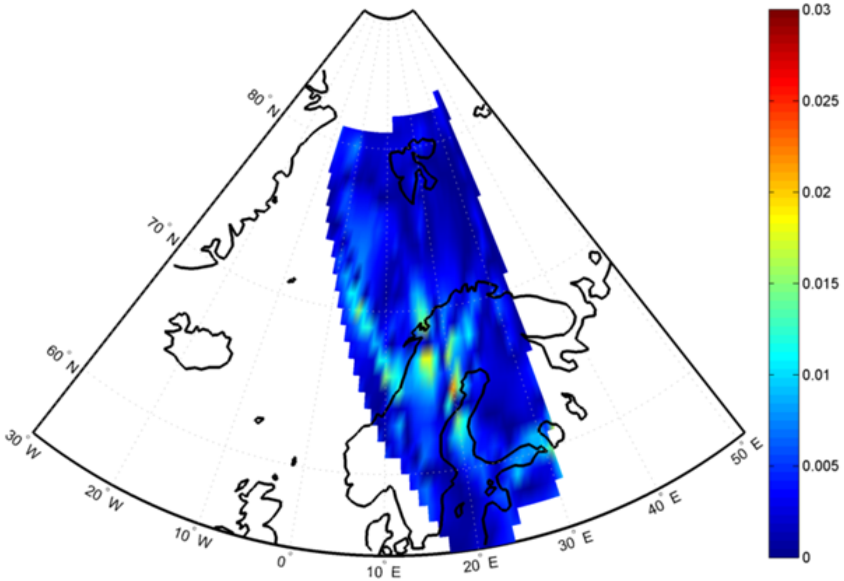
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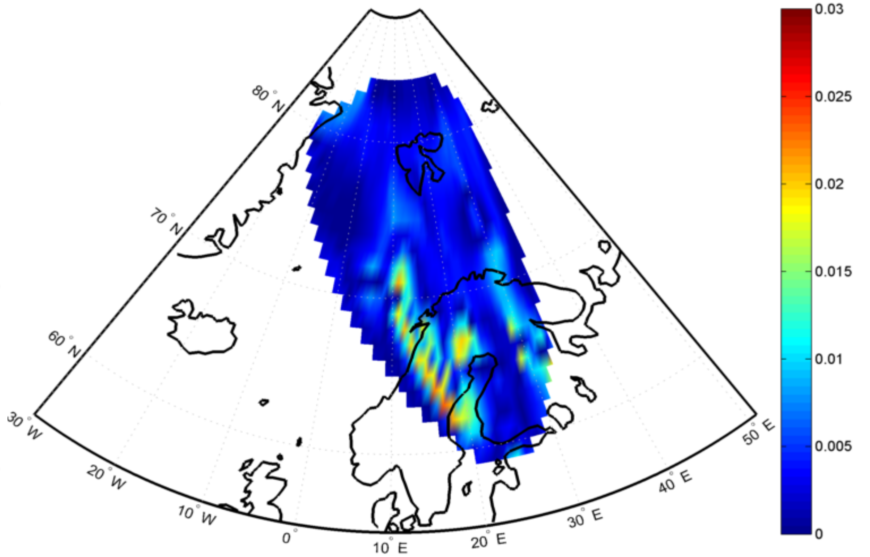
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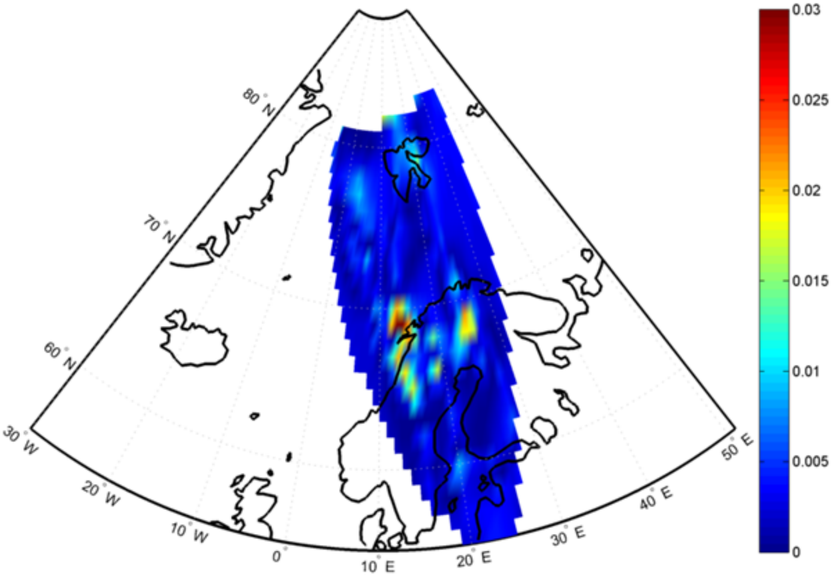
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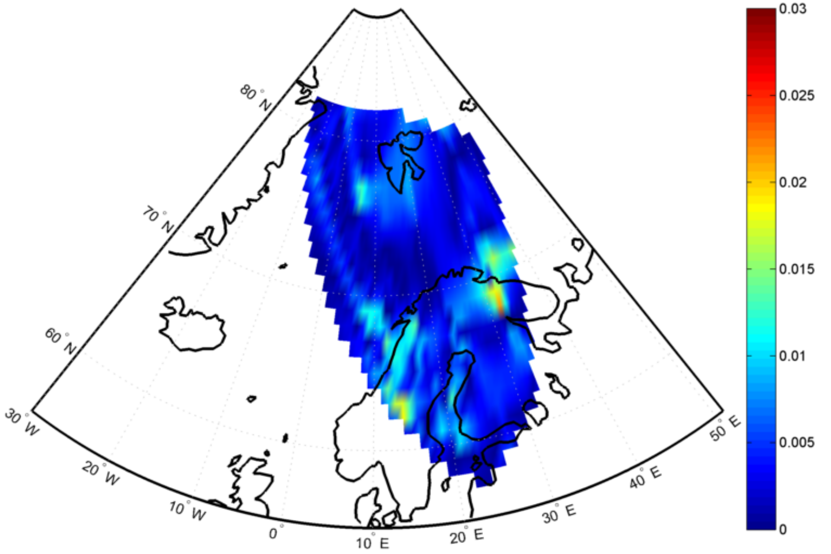
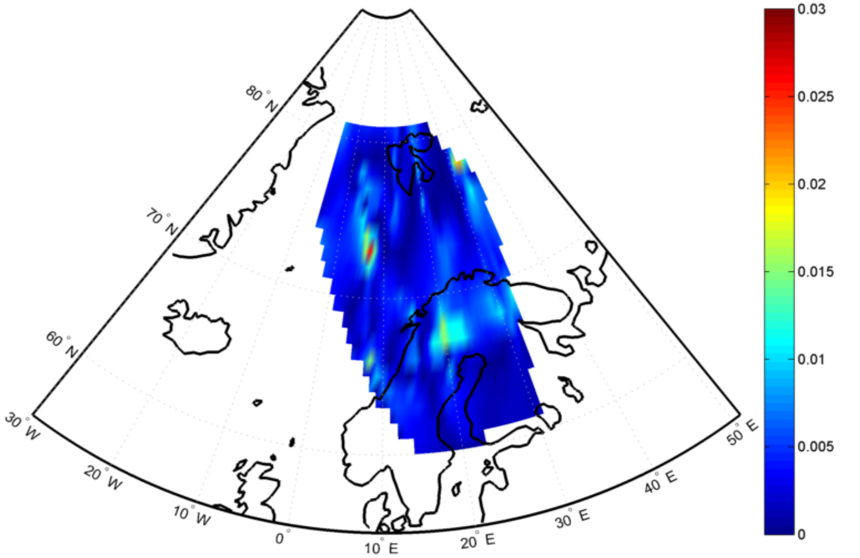

23-Jun-2015 06:00:00 TECU/km N-S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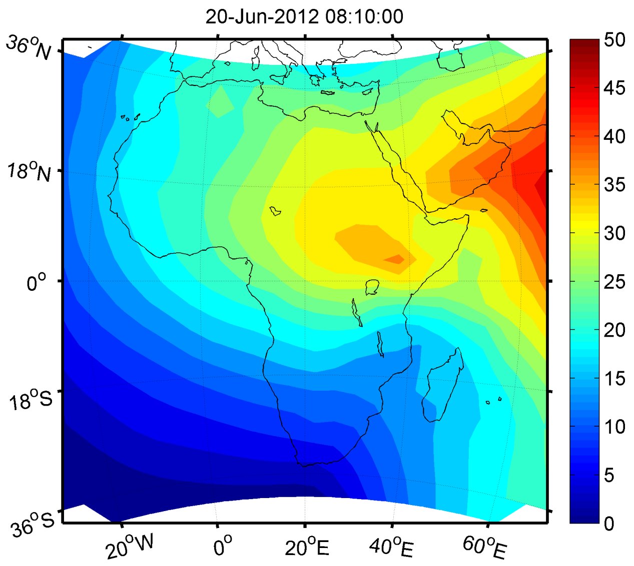
Examples of ionisation structures over African low latitudes

SEVENTH FRAMEWORK PROGRAMME

Examples of ionisation structures over Africa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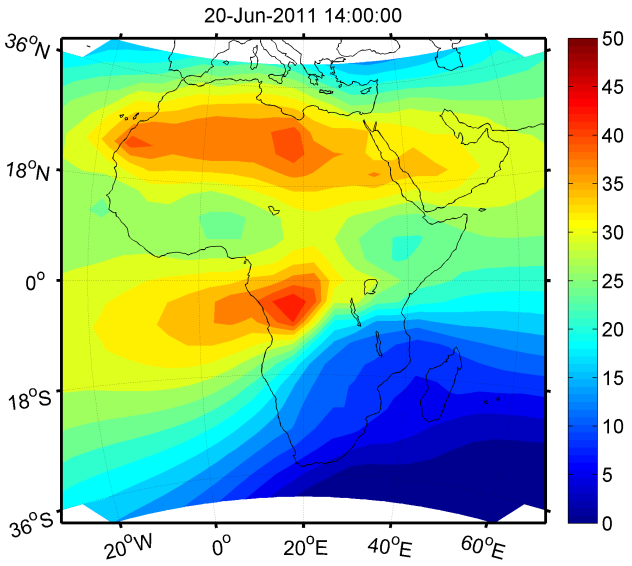
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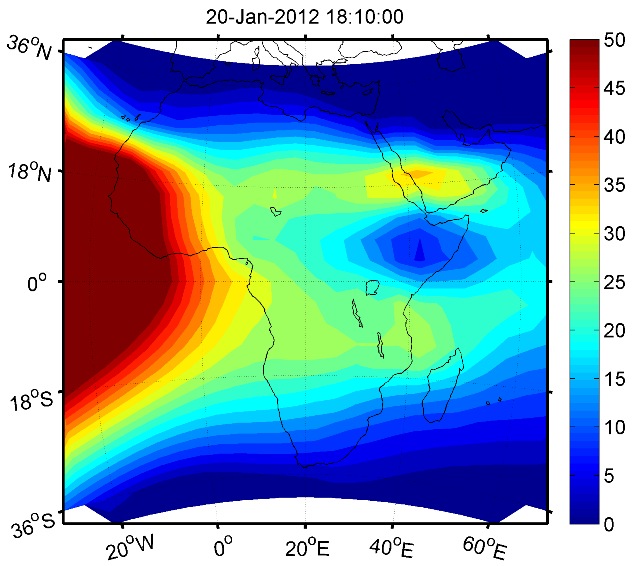
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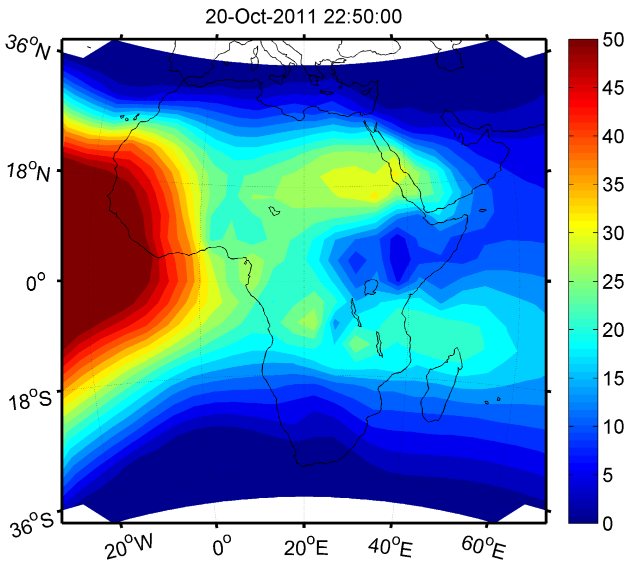
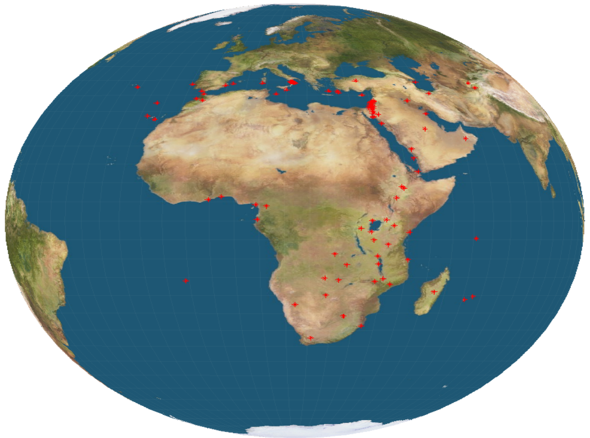

20-Oct-2011 22:50:00

SEVENTH FRAMEWORK PROGRAMME

Example TEC maps over Africa

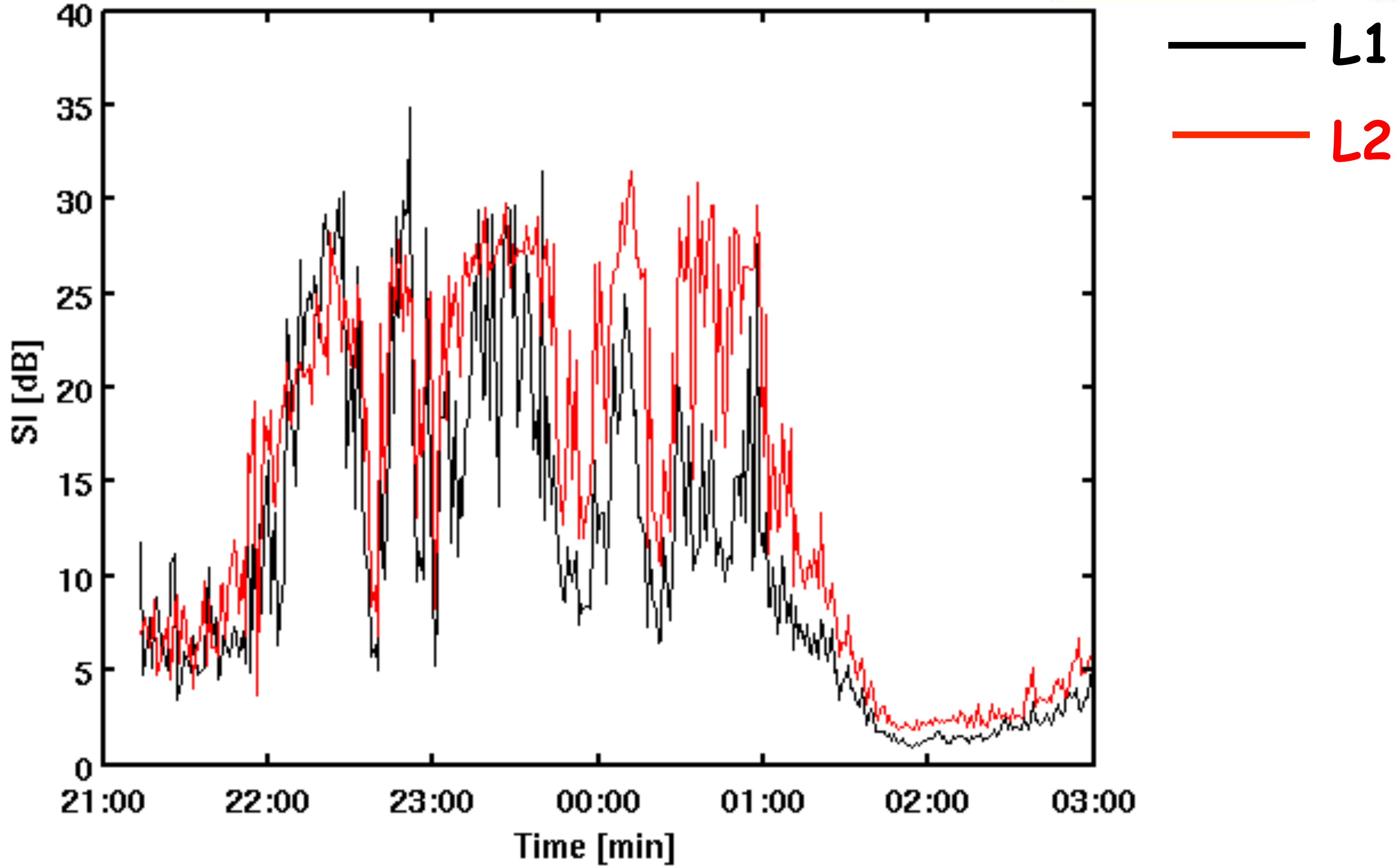


Credit: MIDAS

An additional problem at low latitudes: scintillation

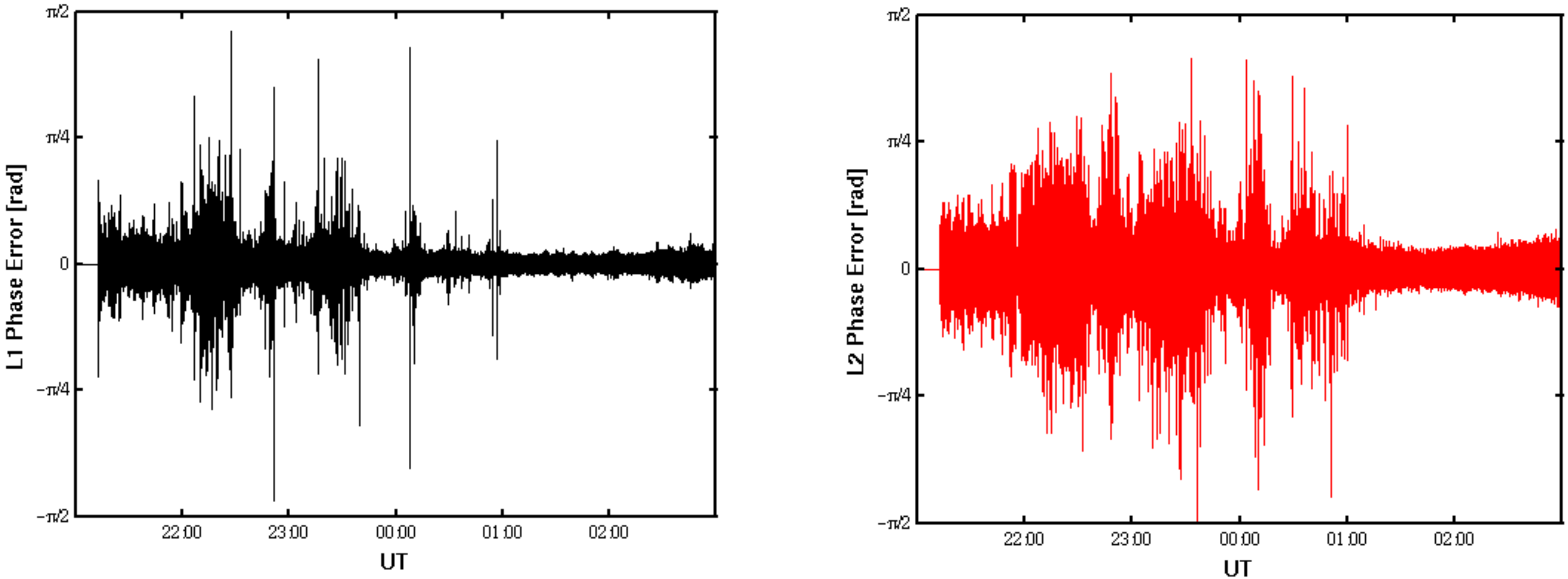
SEVENTH FRAMEWORK PROGRAMME

An additional problem: scintillation

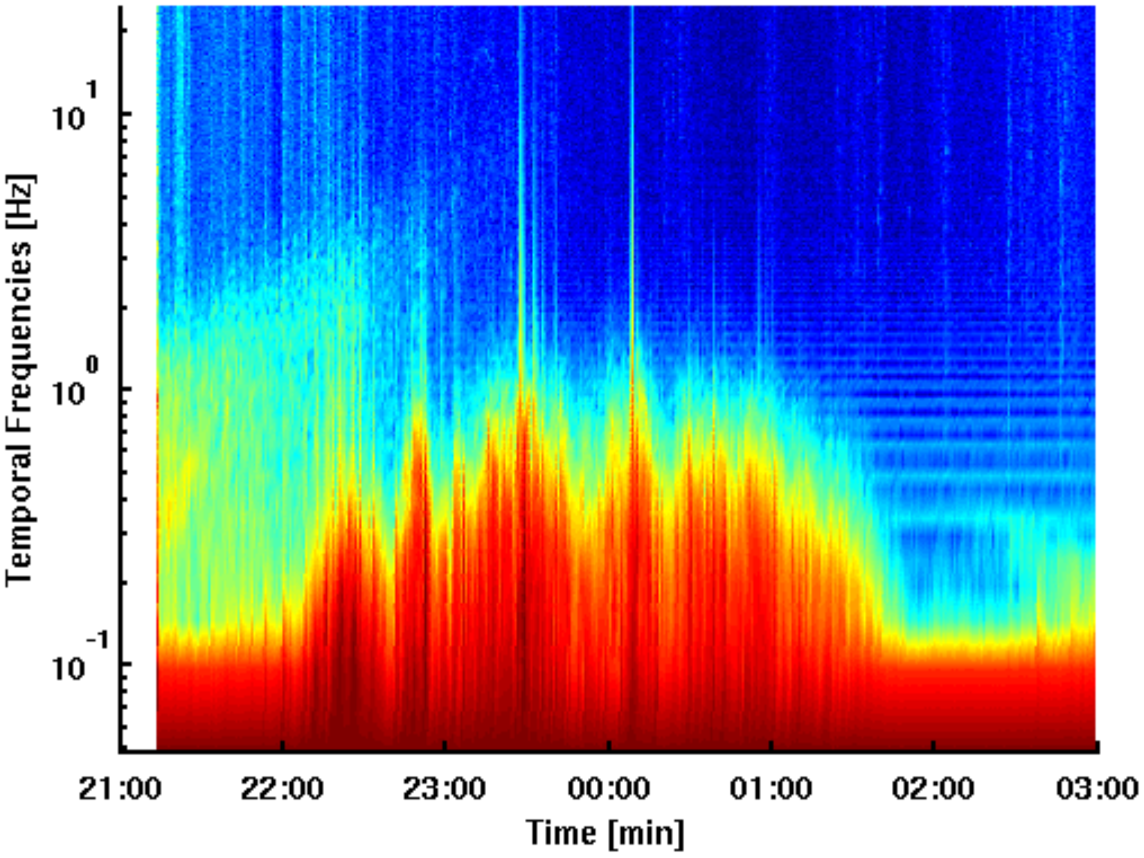


10 March 2012
PRN31

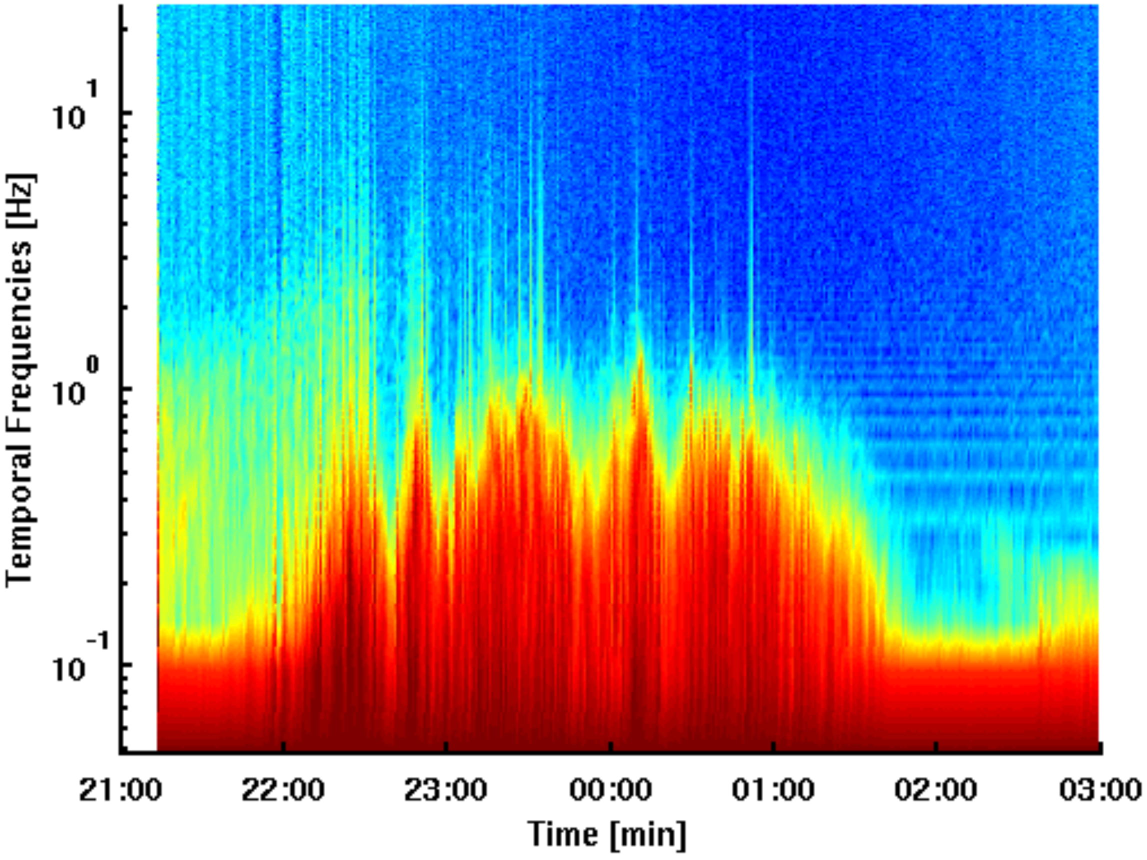
An additional problem: scintillation



An additional problem: scintillation

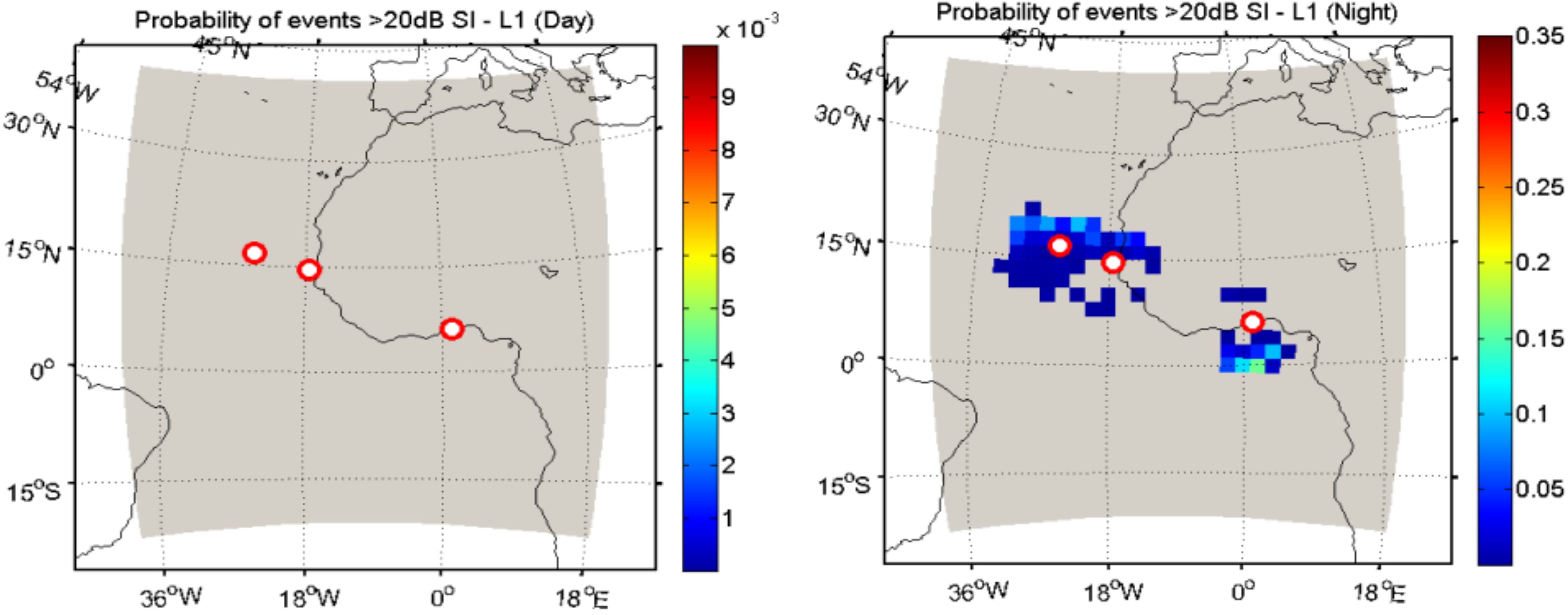


L1



L2

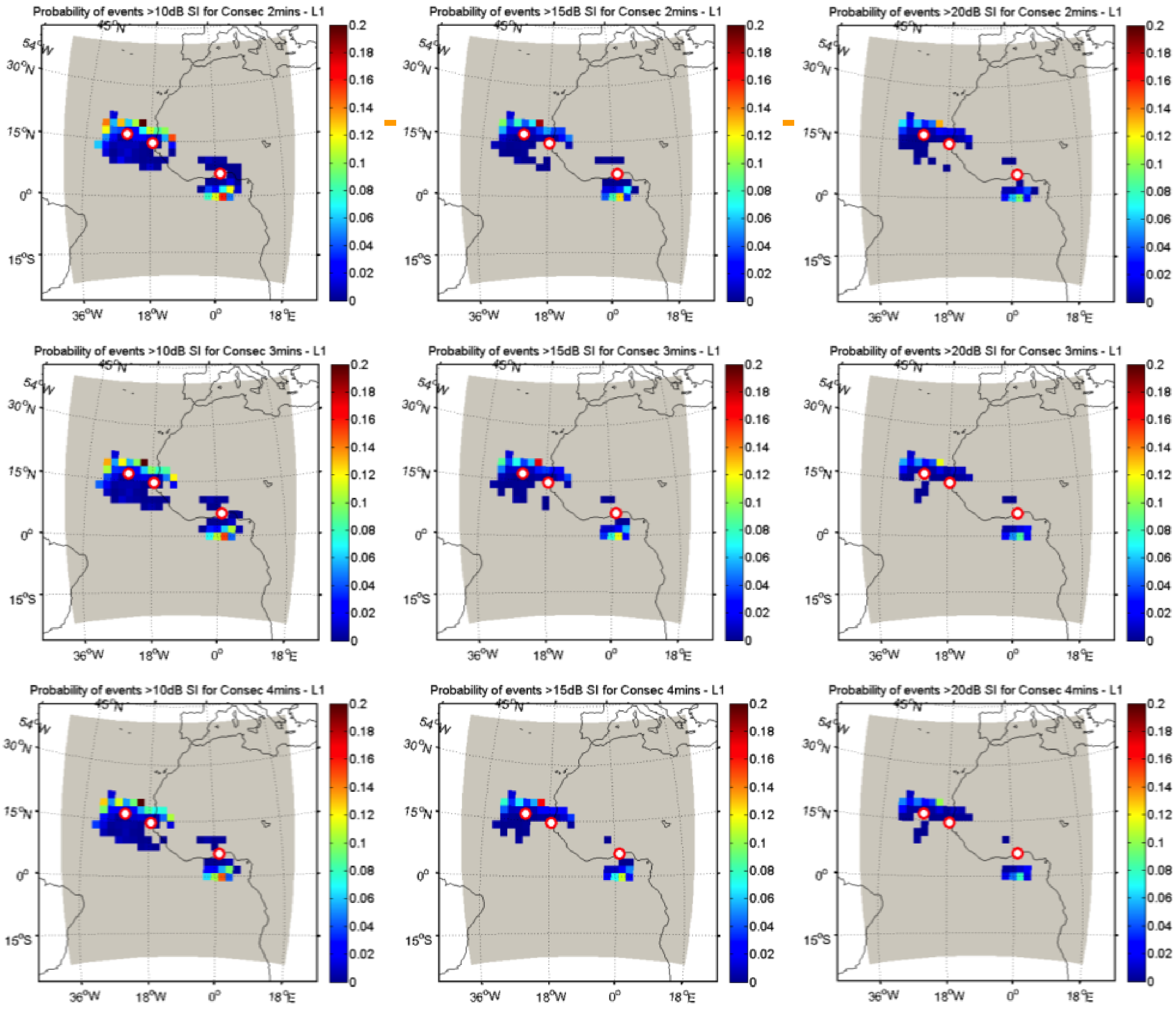
Scintillation: a night-time phenomenon



Probability of events >20dB SI - L1 (Day)

Probability of events >20dB SI - L1 (Night)

SEVENTH FRAMEWORK PROGRAMME



Probability of events >10dB SI for Consec 2mins - L1

Probability of events >15dB SI for Consec 2mins - L1

Probability of events >20dB SI for Consec 2mins - L1

Probability of events >10dB SI for Consec 3mins - L1

Probability of events >15dB SI for Consec 3mins - L1

Probability of events >20dB SI for Consec 3mins - L1

Probability of events >10dB SI for Consec 4mins - L1

Probability of events >15dB SI for Consec 4mins - L1

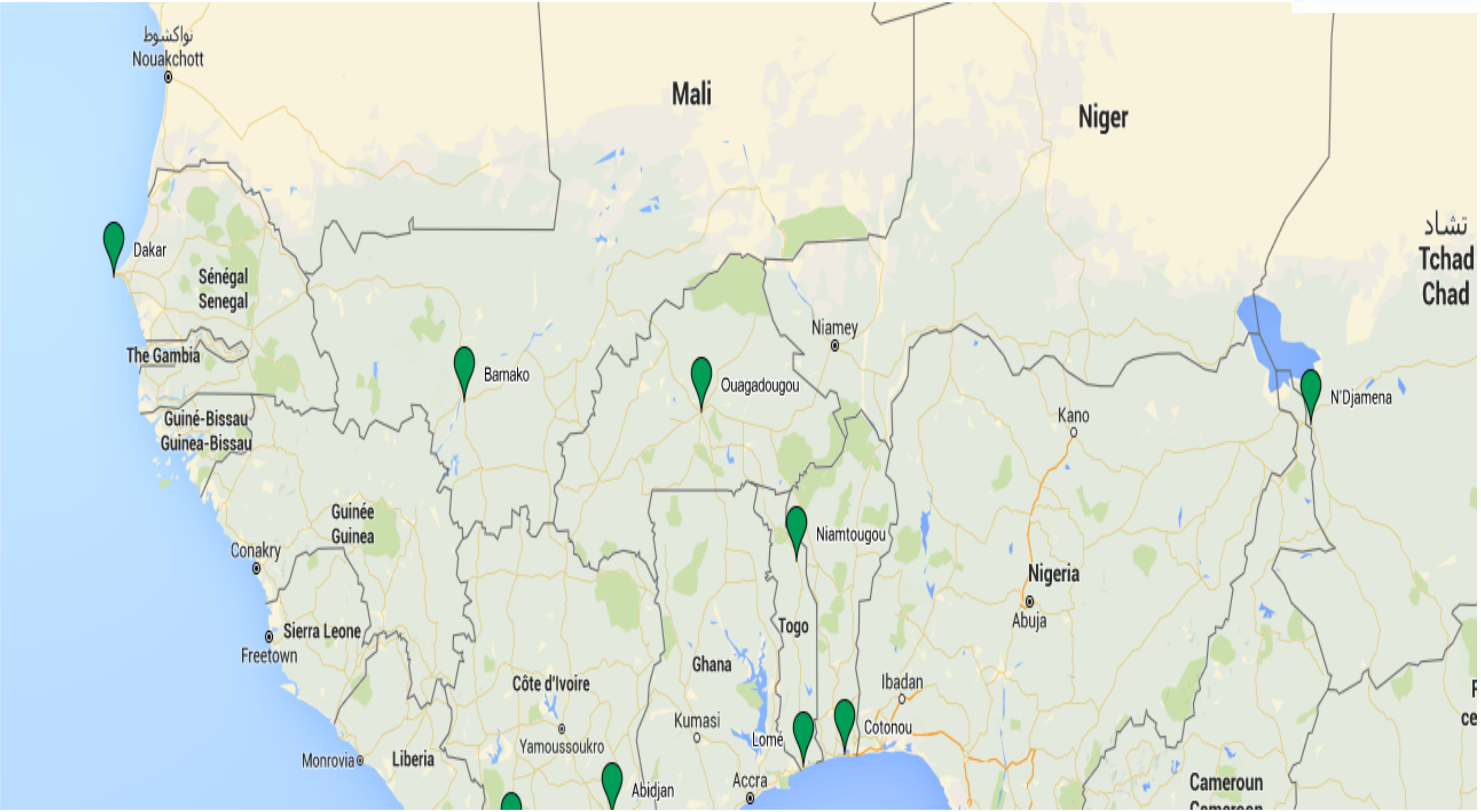
Probability of events >20dB SI for Consec 4mins - L1

Up to 4 consecutive minutes

Modelling EGNOS performance over Africa

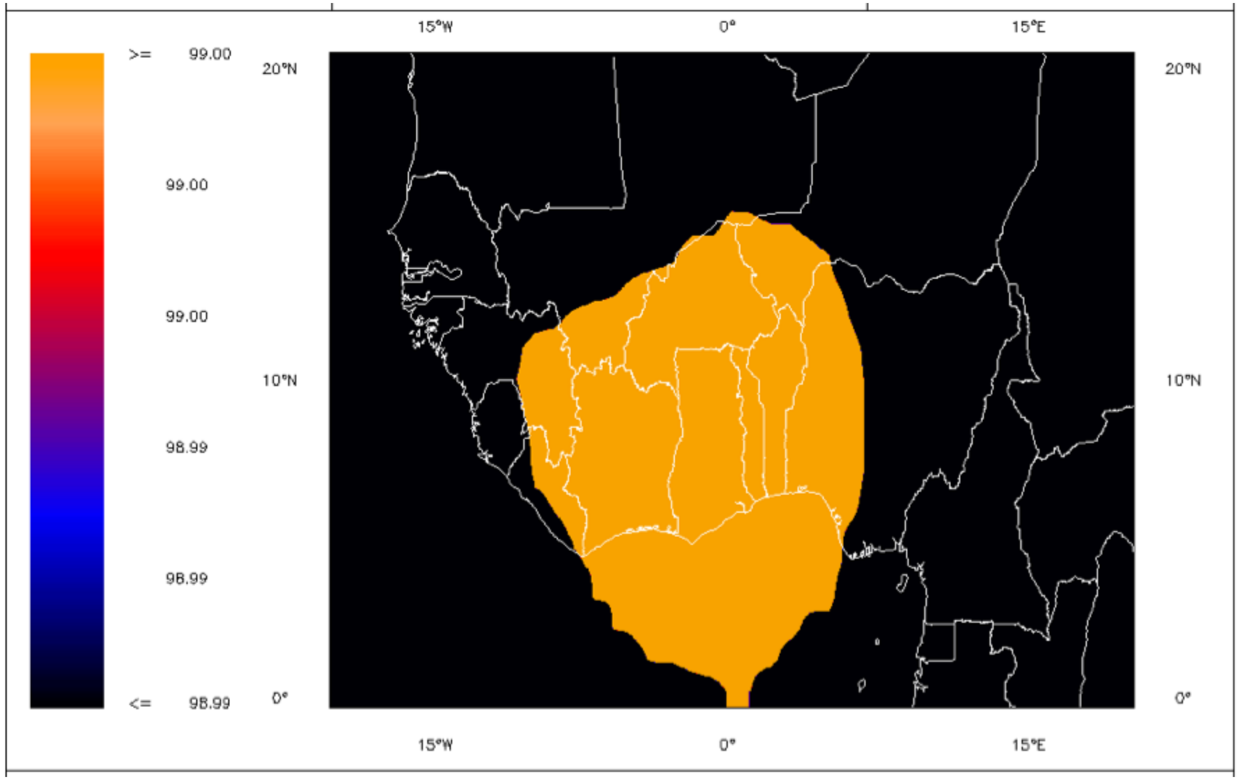
SEVENTH FRAMEWORK PROGRAMME

Data from SAGAIE network – courtesy of CNES

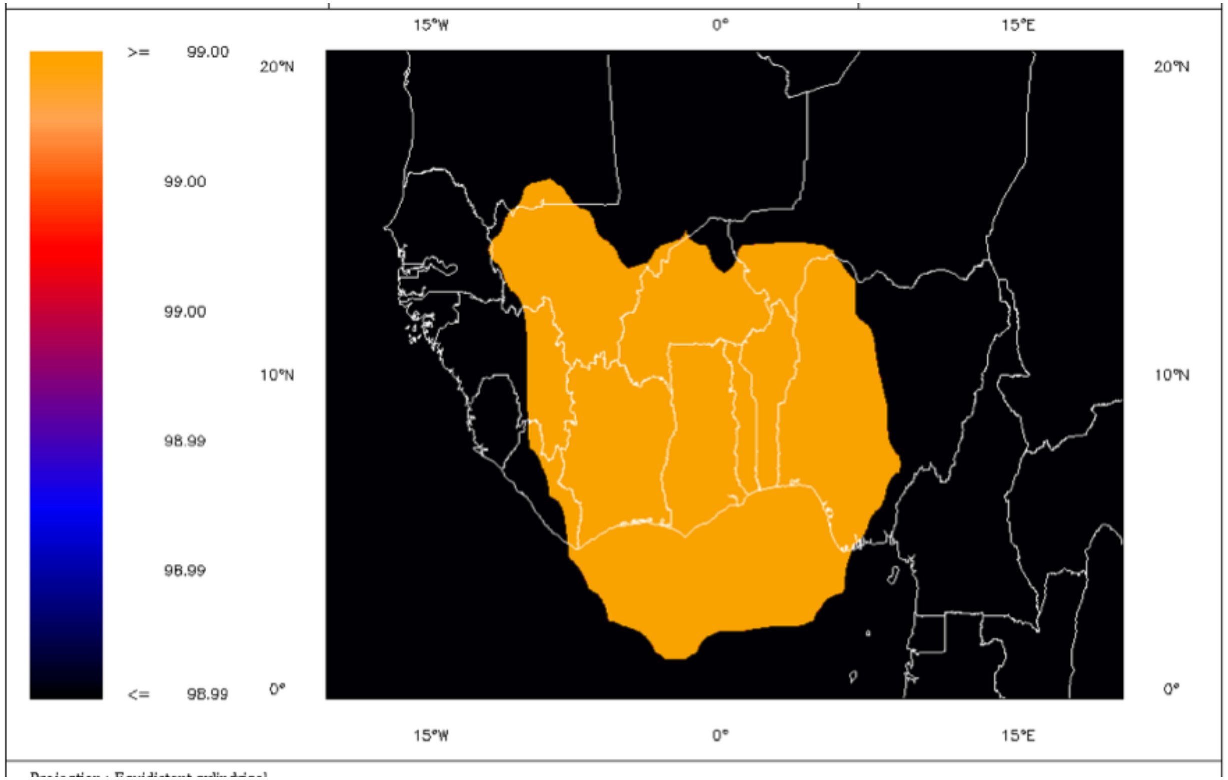


EGNOS availability over the chosen area

08 – 12 LT

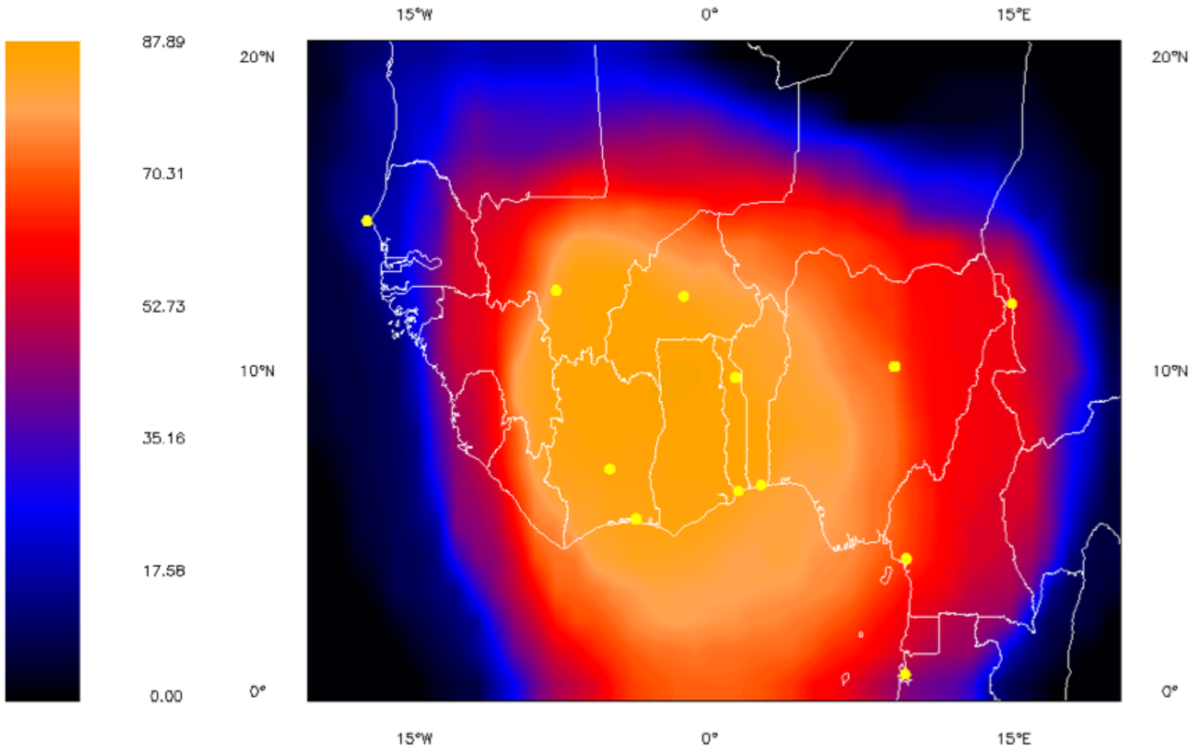


12 – 16 LT

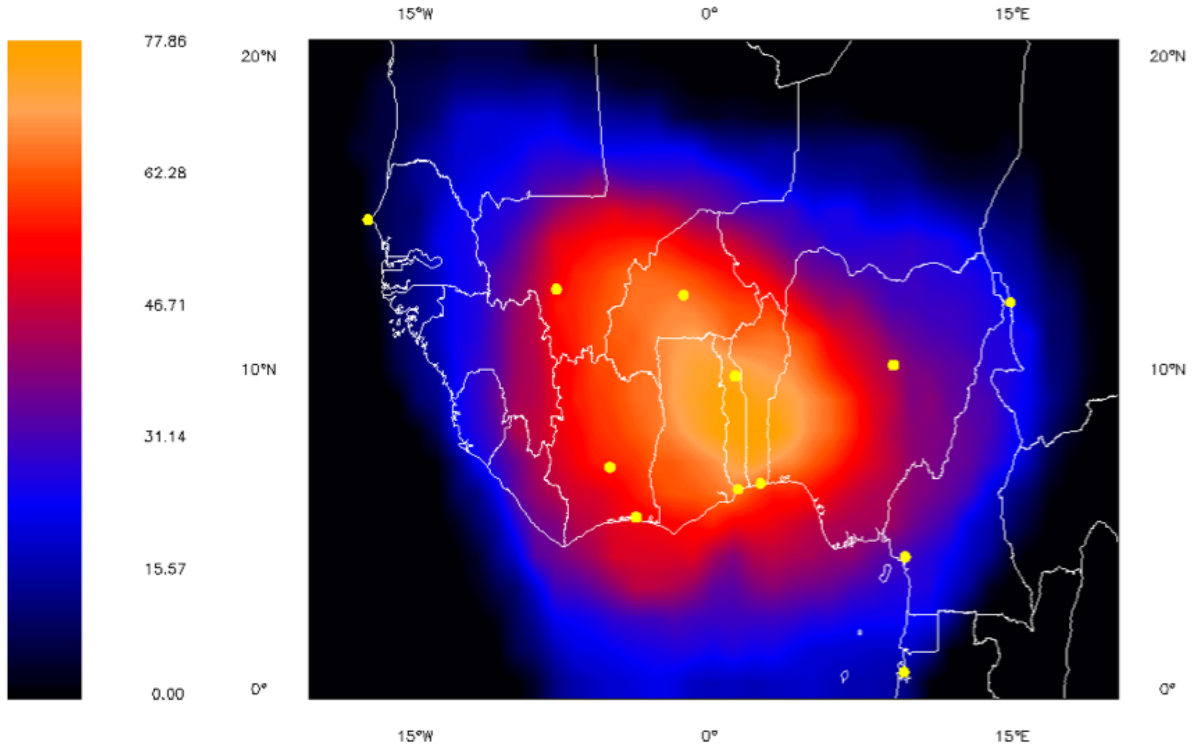


EGNOS availability over the chosen area

16 – 20 LT



20 – 24 LT



New sites for the two GISMO units

SEVENTH FRAMEWORK PROGRAMME

Sites proposed for MISW ▲
stations

Sagaie stations ●

+

Additional ESA stations in the region (awaiting REA confirmation)

+

Potential use of stations in the Eastern African region (through SANSA, awaiting SCINDA - BC confirmation)

Summary and Ideas

1. On-going measurements and modelling of scintillation under various regimes of scattering (BF, RF, MB)
2. Modelling of effects (ray-tracing) on typical LOFAR phase measurements (CC, BF)
3. Use of MISW catalogue of scenarios (high-to-low latitudes, ionisation gradients, and L-band scintillation) (BF, SRC)

Thank you for the attention