Ionospheric Modelling II: TEC gradients and scintillation climatology

Luca Spogli

luca.spogli@ingv.it

Istituto Nazionale di Geofisica e Vulcanologia

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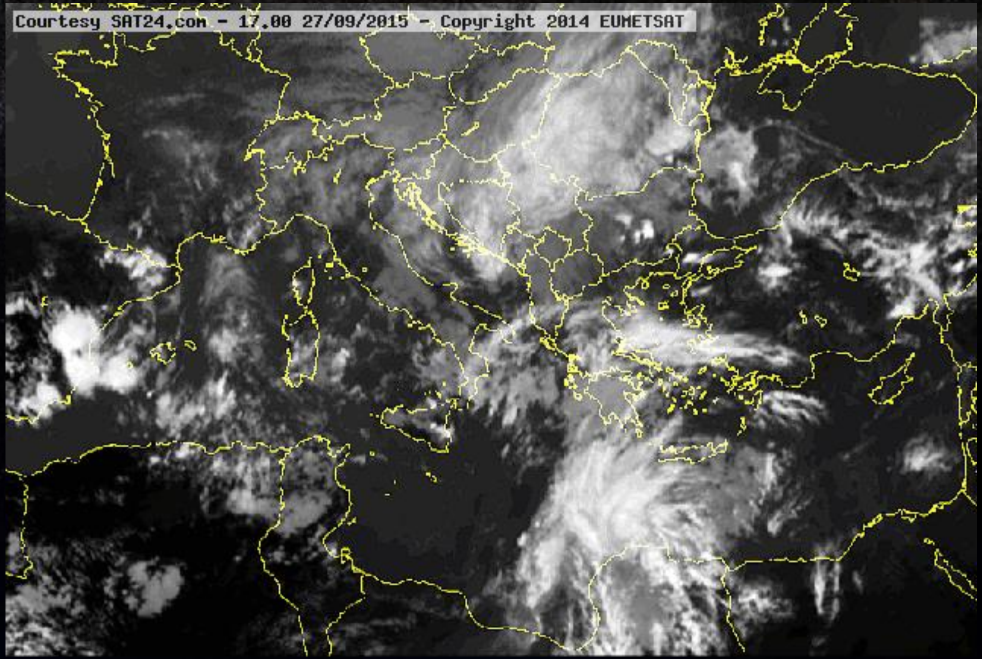
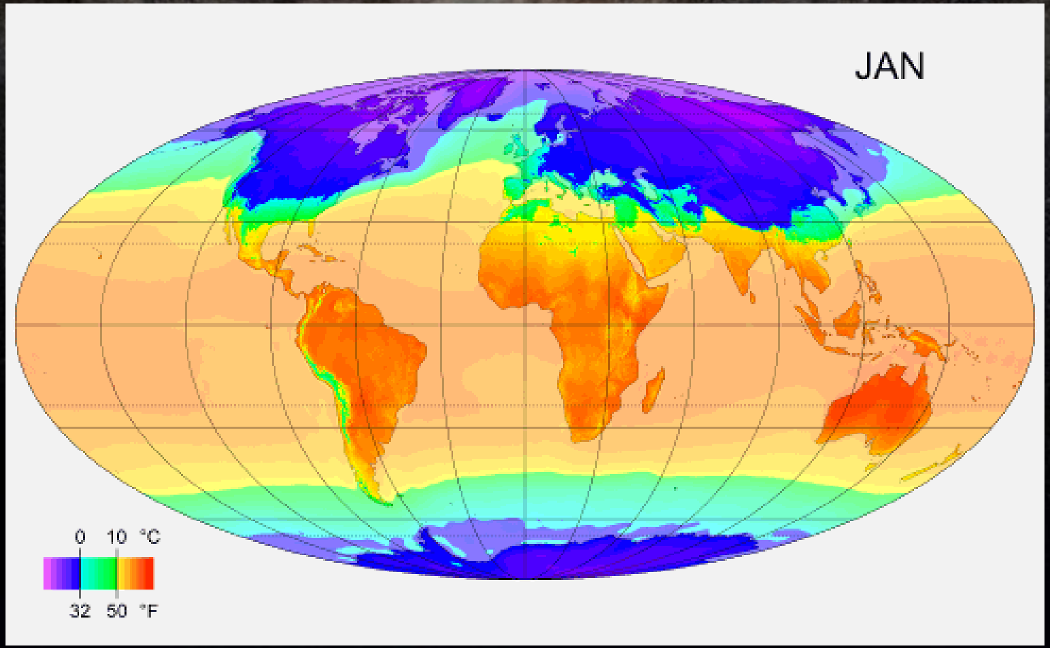
climatology

Weather vs. Climate

<u>**Weather**</u>, state of the atmosphere at a particular place during a <u>short period</u> of time.



<u>**Climate**</u>, conditions of the atmosphere at a particular location over a long period of time; it is the long-term summation of the atmospheric elements (and their variations) that, over short time periods, constitute <u>**weather**</u>.



Lower Atmosphere

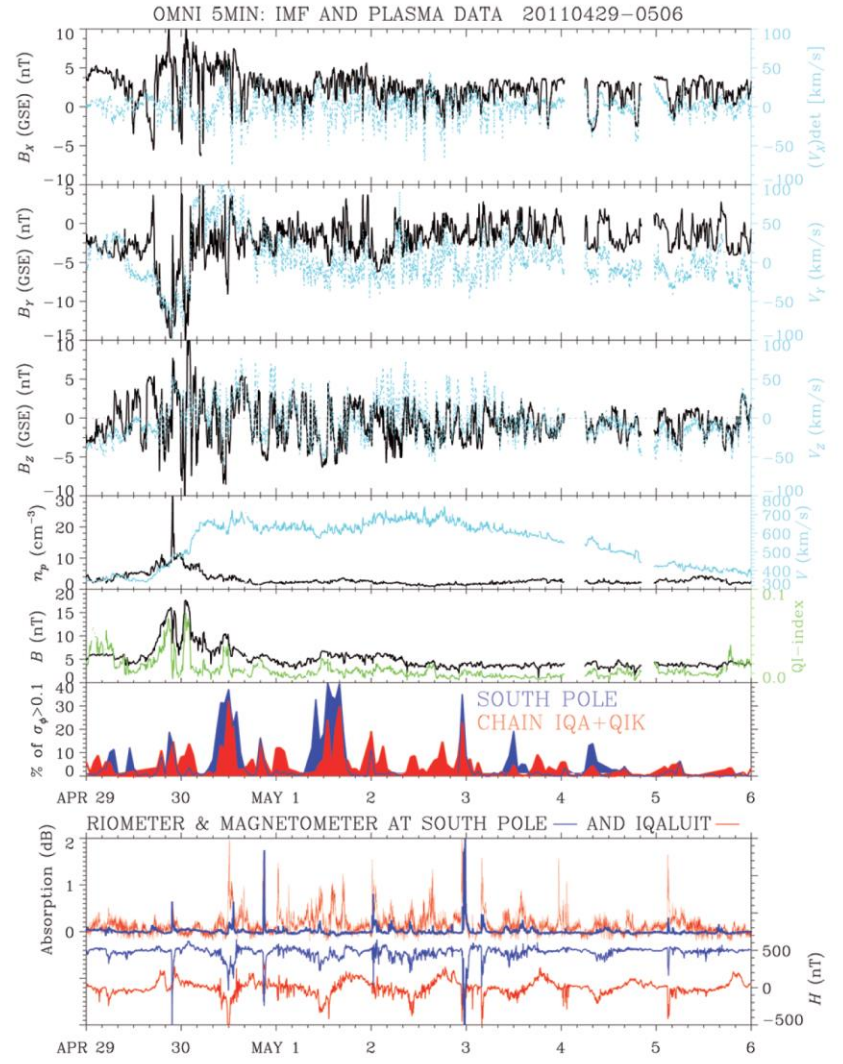
Weather vs. Climate

<u>Weather</u>

In general, weather relates to **<u>case events,</u>** allows studying the conditions of geospace in terms of selected and interesting quantities

This allows to identify possible correlations among physical parameters involved in the investigated phenomena by taking a snapshot in specific time interval.

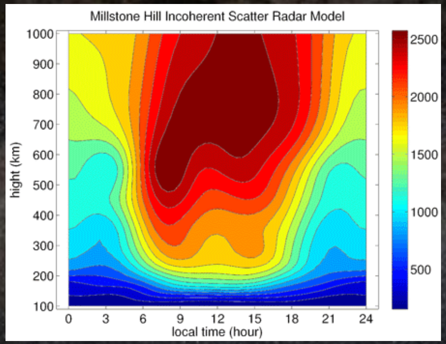
Prikryl et al. (2013), doi:10.4401/ag-6227



Upper Atmosphere

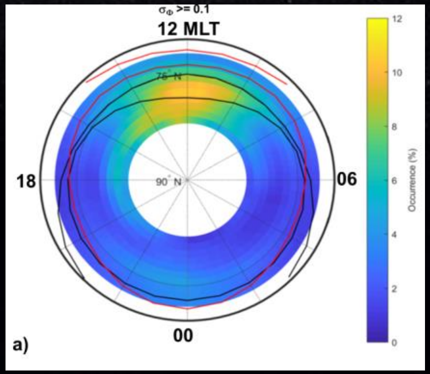
Weather vs. Climate

Climate



Plasma temperature climatology

Ionospheric Climatology: *Studies of ionospheric climatology address general, synthetic, averaged and large spatial scale ionospheric features, in contrast to specific ionospheric and space weather events.* (www.haystack.mit.edu/atm/science/space/ic/index.html)



Probability of phase scintillation over Svalbard

Ionospheric Scintillation Climatology: *To assess the general recurrent features of the ionospheric irregularities dynamics and temporal evolution on long data series, trying to catch eventual correspondences with scintillation occurrence.* (Alfonsi et al., Radio Science 2011).

Upper Atmosphere

Raised questions

What are the pro's and con's of a climatological picture?

What are the main physical phenomena behind Scintillation and TEC gradients occurrence?

What are the sectors of the high-latitude ionosphere more exposed to scintillation?

What are the main features of the high-latitude ionosphere highlighted by climatology?

What's the meaning of a ionospheric scintillation climatology and what's the difference with the (ionospheric) weather

What are the main results of the recent studies?

How to cook a good scintillation climatology?

What's the role of the external drivers in modulating the scintillation occurrence?

Recall on the physical context

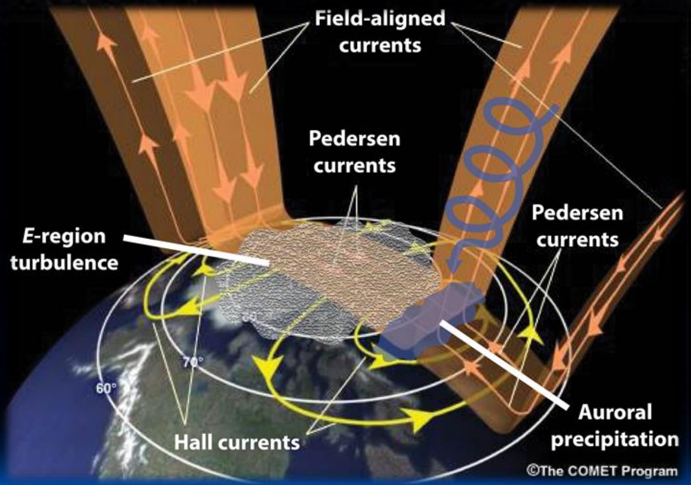
High-latitude ionosphere is directly connected with the Solar Wind through the coupling with the magnetosphere.

Solar events typically disturb the complex system of currents circulating in M-I system

Electron concentration in the ionosphere encounters the formation of spatio-temporal gradients, i.e. **ionospheric irregularities**

- Particle injection (mass/energy inflow/outflow)
- Plasma convection (electric conductance variations)

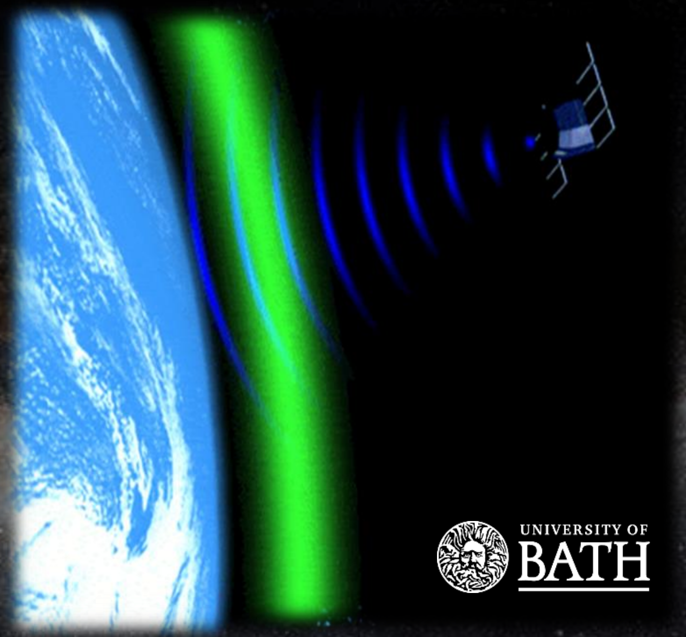
Ionospheric irregularities varies on large number of spatial scales (from few cm's to about 1000 km)



Coronal Mass Ejection events (mainly during Solar Max)

Fast solar wind streams from Coronal Holes (mainly during Solar Min)

Scintillation on GNSS signals



GNSS - Global Navigation Satellite Systems
1. Excellent probe (reliability, robustness, availability, etc.)
2. Must be protected against ionospheric threats

“Irregularities of the ionosphere" may the phase and amplitude of the signal «scintillate»

- Diffraction (if irregularities are of the order of the probing size of the signal; the Fresnel’s scale* is the more effective)
- Refraction (phase modulation), all scales + plasma dynamics

$$\Delta n \approx -\frac{r_e \lambda^2}{2\pi} N$$

$$\Delta\varphi = -2\pi r_e \,\Delta N_T / k_0^2$$

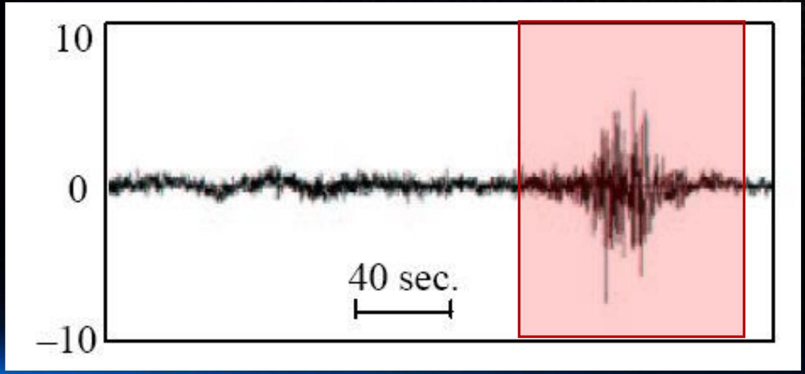
Like star twinkling

“There is no doubt that scintillation of satellite radio signals is a consequence of the existence of random electron-density fluctuations within the ionosphere.”
Wernik, A. W., Secan, J. A., & Fremouw, E. J. (2003). *Advances in Space Research*.

Loss of lock with the satellite

Scintillation

Reduced accuracy of positioning



*hundreds of meters for L-band and assuming irregularities at 350 km

How to measure scintillation

Scintillation is measured by statistical indices:

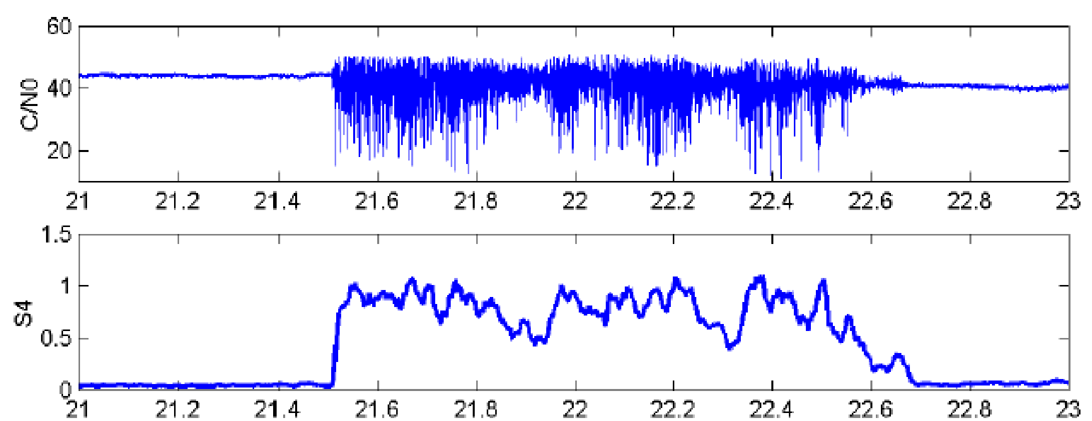
$$\sigma_\phi^2 = \langle \phi^2 \rangle - \langle \phi \rangle^2$$

phase scintillation index (σ_Φ)
amplitude scintillation index (S4)

$$S_4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}}$$

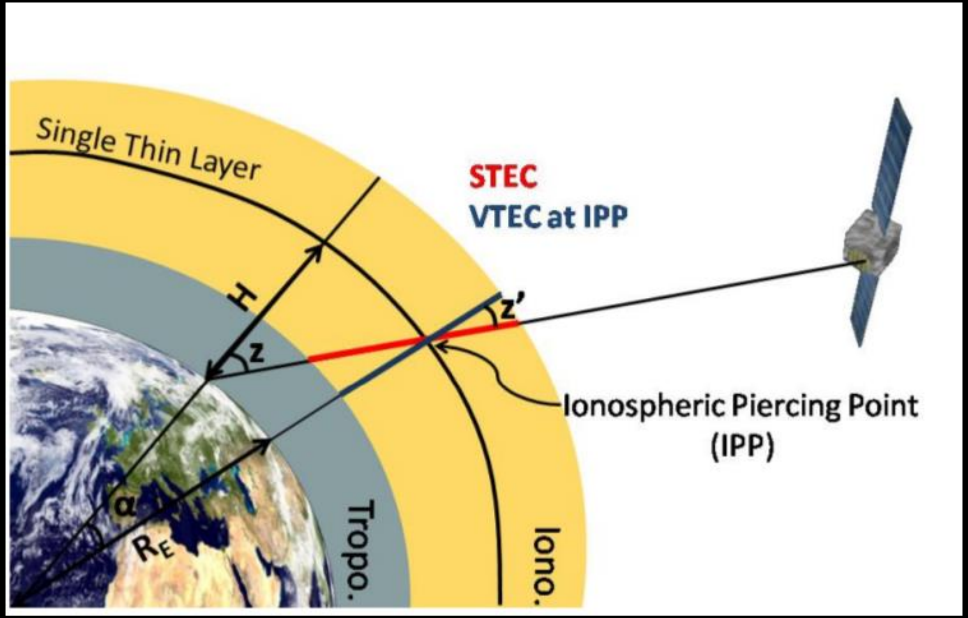
ISMReceivers are able to provide indices every 1 minute starting from 50 Hz (20 ms) data

Larger values of the indices correspond to increased fading of the signal (increased carrier to noise ratio)



Total Electron Content

$$\text{sTEC} = \int_L n_e(l)\,dl$$



$$VTEC = STEC * cos\left[sin^{-1}\frac{R_e * \cos(\theta)}{R_e + H}\right]$$

$$ROT = \Delta STEC/\Delta T$$

Physical measure
No special receivers are needed, only dual-frequency

What we can actually understand with scintillation climatology

Feature	Climatological model	Physical model
Transient phenomena	Not properly modelled	Modelled
New physics/phenomena	Modelled, but only if not transient	Not modelled
Average behaviour of the physical quantities	Modelled	Modelled
Phenomenon not in the data	Not modelled	Modelled
Phenomenon not formalized in a theoretical way	Modelled, if data account for it	Not modelled

Semi-empirical models are often a good compromise

How to cook a good scintillation climatology

How to cook a good scintillation climatology

Ingredients:

Suitable Network(s) of ISMR's
- If not available, geodetic receivers offer proxies

A big bunch of good scintillation data
- The longer, the better
- Data quality, selection and integration is an issue

Clear ideas about the phenomenon you want to model
- System of coordinates
- Cut/Thresholds on investigated parameters
- Physical assumptions

Companion sets of parameters to sort your climatology
- Geomagnetic activity indices
- Solar activity indices
- Solar Wind parameters
- Auroral indices
- …

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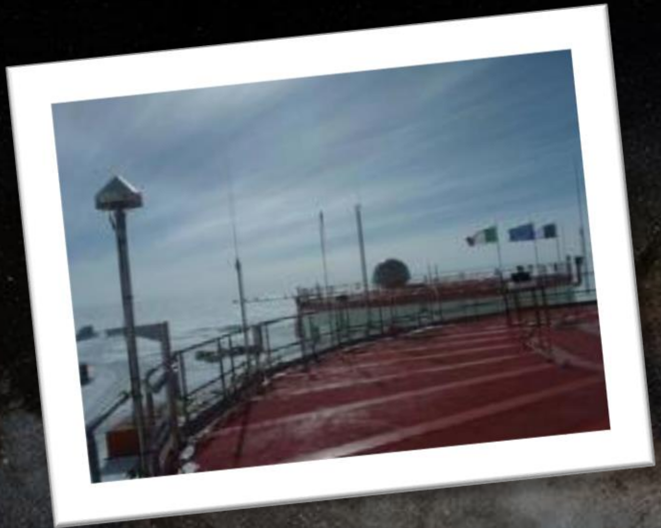
Suitable Network(s) of ISMR's

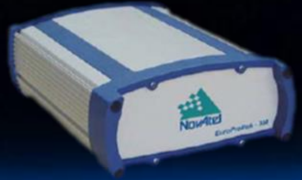
ISMRs are much more expensive (about 1 order of magnitude) than traditional geodetic receivers.

High-latitude sites pose often serious limitations due to the logistics

- Extreme environment
- Data transfer
- Station maintenance
- Many other small issues…



GSV4004



PolaRx(5)S

Suitable Network(s) of ISMR’s

“GNSS Research and Application for Polar Environment” (GRAPE)

Expert Group in the frame of SCAR

Leader: Giorgiana De Franceschi - INGV

GNSS receivers for scintillation in the Arctic

http://www.grape.scar.org/

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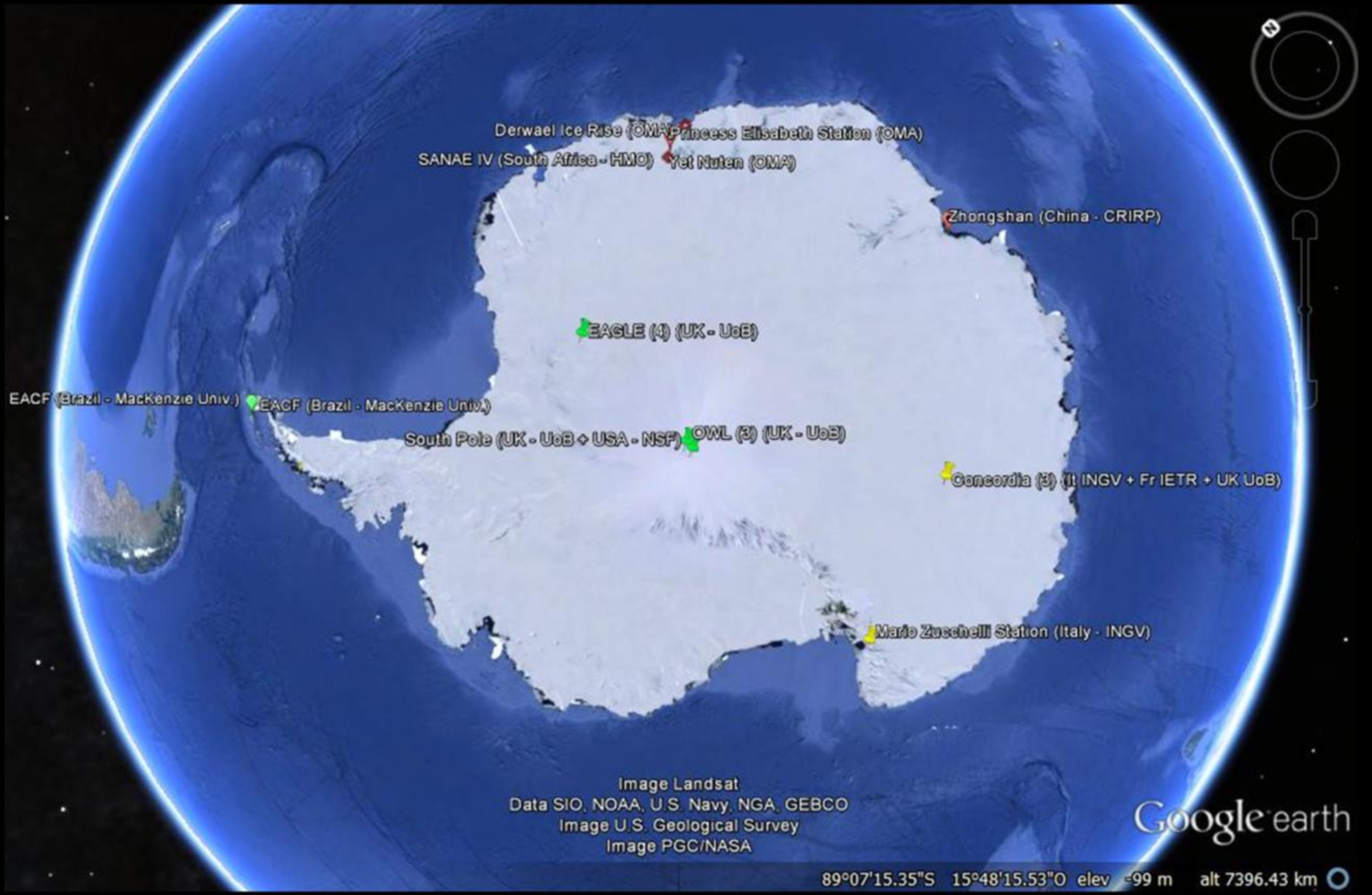


GNSS receivers for scintillation in Antarctica

http://www.grape.scar.org/

Ground Based Scintillation Climatology

- Maps of ionospheric scintillation and TEC derived parameters
  1. Mean value and standard deviation "MEANMAP"
  2. Occurrence "OCCUMAP"

of the main parameters measured by modern GNSS receivers for scintillation

- Mainly Scintillation indices (S_4 and σ_Φ) and TEC derived parameters (sTEC, vTEC, ROT), but also receiver behaviour parameters such as C/n, Standard Deviation of the Code Carrier, Loss of Lock events.
- System of reference: Geographic and geomagnetic coordinates (AACGM), Universal and Magnetic Local Times*, Azimuth, Elevation
- Different geomagnetic conditions can be selected (Kp, IMF, Dst, R12, AU/AL/AE/AO)
- Homemade at INGV
- Developed for: GISTM, PolaRx(5)S, SCINTMON, Javad receivers, geodetic receivers (TEC and Scintillation proxies)

*Expressed@ the IPP

Altitude Adjusted Corrected Geomagnetic Coordinates

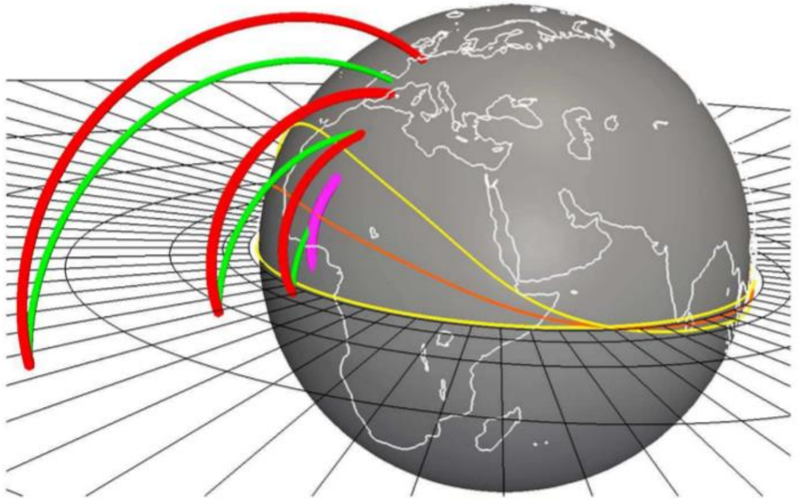
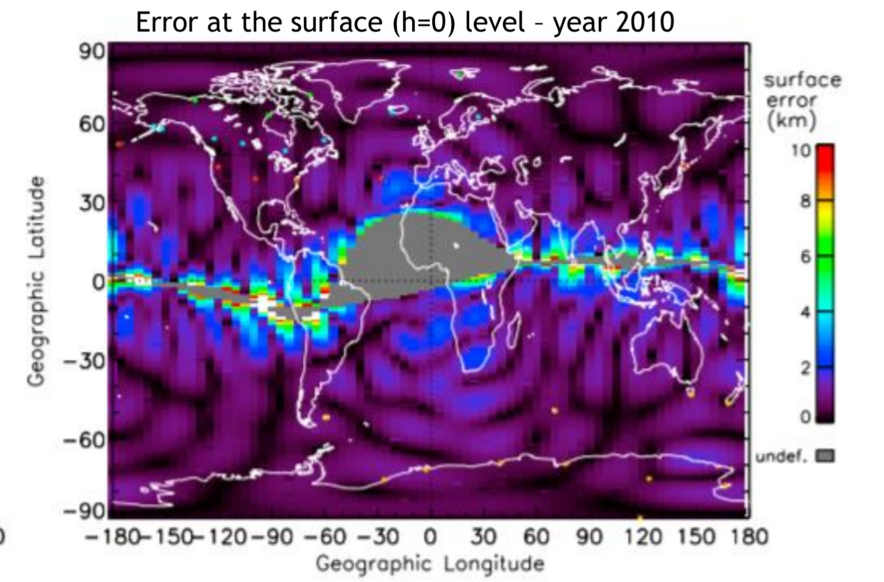


Figure 1. Examples of determining AACGM coordinates for four geographic locations along the prime meridian. Red lines represent IGRF field lines emanating from geographic starting locations at 50°, 40°, and 30° latitude, and ending at the Earth-centered magnetic dipole equator. AACGM coordinates are given by the coordinates dipole field lines, shown in green. The magenta line shows the IGRF field line starting at 20° latitude, which intersects the surface of Earth before the dipole equator. AACGM coordinates are undefined for such locations. The region near the magnetic dip equator (orange line) which includes these field lines is marked by yellow lines on Earth's surface.

The AACGM coordinates of a given point, specified by its geographic latitude, longitude and altitude (h) above the surface of the Earth, are determined by following the magnetic field line from the geographic starting point to the magnetic dipole equator. The AACGM coordinates are then given by the latitude and longitude of the dipole field line that connects the point on the magnetic equator to the surface of the Earth

All points along a magnetic field line have the same geomagnetic latitude and longitude.



Software for GEO<-- →AACGM conversion at:
http://vt.superdarn.org/tiki-index.php?page=software

Baker, K. B. and Wing, S.: A new magnetic coordinate system for conjugate studies at high latitudes, JGR, 1989.
Shepherd, S. G. (2014). Altitude-adjusted corrected geomagnetic coordinates: Definition and functional approximations. JGR.

GBSC selectable features

Quantity	Description	Typical assumption
Elevation angle	Reduce the impact of large values of the indices not related with scintillation (ex. multipath)	30 degrees
Vertical/Slant	Scintillation indices and TEC can be projected to the vertical to minimize the impact of the geometry $S_4^{vert} = S_4^{slant} \left(\frac{1}{F(\alpha_{elev})}\right)^b$ $\sigma_\Phi^{vert} = \sigma_\Phi^{slant} \left(\frac{1}{F(\alpha_{elev})}\right)^a$ $vTEC = \frac{sTEC}{F(\alpha_{elev})}$	Vertical
Statistical accuracy	Remove the contribution of bins with low statistics $R = 100 \times \frac{\sigma(N_{tot})}{N_{tot}} = \frac{100}{\sqrt{N_{tot}}}$	2.5 - 10 %
Geomagnetic condition	A selection of the geomagnetic behavior of each day, based on the Kp and DST index	Quiet/Disturbed/All
IMF condition	A selection on the IMF component	Bx,By,Bz (GSM) > or < 0 No IMF selection
Solar Cycle	Selection on the R12 index	Low, Medium, High Rising phase, Descending phase

Concerning projecting to the vertical

Scintillation indices and slant TEC can be projected to the vertical at the IPP, in order to account for geometrical effects on the measurements made at different elevation angles

$$\sigma_\Phi^{vert} = \frac{\sigma_\Phi^{slant}}{(F(\alpha_{elev}))^{\frac{1}{2}}}, \quad S_4^{vert} = \frac{S_4^{slant}}{(F(\alpha_{elev}))^{b}}, \quad vTEC = \frac{sTEC}{F(\alpha_{elev})}$$

•With:

$$F(\alpha_{elev}) = \frac{1}{\sqrt{1-\left(\frac{R_E \cos\alpha_{elev}}{R_E + H_{IPP}}\right)^2}}$$

Mannucci et al., 1993

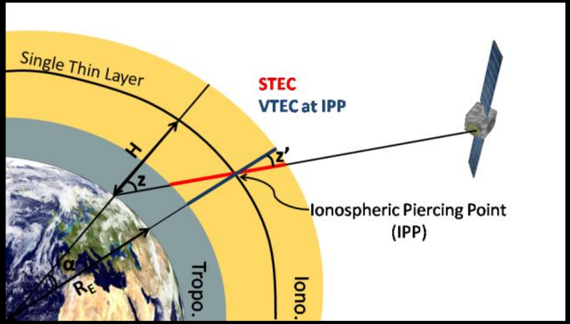
•The dependence of the scintillation indices on the zenith angle is deeply discussed in *Rino et al (1979), from which:*

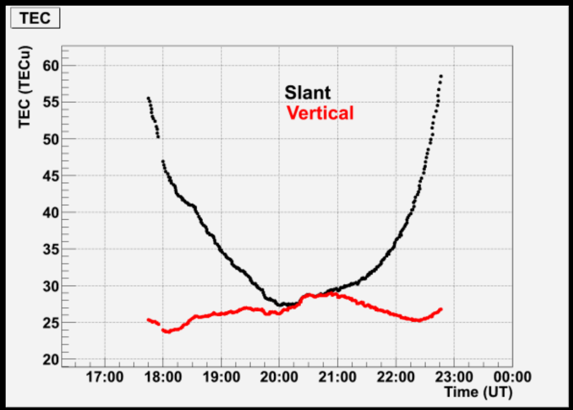
$$b = \frac{p+1}{4}$$

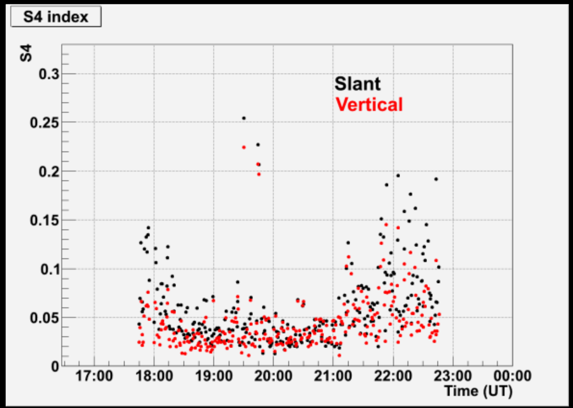
•As described in *Spogli et al.* (2009) and *Alfonsi et al. (2011)* and by following the consideration in *Wernik et al. (2003)*, if not directly measured (as in the case of PolaRxS), the exponent *p* could be reasonably chosen to be *p*=2.6, corresponding to *b*=0.9.

•This value is reasonable for high latitude data and it is derived from consideration about plasma drift velocity.

•Weak scintillation approximation: underestimation of the real scintillation







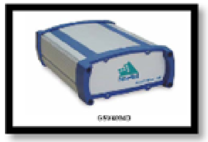
More on verticalisation in:
Spogli et al. (2013). Assessing the GNSS scintillation climate over Brazil under increasing solar activity. JASTP.

Table III. ISMRB Data Log - Message ID = 274

Message byte count = H + 4 + (n * 152) (n = number of SVs being tracked)

Field #	Data	Bytes	Format	Units	Offset
1	Header	H			0
2	Number of SV observations	4	integer	N/A	H
	For First SV observation				
3	PRN	2	integer	N/A	H+4
4	SV Azimuth angle[1]	4	float	degrees	H+8
5	SV Elevation angle[1]	4	float	degrees	H+12
6	C/N_0	8	double	dB-Hz	H+16
7	Total S4	8	double	dimensionless	H+24
8	Correction to total S4	8	double	dimensionless	H+32
9	1-second phase sigma	8	double	radians	H+40
10	3-second phase sigma	8	double	radians	H+48
11	10-second phase sigma	8	double	radians	H+56
12	30-second phase sigma	8	double	radians	H+64
13	60-second phase sigma	8	double	radians	H+72
14	Average of Code/Carrier divergence	8	double	meters	H+80
15	Sigma of Code/Carrier Divergence	8	double	meters	H+88
16	TEC at TOW - 45	4	float	TECU	H+96
17	ΔTEC from TOW - 60 to TOW - 45	4	float	TECU	H+100
18	TEC at TOW - 30	4	float	TECU	H+104
19	ΔTEC from TOW - 45 to TOW - 30	4	float	TECU	H+108
20	TEC at TOW - 15	4	float	TECU	H+112
21	ΔTEC from TOW - 30 to TOW - 15	4	float	TECU	H+116
22	TEC at TOW	4	float	TECU	H+120
23	ΔTEC from TOW - 15 to TOW	4	float	TECU	H+124
24	L1 Lock time	8	double	seconds	H+128
25	Channel status	4	integer		H+136
26	L2 Lock Time	8	double	seconds	H+140
27	L2 C/N_0	8	double	dB-Hz	H+148
28...	For Next SV Observation				

Note 1: Data may also be included for SVs that are unhealthy. However, the Azimuth and Elevation may be set to 0. All scintillation data will still be valid. The TEC values may be set to 0 because of the unavailability of the Tau_GD value.



GISTM data record

Amplitude scintillation index (S4), and phase scintillation index (σϕ), computed over 1, 3, 10, 30 and 60 seconds.

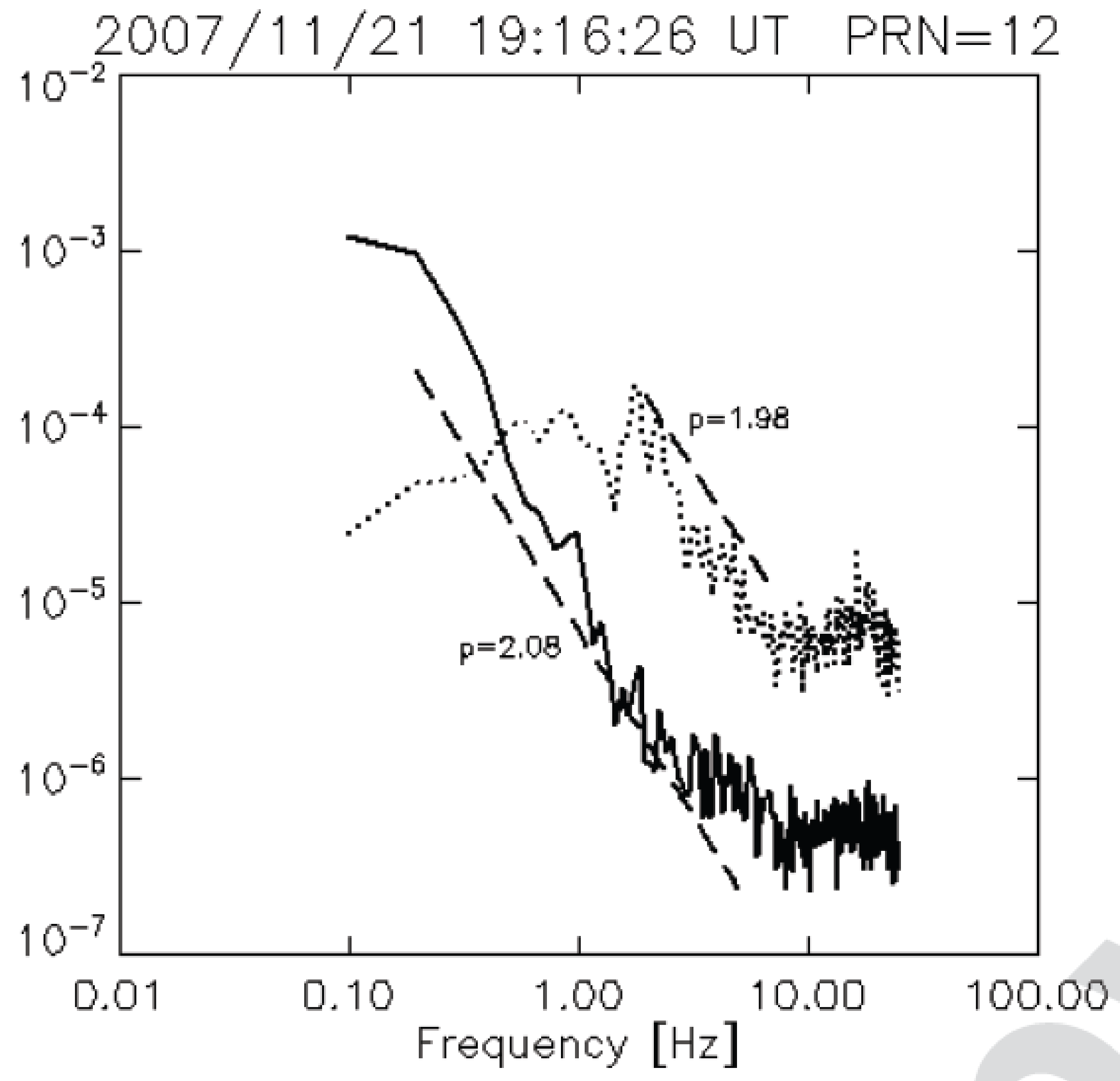
TEC and TEC change are each logged every 15 seconds.

Parameters related to the signal status, quality, multipath, etc.

PolaRxS has many fields more (more frequencies)
SCINTMON is a single frequency: no TEC, S4 only

GBSC: Physical assumptions

- Ionospheric piercing point at 350 km
  - Both in the vertical projection and in the AACGM
- Geometry ambiguity faced trough verticalization
  - Allows merging different receivers
  - Vert. of scintillation indices: weak scintillation approximation
    - Underestimation of the real scintillation
- Phase spectral index:
  - Phase spectrum approximation (single p)
  - Assumed as constant for GSV4004, Scintmon, Javad
  - Measured by PolaRx(5)S



Wernik et al., 2008

Highlights from recent results

Spogli et al. (2009). Climatology of GPS ionospheric scintillations over high and mid-latitude European regions. Ann. Geophys, 27, 3429-3437.

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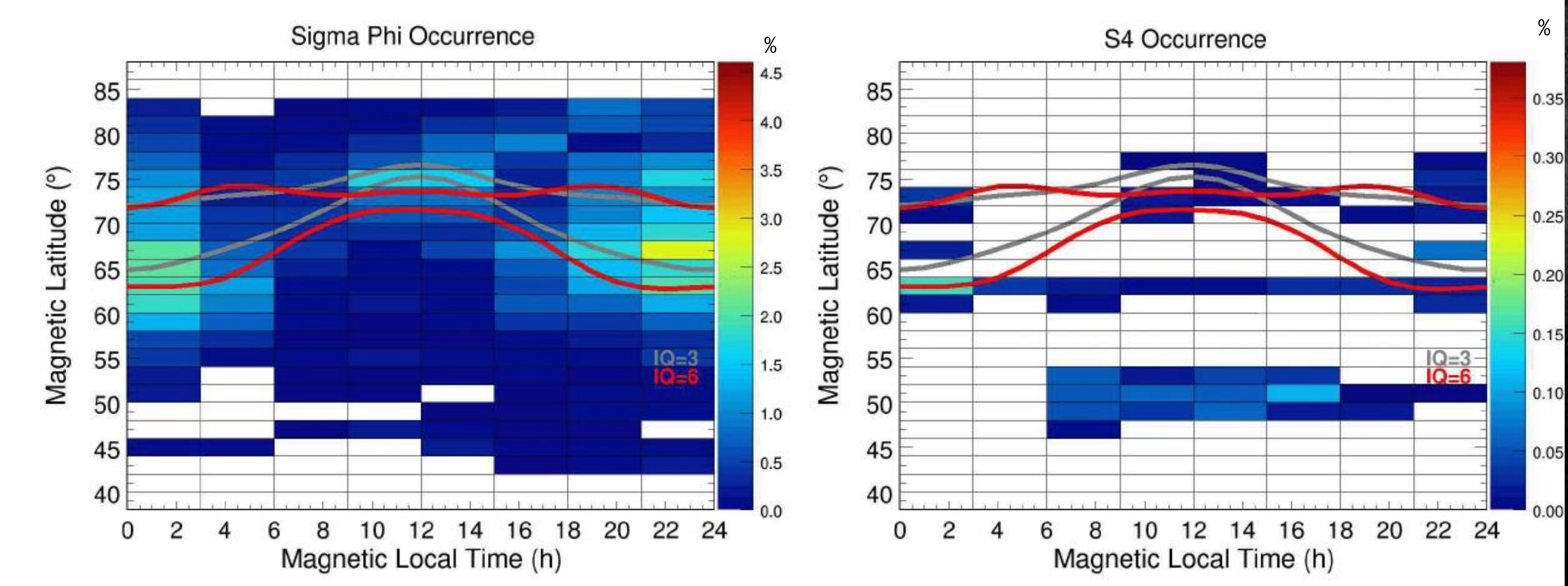

Phase scintillation has a larger occurrence:

- Phase scintillation: refractive (plasma dynamics, large scales) + diffractive (small scales*)
- Amplitude scintillation: diffractive (small scales*)

*small scales, i.e. below the Fresnel's scale

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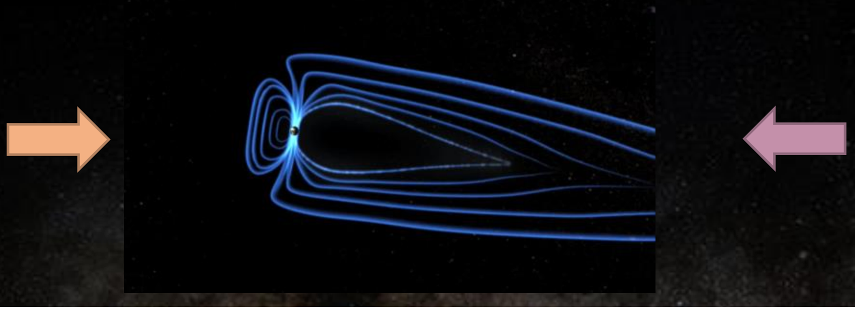
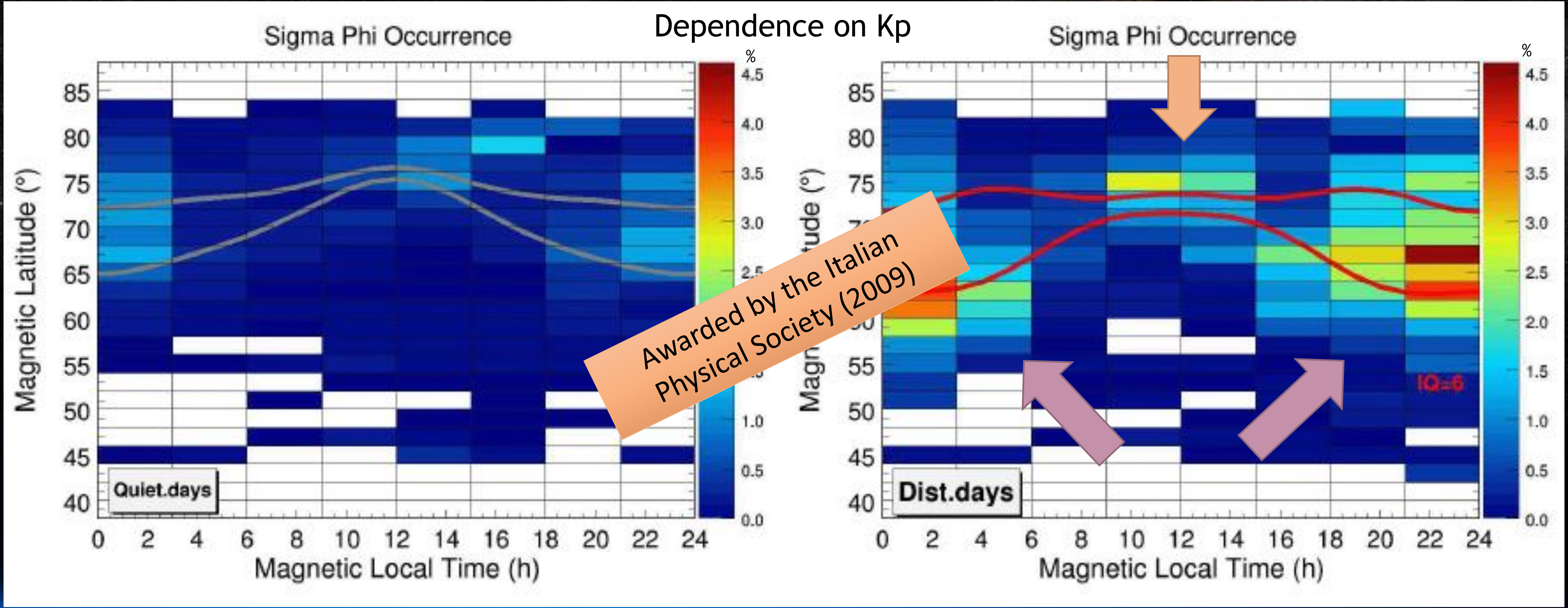
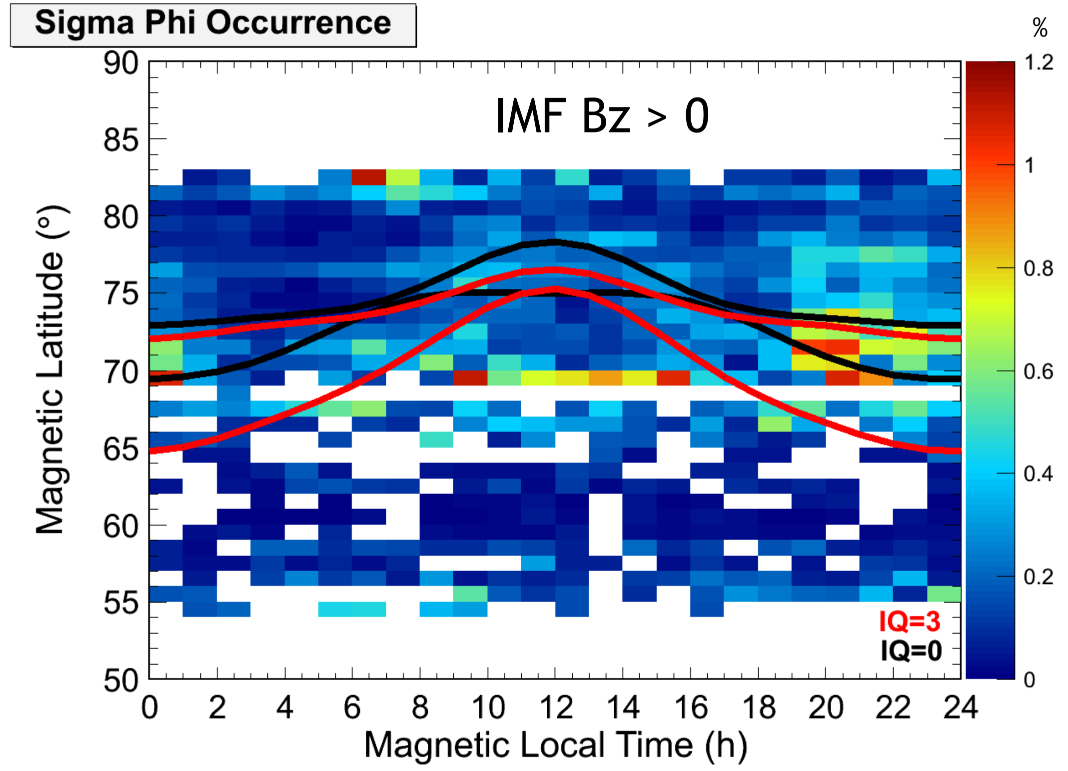
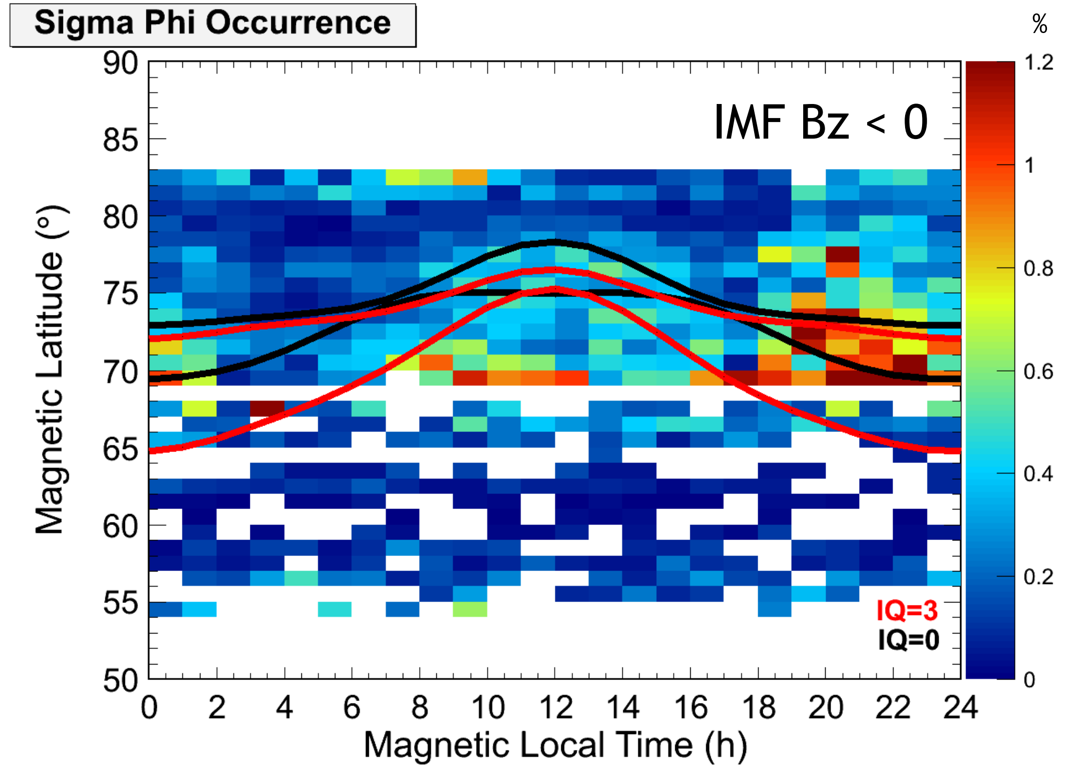




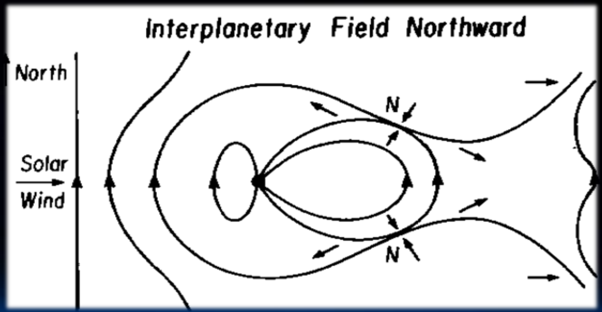
Highlights from recent results

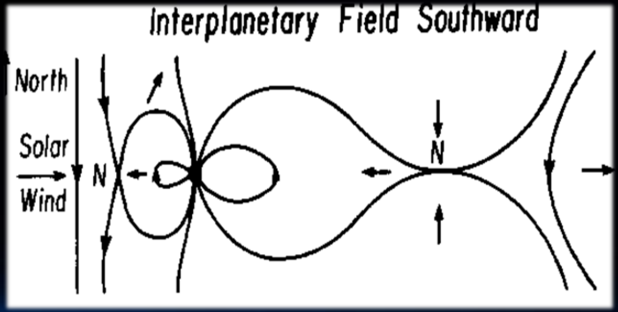
Alfonsi et al. (2011). Bipolar climatology of GPS ionospheric scintillation at solar minimum. Radio Science, 46(3).





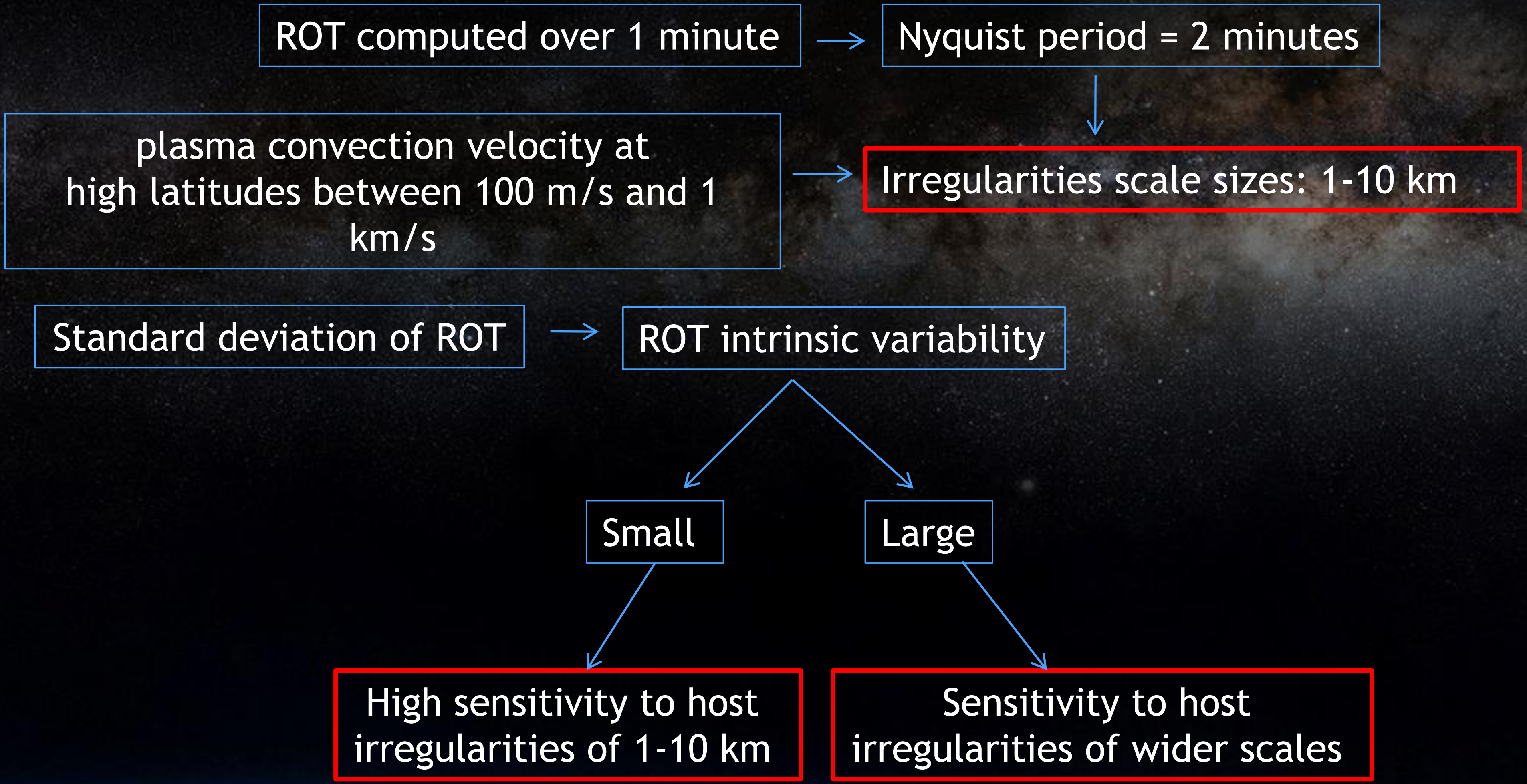
Closed magnetosphere





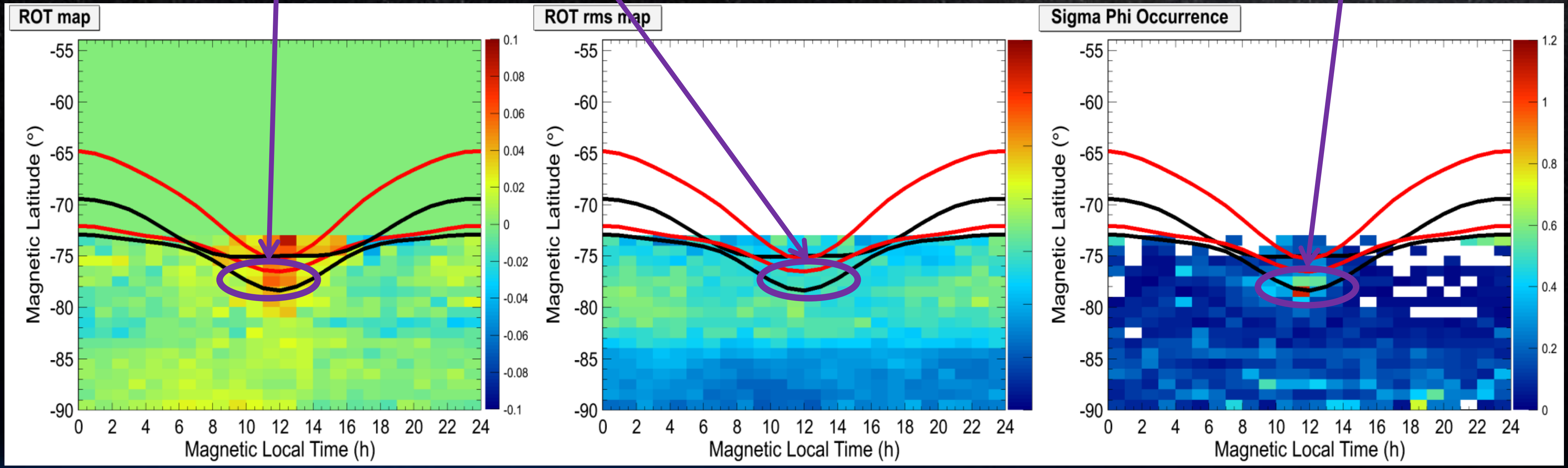
Open magnetosphere

Can GBSC provide information on the irregularities scale sizes?



Highlights from recent results
Speculation on irregularities scale size and scintillation occurrence

Case	|ROT|	ROTrms	Active Range	Scintillations
1	High	high	all scales	σ_Φ, S_4
2	High	low	predominant few kilometers scale	predominant σ_Φ
3	Low	low	little few kilometers scale	not defined
4	Low	high	all scales	σ_Φ, S_4



Alfonsi et al., 2011

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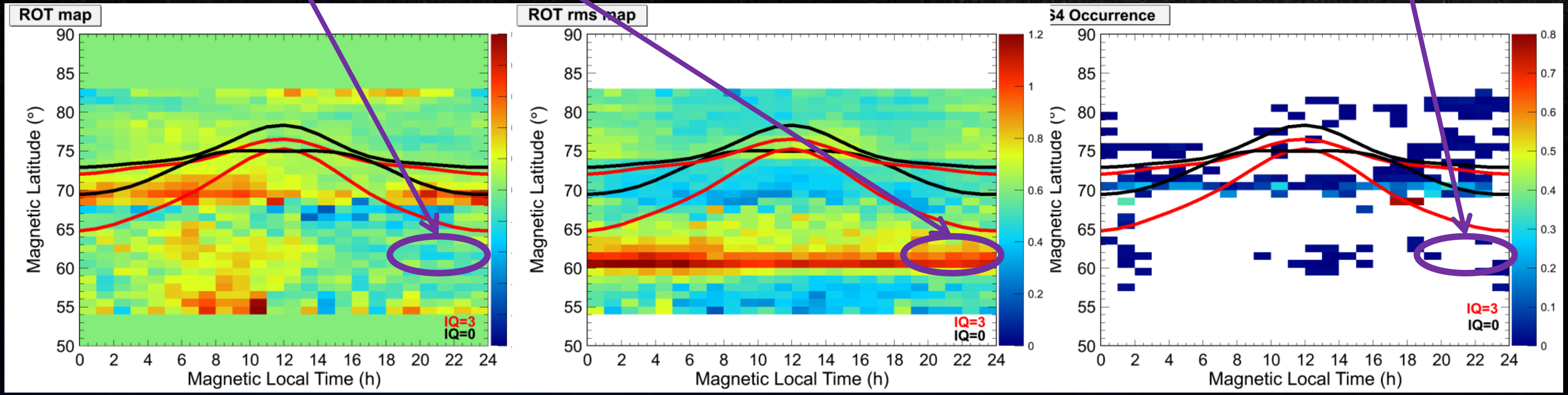
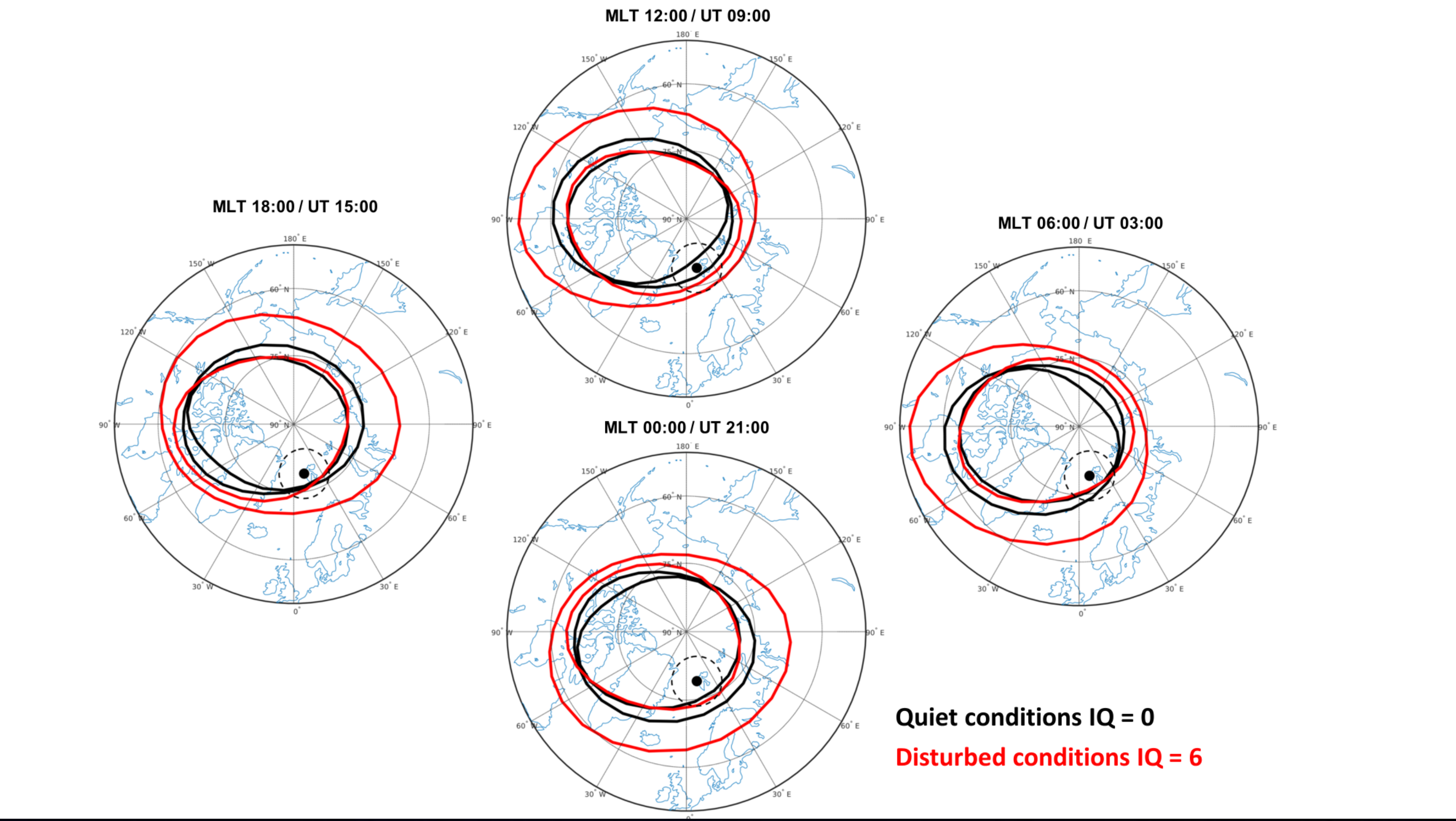


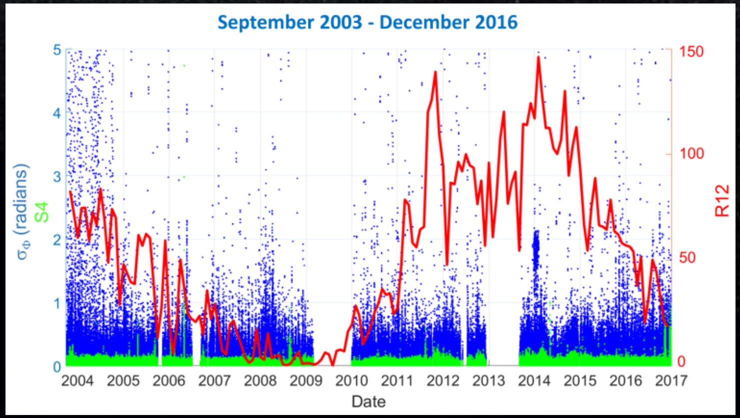
Highlights from recent results
Climatology over (more than) 1 solar-cycle!

De Franceschi et al., under review in Scientific Reports



September 2003

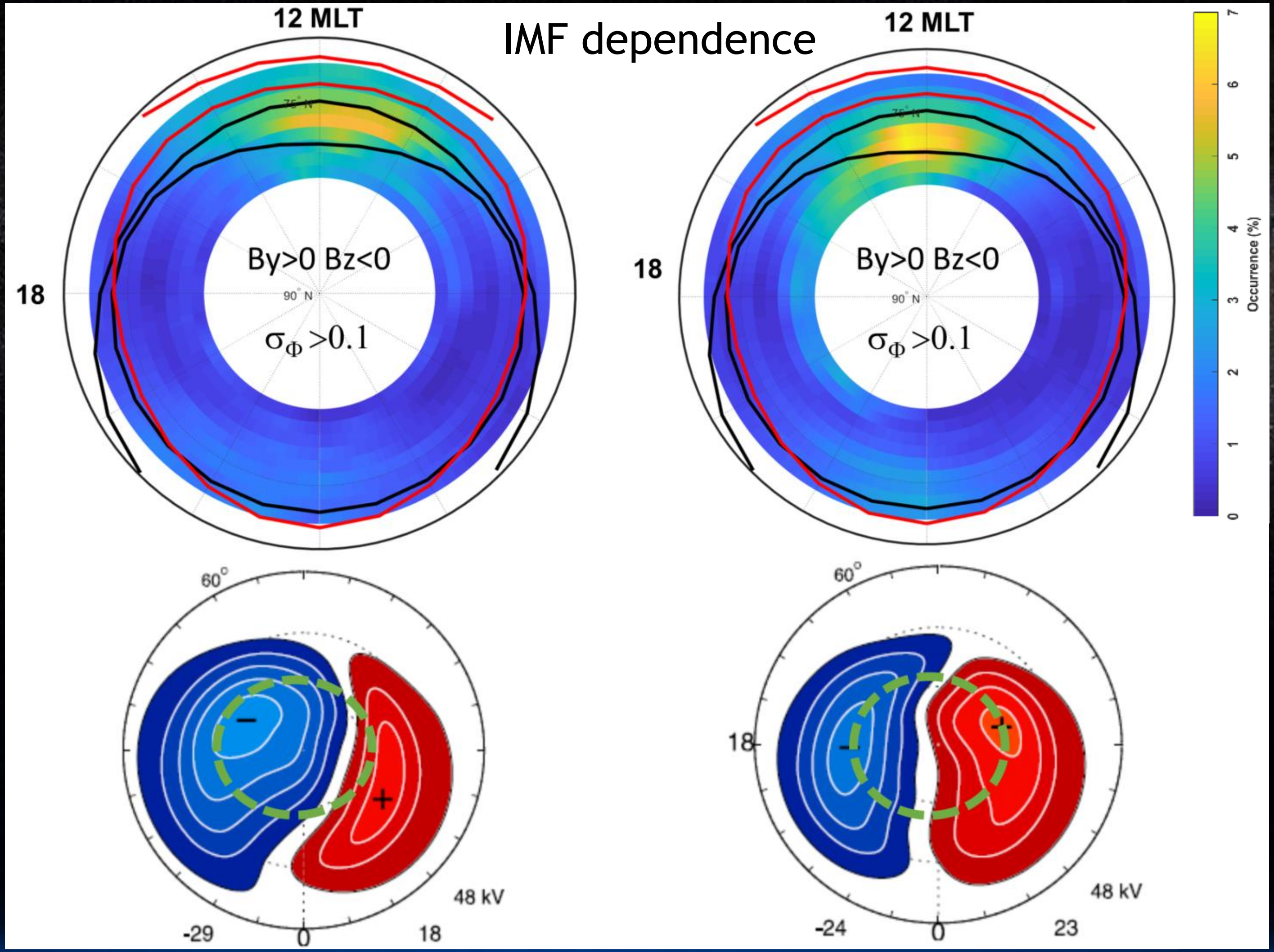
November 2015



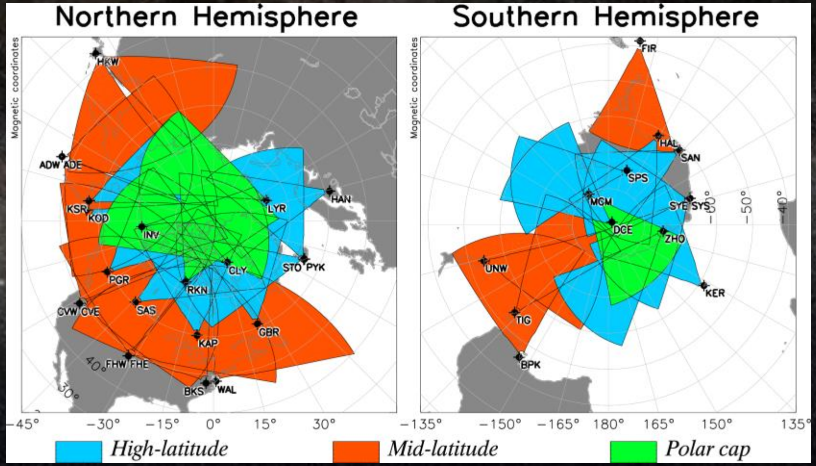
The Ny-Ålesund ionospheric station is the perfect site to study scintillations in the auroral/cusp/cap regions

Highlights from recent results
Climatology over (more than) 1 solar-cycle!

De Franceschi et al., under review in Scientific Reports



SuperDARN

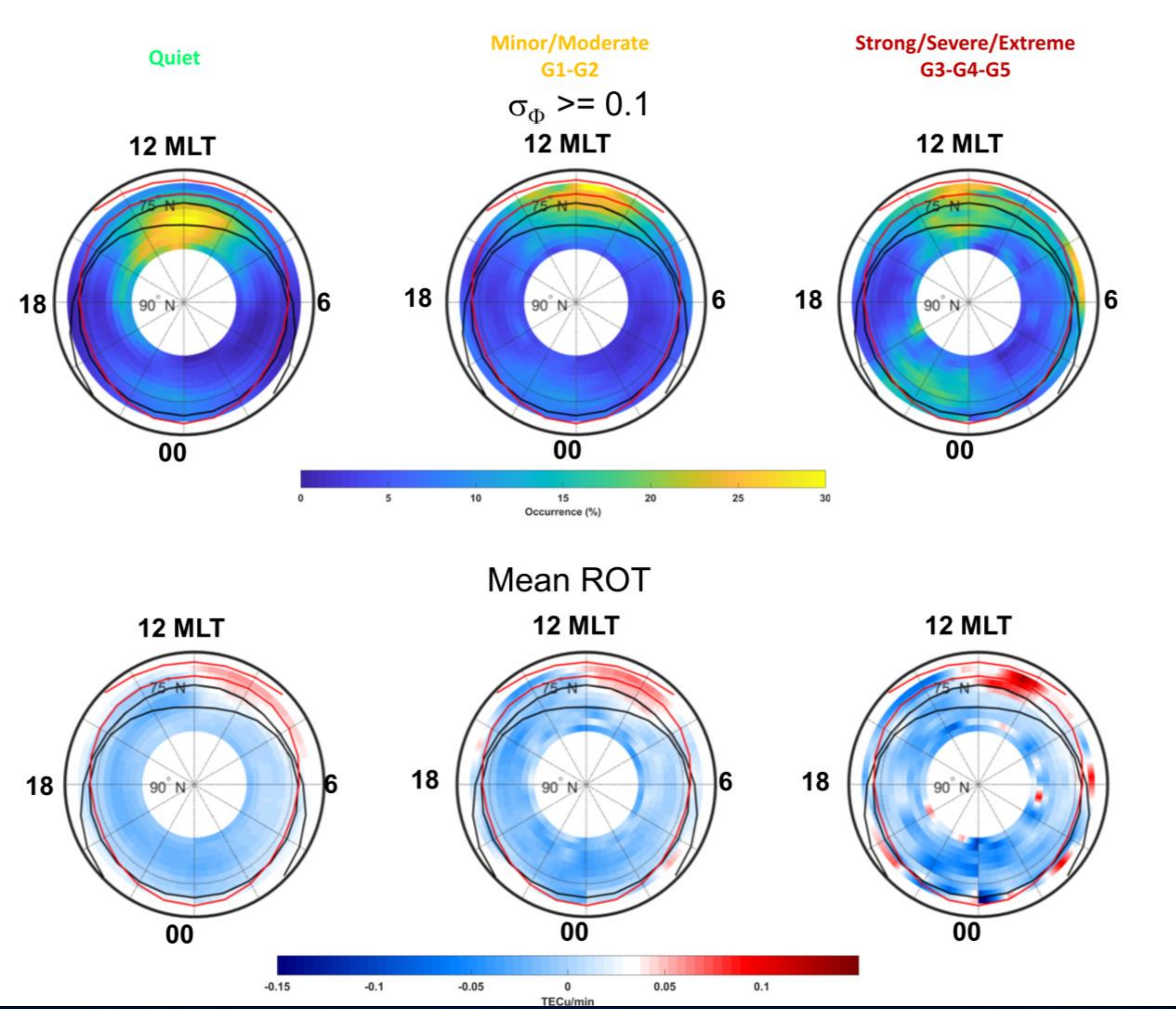


Statistical convection patterns sorted by IMF clock angle for 5 nT < BT < 10 nT. Color indicates the electric potential from SuperDarn measurements.

Pettigrew, E. D. et al., 2010

Highlights from recent results
Climatology over (more than) 1 solar-cycle!

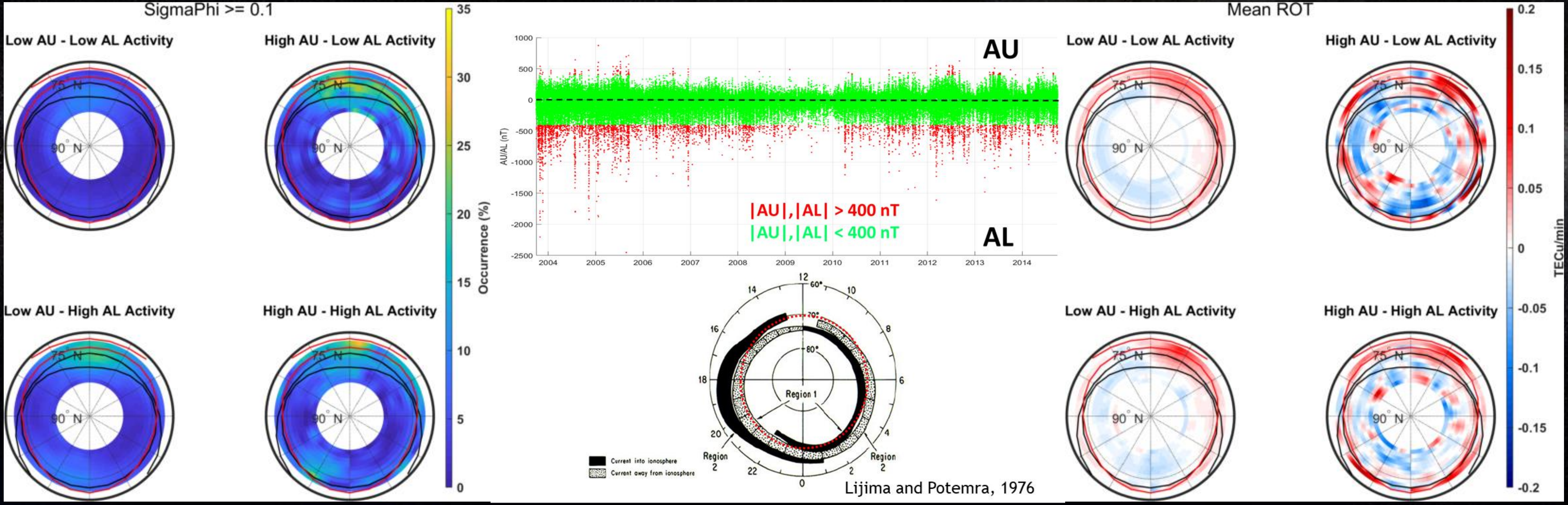
De Franceschi et al., under review in Scientific Reports



Dependence on storm intensity (NOAA G-scale based on Kp)

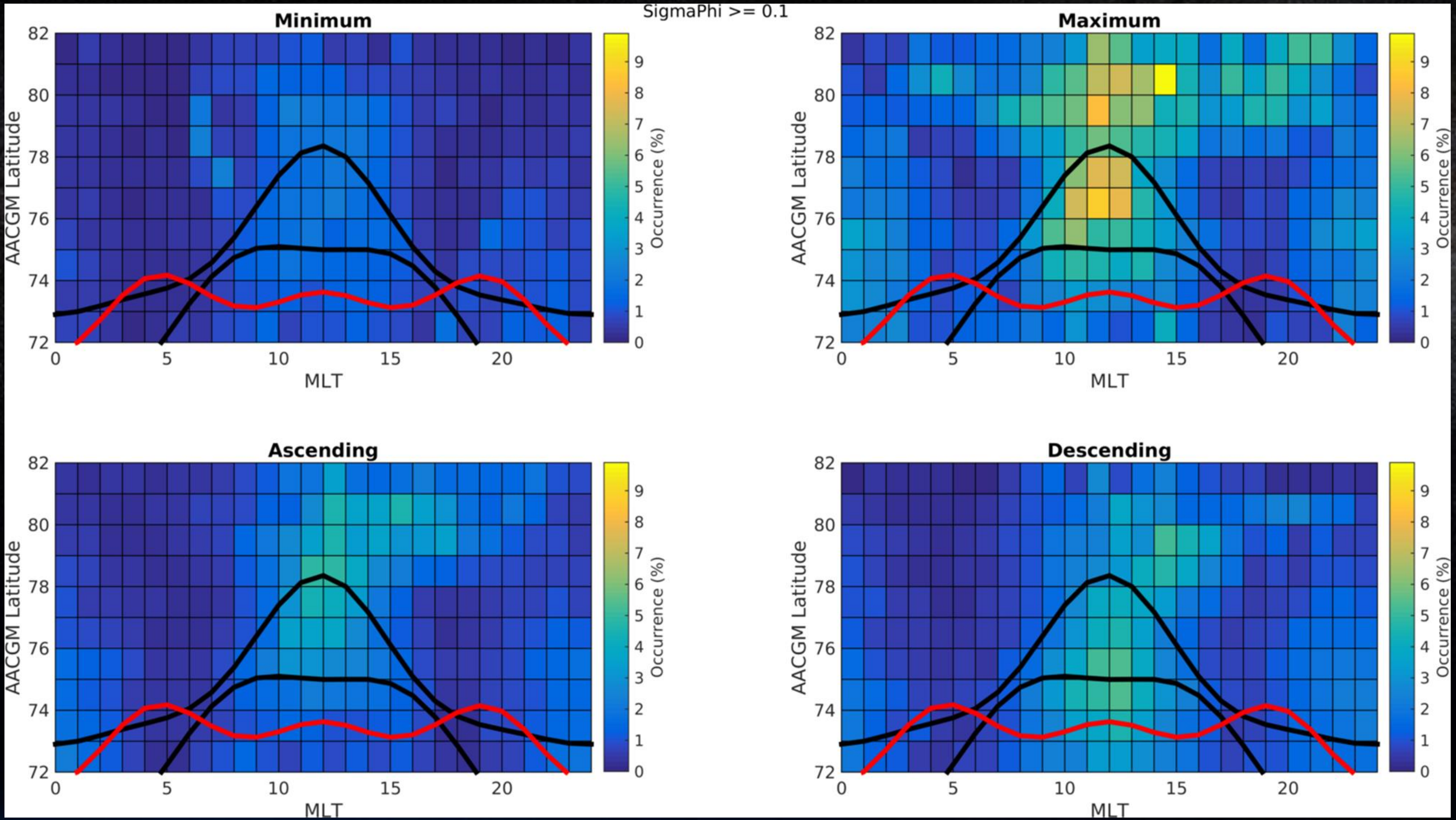
Highlights from recent results
Climatology over (more than) 1 solar-cycle!

De Franceschi et al., under review in Scientific Reports



Highlights from recent results
Climatology over (more than) 1 solar-cycle!

De Franceschi et al., under review in Scientific Reports



Highlights from recent results
The Canadian sector

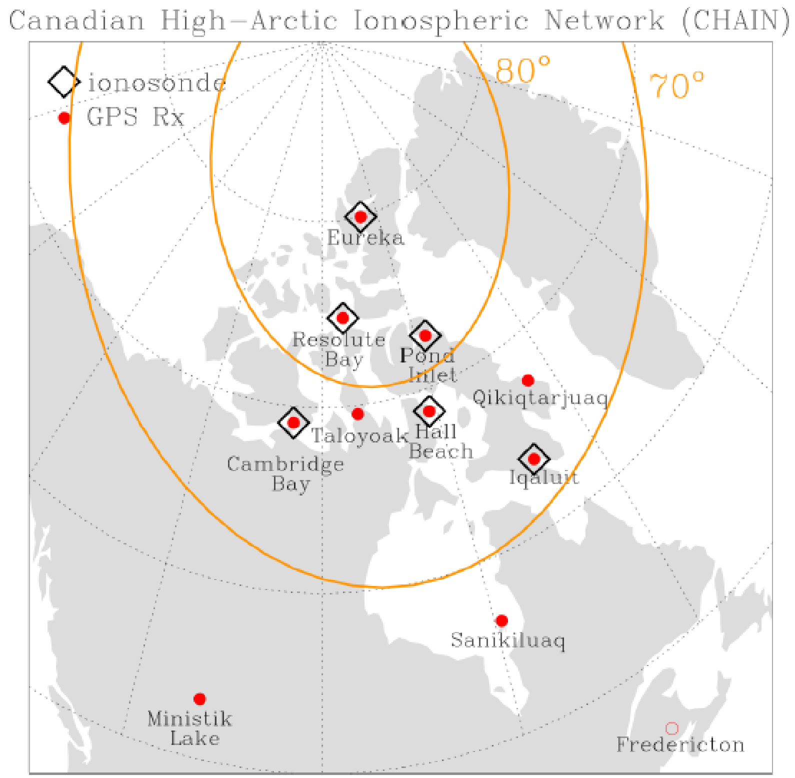


Figure 1. Canadian High Arctic Ionospheric Network (CHAIN): the GPS Ionospheric Scintillation and TEC Monitors and Canadian Advanced Digital Ionosondes (CADIs). The corrected geomagnetic (CGM) latitudes 70 and 80°, in yellow, are superposed over the geographic grid.

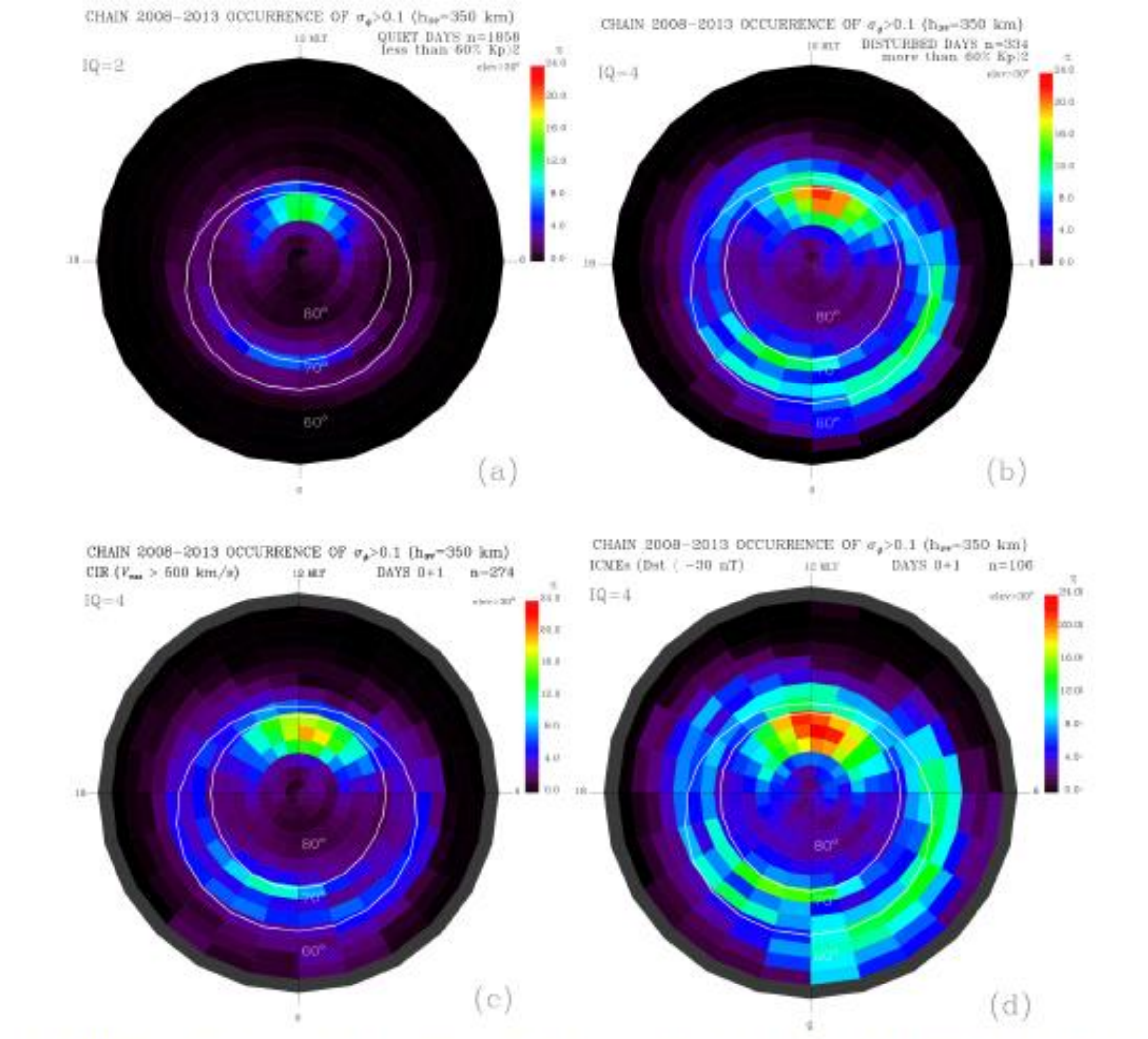


Figure 2. The 2008–2013 phase scintillation occurrence maps for geomagnetically (a) quiet and (b) disturbed days, and for (c) CIR/HSS and (d) ICME days.

Prikryl et al. (2015). Climatology of GPS phase scintillation at northern high latitudes for the period from 2008 to 2013. *Annales Geophysicae (09927689)*, *33*(5).

Highlights from recent results: plasma velocity and Scintillation

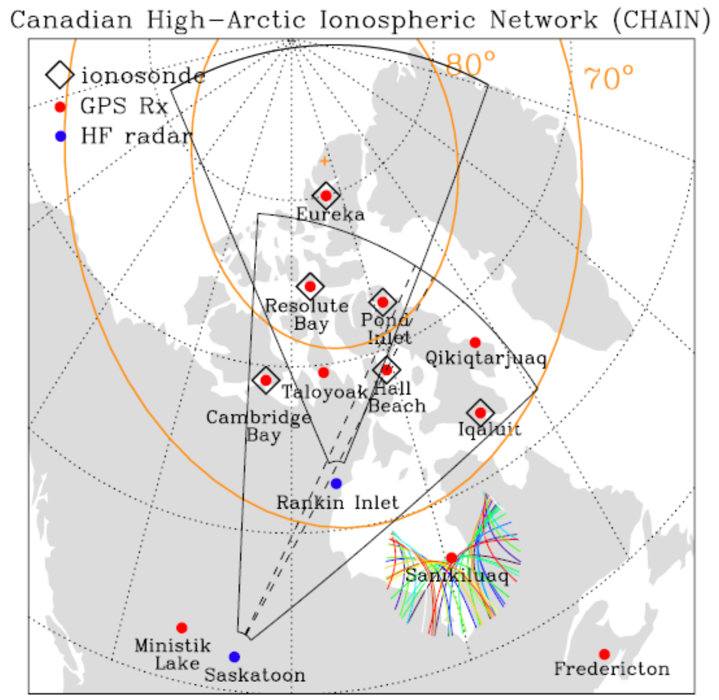


Fig. 1. Canadian High Arctic Ionospheric Network (CHAIN). The loci of ionospheric pierce points (IPPs) at 350 km altitude for all GPS satellites as seen from Sanikiluaq at elevation angles above 30° during one day are shown. The corrected geomagnetic (CGM) latitudes 70° and 80° and fields of view of two SuperDARN radars are superposed over the geographic grid. Beam 8 for the Saskatoon radar that is used in the statistical study is shown with dashed line.

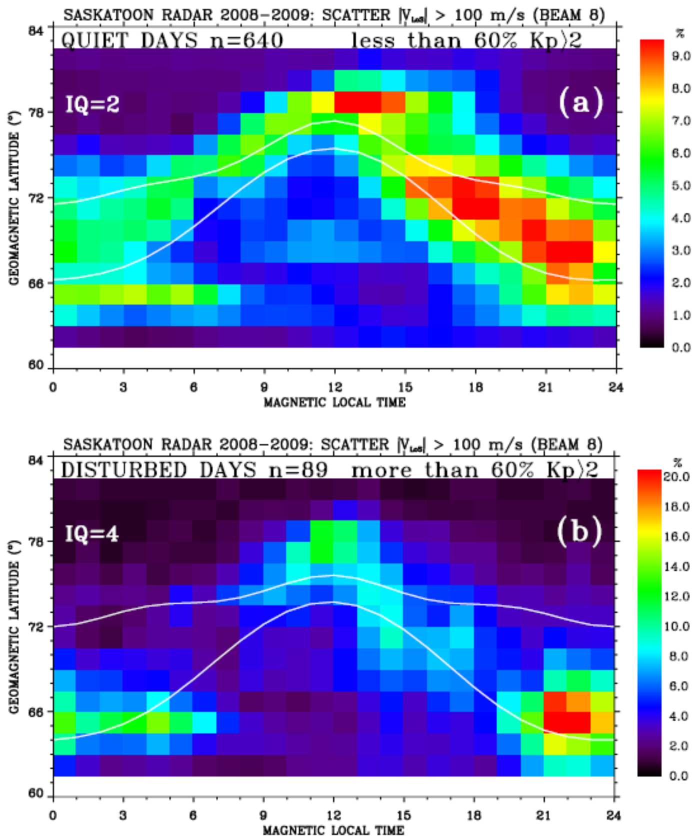


Fig. 9. The occurrence of E- and F-region ionospheric backscatter with absolute value of LoS velocity exceeding 100 m s^{-1} observed by the Saskatoon radar beam 8 during geomagnetically **(a)** quiet and **(b)** moderately disturbed days.

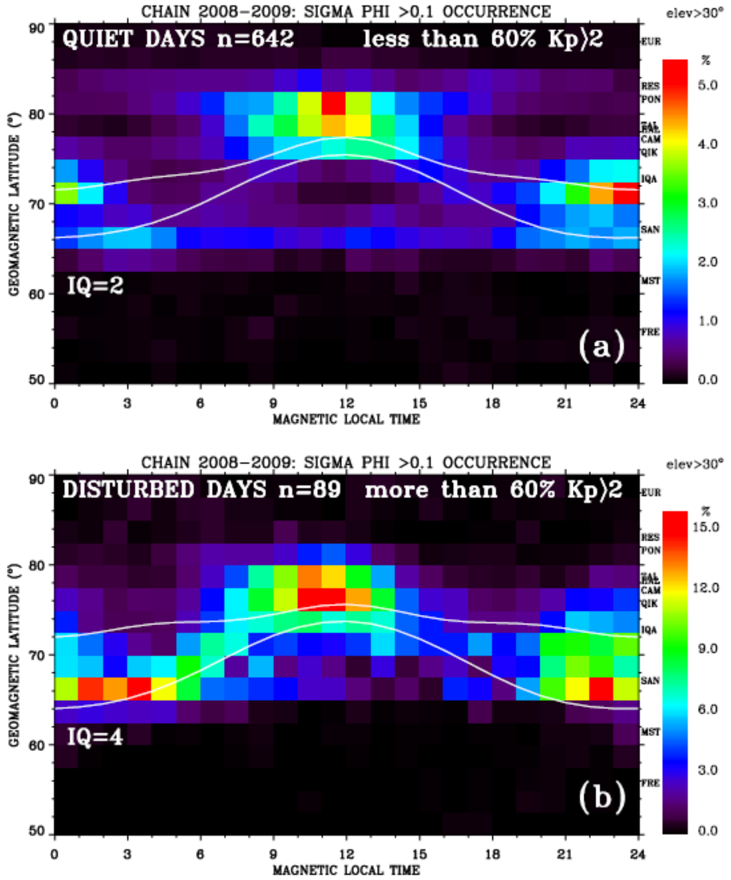


Fig. 8. Phase scintillation maps for geomagnetically **(a)** quiet and **(b)** disturbed days. Note different color scales.

Prikryl, P. et al. (2011). Climatology of GPS phase scintillation and HF radar backscatter for the high-latitude ionosphere under solar minimum conditions. *Annales Geophysicae (09927689)*, *29*(2).

Highlights from recent results: Aurora and Scintillation

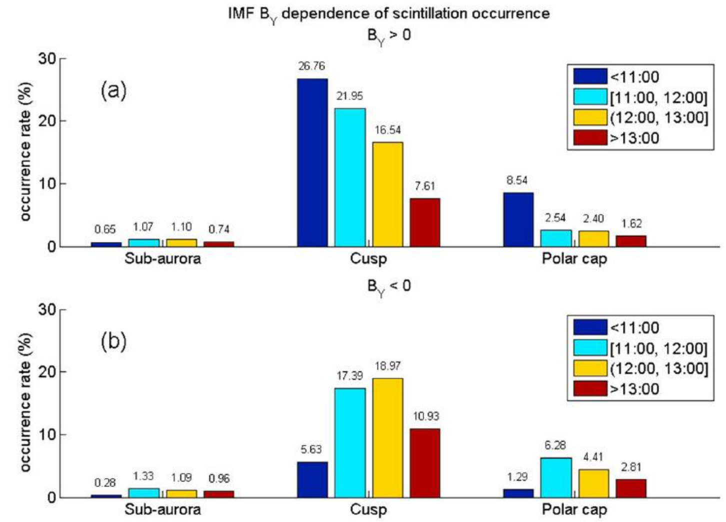


Figure 6. The scintillation occurrence rates for different IMF B_y conditions. The distribution for (a) IMF B_y positive and for (b) IMF B_y negative. The blue, cyan, yellow, and red bars show the occurrence rates of $\sigma_\phi \geq 0.1$ rad in prenoon (<11:00 MLT), noon 1 (11:00–12:00 MLT), noon 2 (12:00–13:00 MLT), and postnoon (>13:00 MLT), respectively.

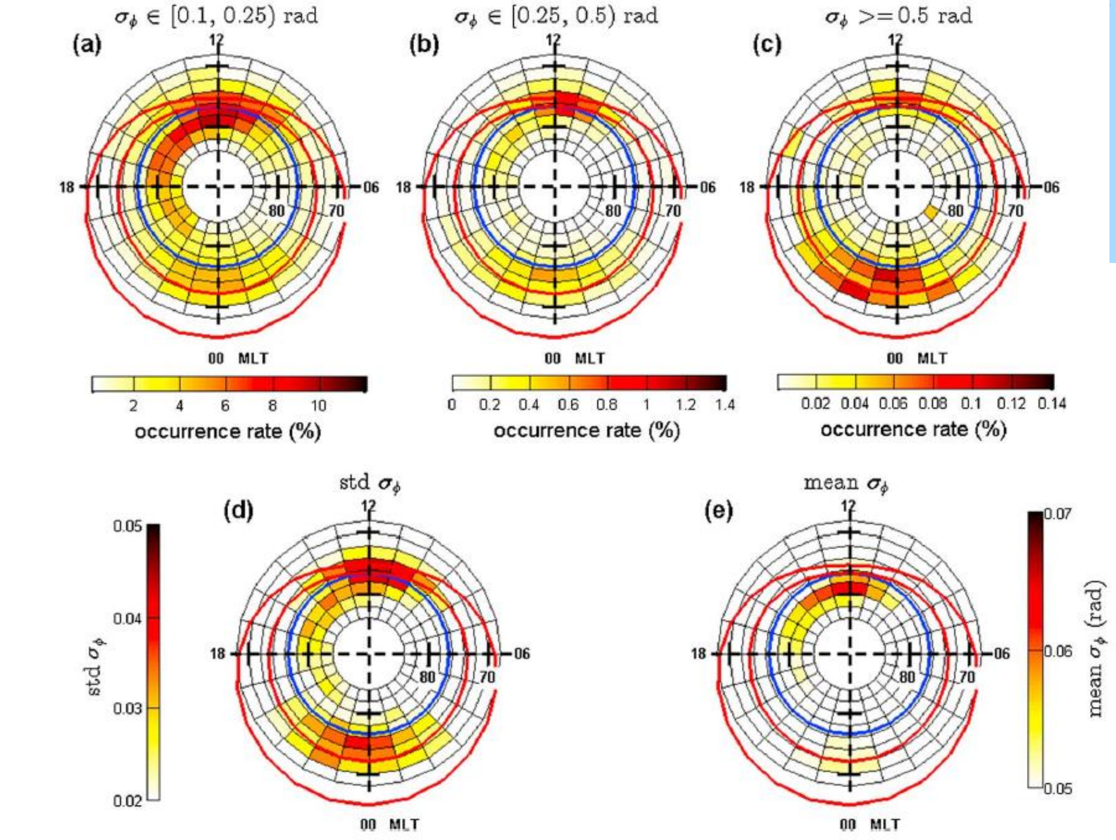


Figure 3. MLAT-MLT maps show the GPS phase scintillation occurrence rate for observations from year 2010 to 2013 at Ny-Ålesund binned by σ_ϕ from (a) (0.1, 0.25) rad, (b) (0.25, 0.5) rad, and (c) ≥0.5 rad. The MLAT 70° and 80° and MLT 00, 06, 12, and 18 are marked in each panel. Note that the occurrence rate color bar is different in each panel. (d and e) The standard deviation (std) and mean value of σ_ϕ, respectively. In each panel, the solid red lines denote the auroral oval calculated with the Feldstein model for IQ = 3 and the blue circle shows the MLAT of Ny-Ålesund station.

Jin et al. (2015). On the collocation of the cusp aurora and the GPS phase scintillation: A statistical study. *Journal of Geophysical Research: Space Physics*, *120*(10), 9176-9191.tel

Highlights from recent results: scintillation proxy

Delta phase rate, DPR

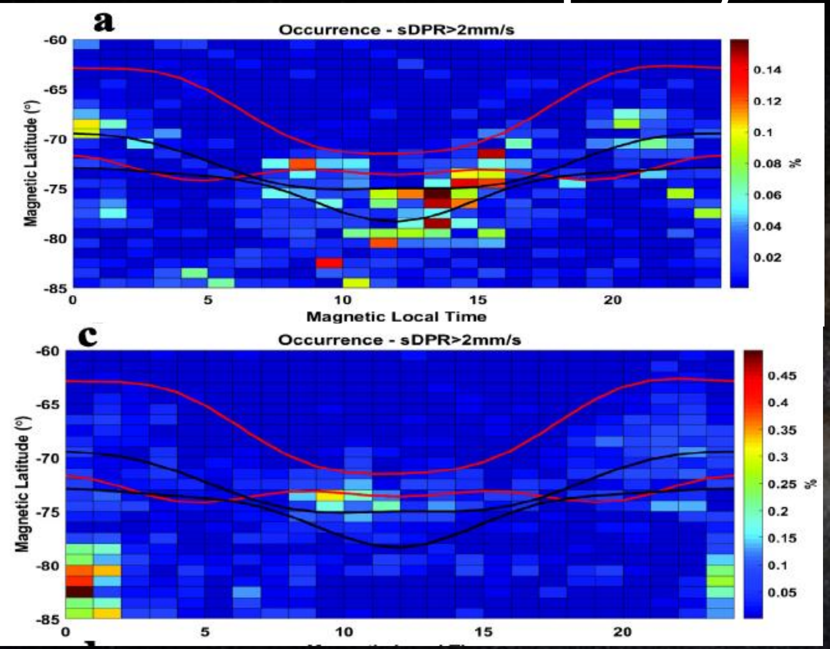
$$\mathrm{DPR} = \frac{\sum_{i=0}^{n} \psi_i}{n}$$

$$\psi_i = \frac{\varphi_g^{t_{i+1}} - \varphi_g^{t_i}}{t_{i+1} - t_i}$$

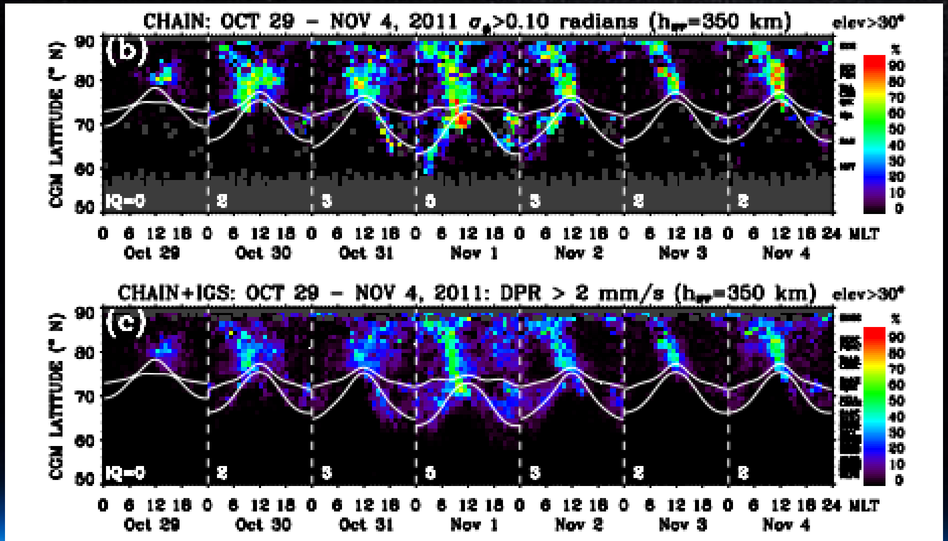
$\varphi_g = \lambda_1 L_1 - \lambda_2 L_2$
L_1, L_2 carrier phase measurements
λ_1, λ_2 wavelengths.

$$sDPR = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\overline{\psi} - \psi_i)^2}$$

sDPR @ 60 seconds from 1 Hz data



Priyadarshi, S., Zhang, Q. H., Thomas, E. G., Spogli, L., & Cesaroni, C. (2018). Polar Traveling Ionospheric Disturbances inferred with the B-Spline Method and Associated Scintillations in the Southern Hemisphere. Advances in Space Research.

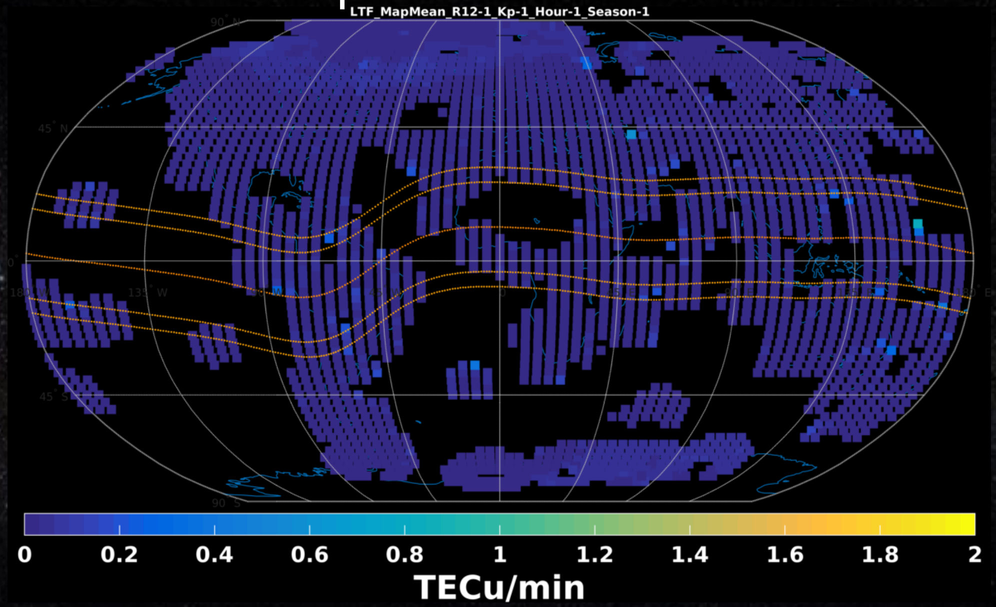


Prikryl, P., Ghoddousi-Fard, R., Kunduri, B. S. R., Thomas, E. G., Coster, A. J., Jayachandran, P. T., ... & Danskin, D. W. (2013). GPS phase scintillation and proxy index at high latitudes during a moderate geomagnetic storm.

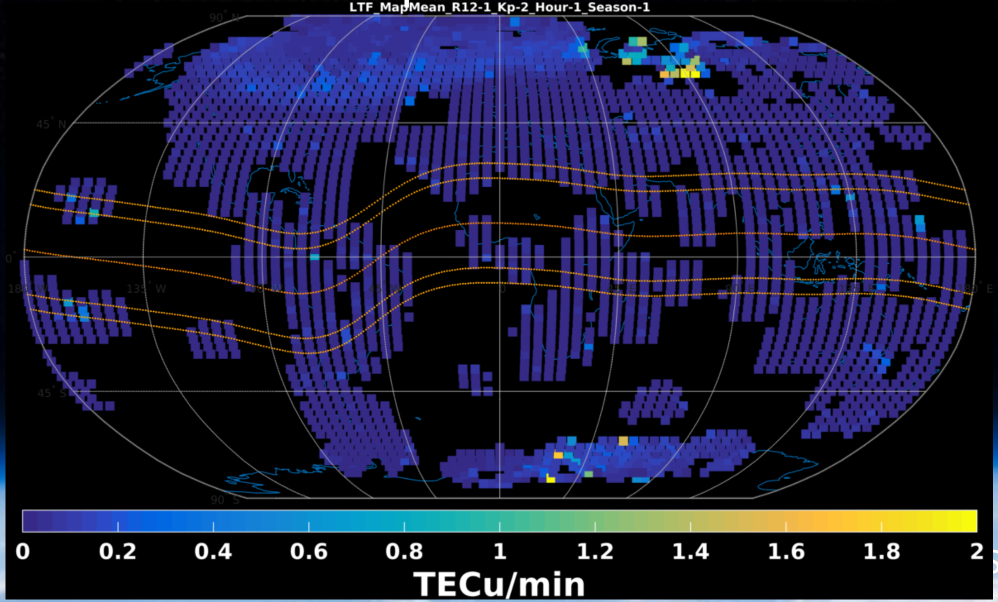
Ghoddousi-Fard, R., Prikryl, P., & Lahaye, F. (2013). GPS phase difference variation statistics: A comparison between phase scintillation index and proxy indices. Advances in Space Research, 52(8), 1397-1405.

Highlights from recent results: scintillation proxy

Kp<5 - R12 < 50



5<=Kp<7 - R12 < 50



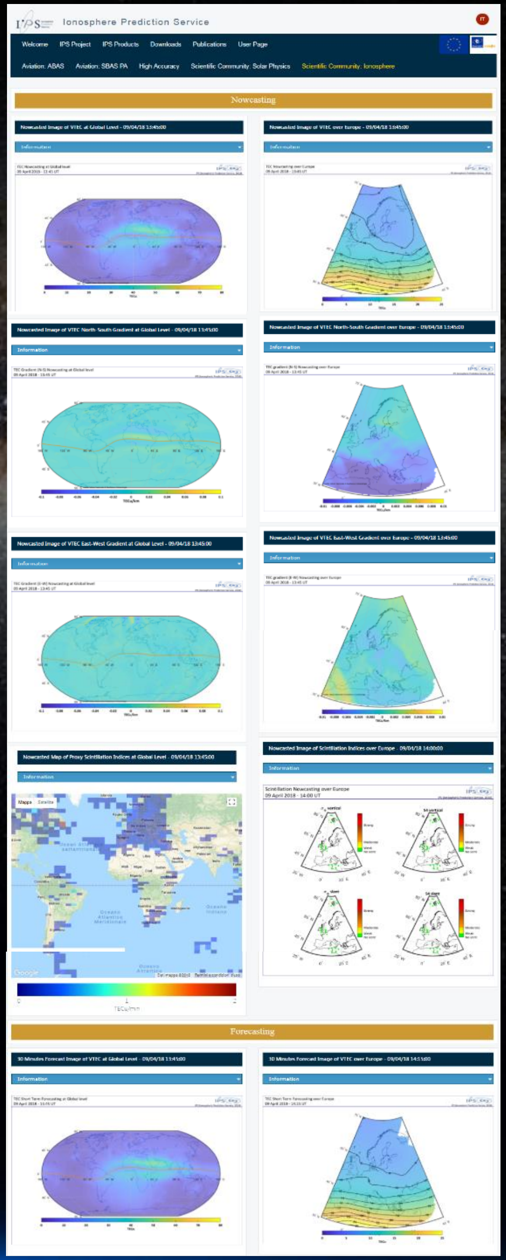
Rate of TEC change Index
5 minutes

$$ROTI = \sqrt{\langle ROT^2 \rangle - \langle ROT \rangle^2}.$$

Long Term Forecasting at global level of the Scintillation proxy based on GBSC

IPS Ionosphere Prediction Service

IPS is a prototype of a service for the monitoring and prediction of the Ionosphere effects on the GNSS user.
https://ips.telespazio.com/



Raised ~~Q~~uestions → Takehome messages

What are the main physical phenomena behind Scintillation and TEC gradients occurrence?
High-latitude ionosphere is exposed to the forcing of geospace that leads to ionospheric irregularities, possibly leading to scintillation.

What are the pro's and con's of a climatological picture?
The climatological approach allows modeling the average behavior sorted according helio-geophysical parameters. Differences with pure physical models are crucial

What are the sectors of the high-latitude ionosphere more exposed to scintillation?
Auroral oval boundaries, polar cap, ionospheric through, magnetic noon and cusp.

What are the main features of the high-latitude ionosphere highlighted by climatology?
Areas of enhanced probability of formation of irregularities and scintillation.

What's the meaning of a ionospheric scintillation climatology and what's the difference with the (ionospheric) weather.
To assess the general recurrent features of the ionospheric irregularities dynamics and temporal evolution on long data series, trying to catch eventual correspondences with scintillation occurrence.

What are the main results of the recent studies?
Several interesting studies have investigated the main features of the high-latitude ionosphere

What's the role of the external drivers in modulating the scintillation occurrence?
IMF, Geomagnetic and Auroral Indices and phase of the solar cycle highlight the scintillation patterns

How to cook a good scintillation climatology?
Good data, wise data preparation, clear idea of what to model

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Questions ?

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