Ionospheric irregularities & scintillations

Luca Spogli

luca.spogli@ingv.it

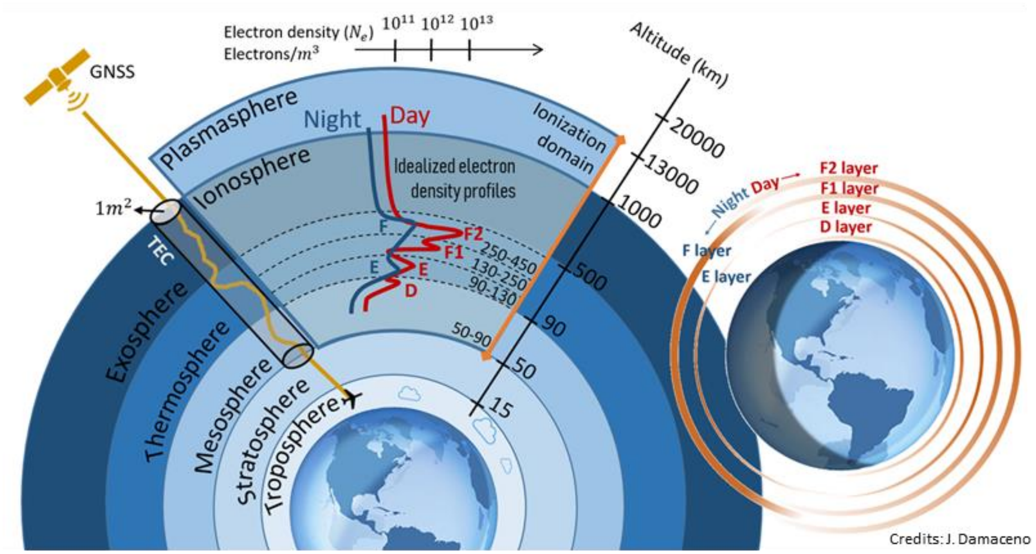
ISTITUTO NAZIONALE
DI GEOFISICA E VULCANOLOGIA

2nd PITHIA-NRF Training School supported by T-FORS project
February 5 - 9, 2024, Leuven

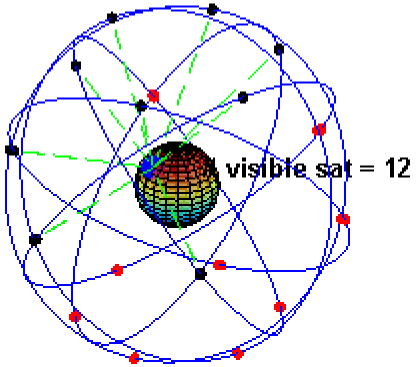
Ground-based GNSS receivers

Probing the ionosphere with GNSS*

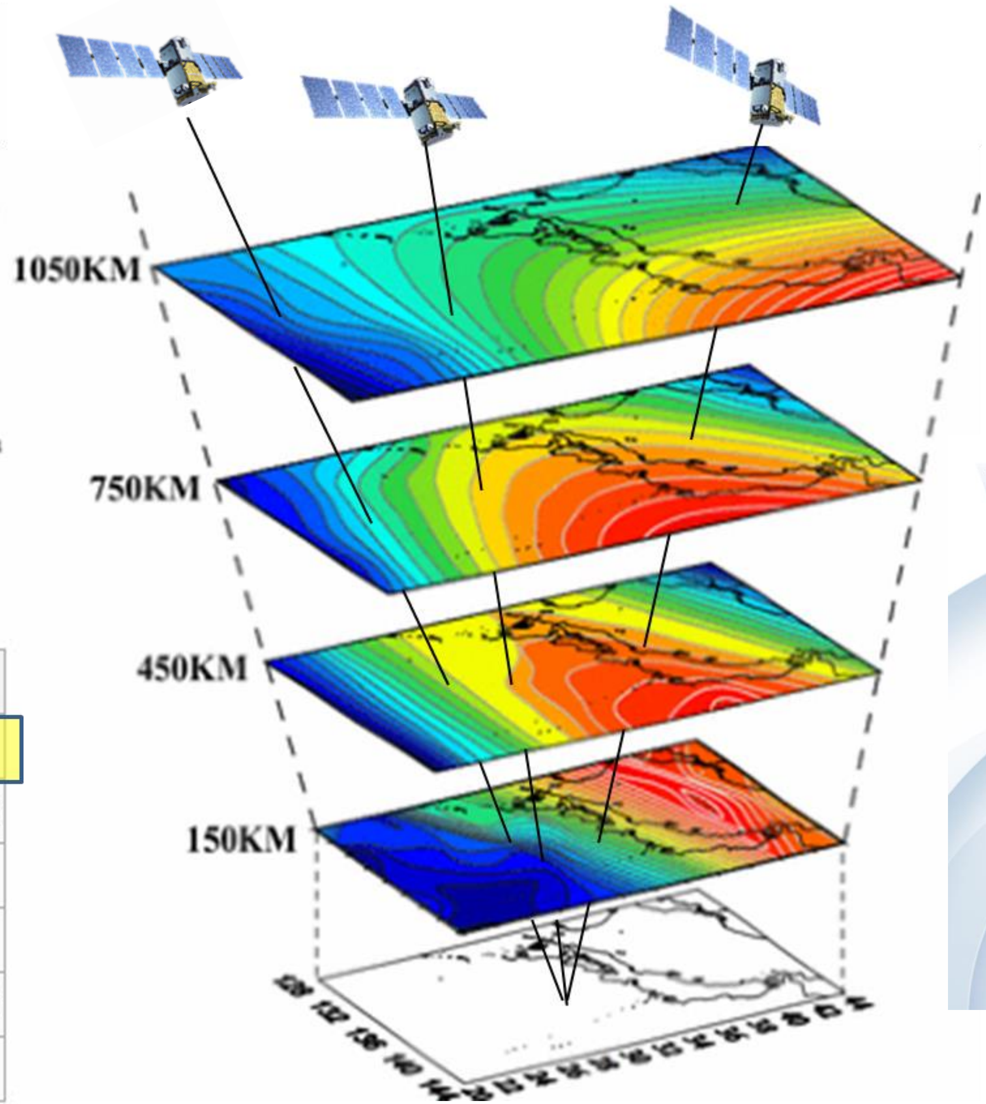
Global Navigation Satellite System (GNSS) is the standard generic term for satellite navigation systems that provide **autonomous geo-spatial positioning with global coverage**. This term includes e.g. the GPS, GLONASS, Galileo, Beidou and other regional systems.

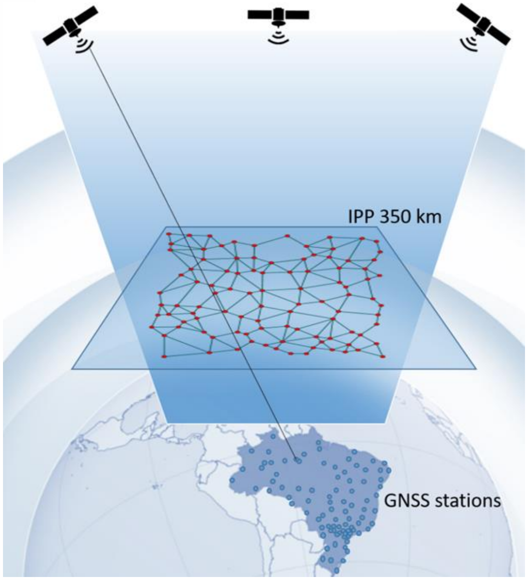


GNSS signals pass through the entire ionosphere



Source	Effect
Ionospheric effects	± 5 m
Ephemeris errors	± 2.5 m
Satellite clock errors	± 2 m
Multipath distortion	± 1 m
Tropospheric effects	± 0.5 m
Numerical errors	± 1 m





*Global Navigation Satellite System

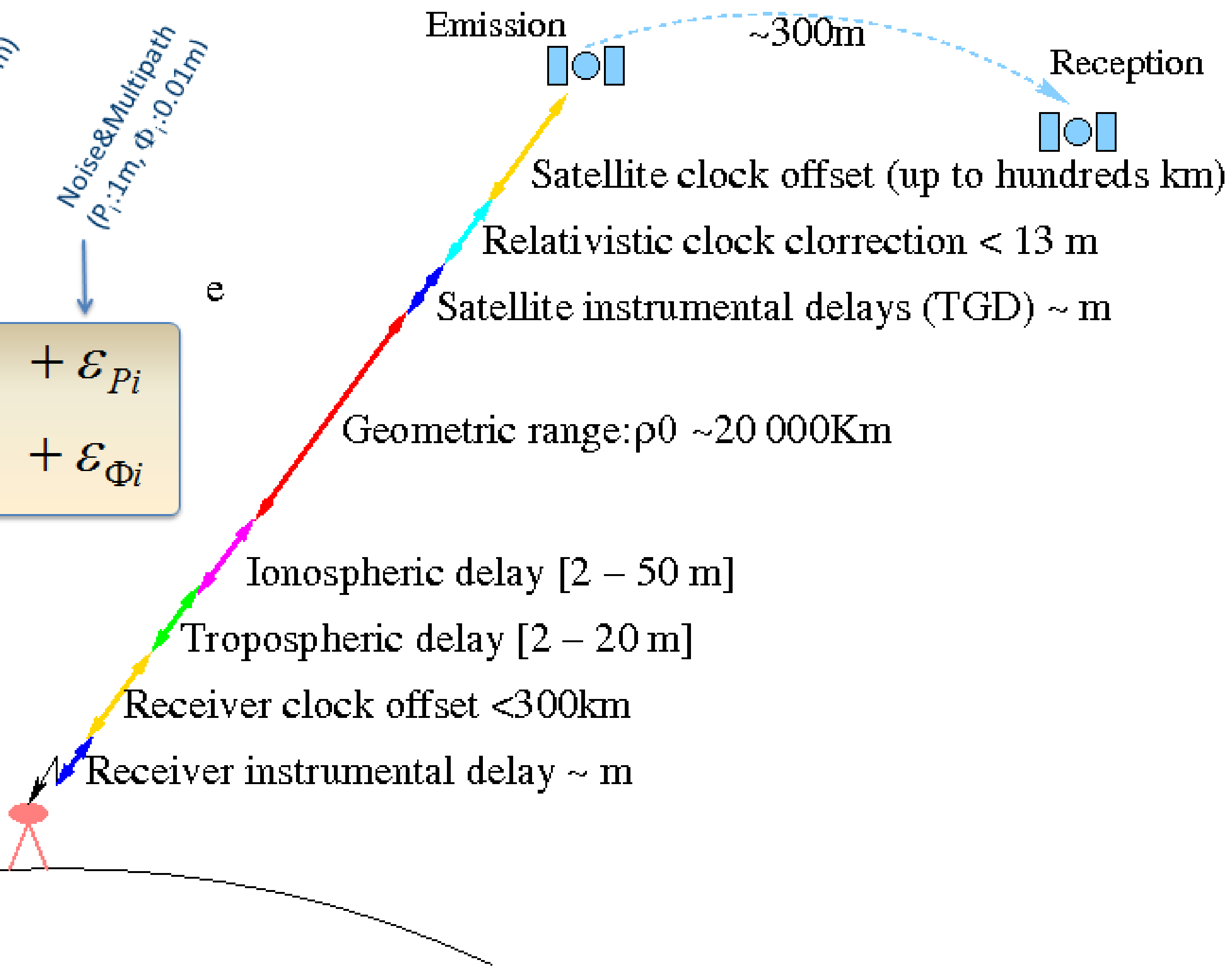
Code and Carrier phase measurements equations

Geometric range (e.g. 20000km) | Clock offset (e.g. 500km) | Troposphere (e.g. 3m) | Ionosphere (e.g. 15m) | Carrier ambiguity (e.g. 2m) | Hardware biases (P_i:2m, Φ_i:0.05m) | Noise&Multipath (P_i:1m, Φ_i:0.01m)

$$P_i = \rho + c \cdot dt + T + I_i + B_{Pi} + \varepsilon_{Pi}$$

$$\Phi_i = \rho + c \cdot dt + T - I_i + N_i \lambda_i + B_{\Phi i} + \varepsilon_{\Phi i}$$

i= $carrier\ frequency\ (e.g.\ L_1, L_2)$



The ionosphere will introduce a delay of the modulation (the code measurement will be larger than in vacuum), and an advance of the carrier phase (the carrier phase measurement will be smaller than in vacuum).

Linear Combination of GNSS Measurements

IONOSPHERE-FREE LINEAR COMBINATION

$$\Phi_{\text{iono-free}} = \frac{f_1^2\ \Phi_{L_1} - f_2^2\ \Phi_{L_2}}{f_1^2 - f_2^2}$$

It removes the first order (up to 99.9%) ionospheric effect, which depends on the inverse square of the frequency

↓ Positioning

↓ **Assessment of higher order ionospheric effects**

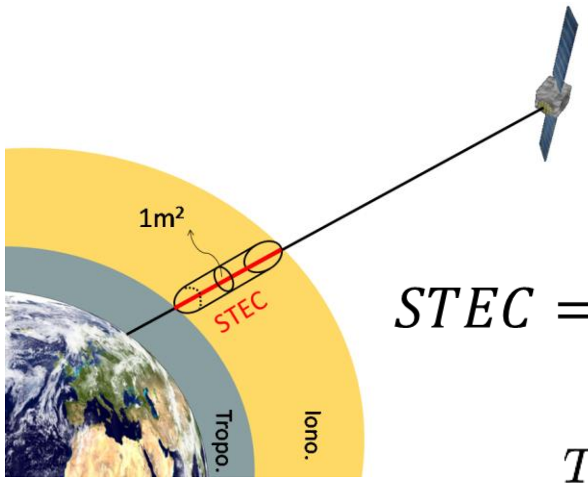
GEOMETRY-FREE COMBINATION

$$\Phi_{LI} = \Phi_{L1} - \Phi_{L2}$$

It cancels the geometric part of the measurement, leaving all the frequency-dependent effects (i.e., ionospheric refraction, instrumental delays, wind-up) besides multipath and measurement noise

↓ **Estimation of Total Electron Content (TEC)**

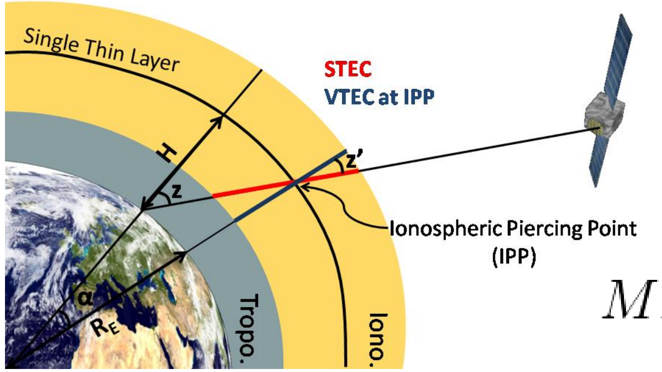
Total Electron Content



$$STEC = \int Ne\, ds_0$$

$$STEC = \frac{1}{40{,}3}\left(\frac{L1^2 L2^2}{L2^2 - L1^2}\right)(P_2 - P_1) - \varepsilon$$

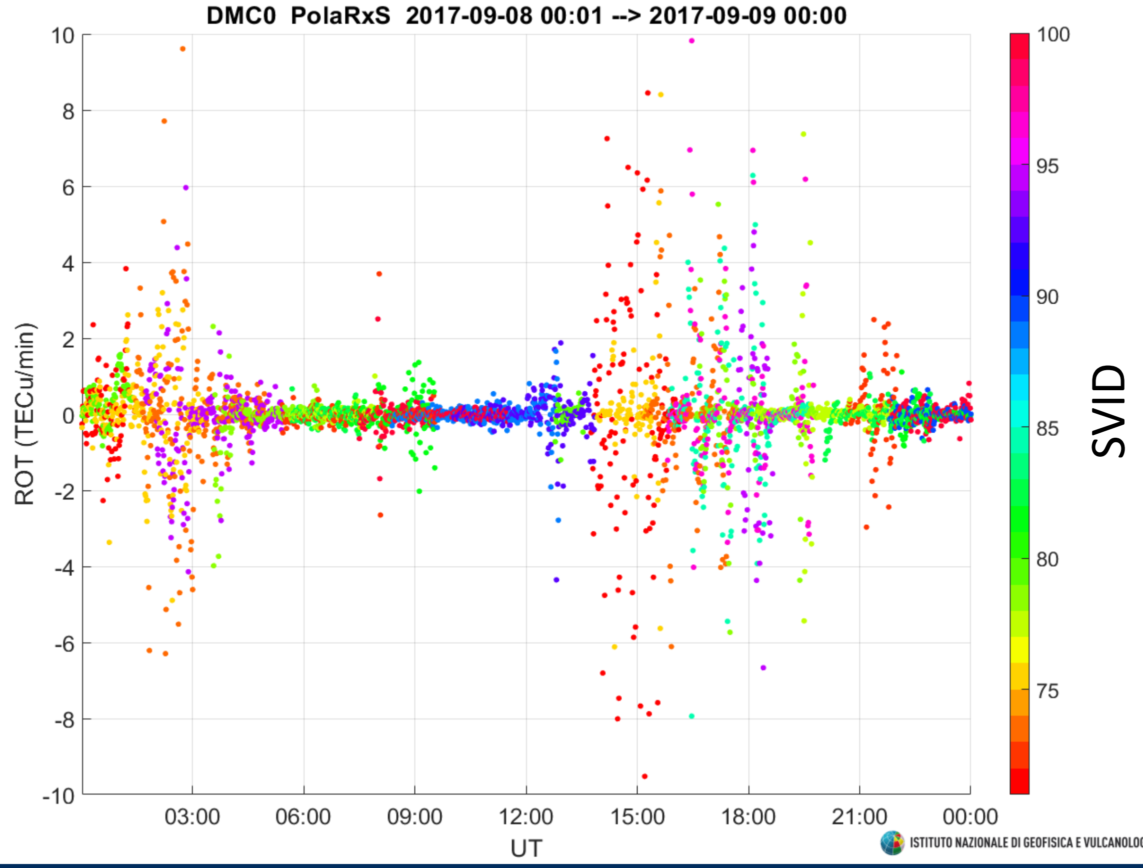
$$TECU = 10^{16}\text{electrons per m}^2$$



$$MF_I(z) = \frac{STEC}{VTEC} = \frac{1}{\cos z'}$$

Rate Of TEC change

$$ROT_m = \frac{TEC_m - TEC_{m-1}}{t_m - t_{m-1}}$$



ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

Ionospheric Scintillation

Categories of scintillation

Phenomenon	Cause	Effect
Interplanetary scintillation	Inhomogeneities in the Solar Wind	Fluctuations of the intensity of radio stars
Tropospheric scintillation	Neutral turbulence	Fluctuation of the optical ray paths (twinkling of stars)
Ionospheric scintillation	Ionospheric irregularities	Fluctuations of the amplitude and phase of the signal

*adapted from a slide by Jayachandran (UNB)

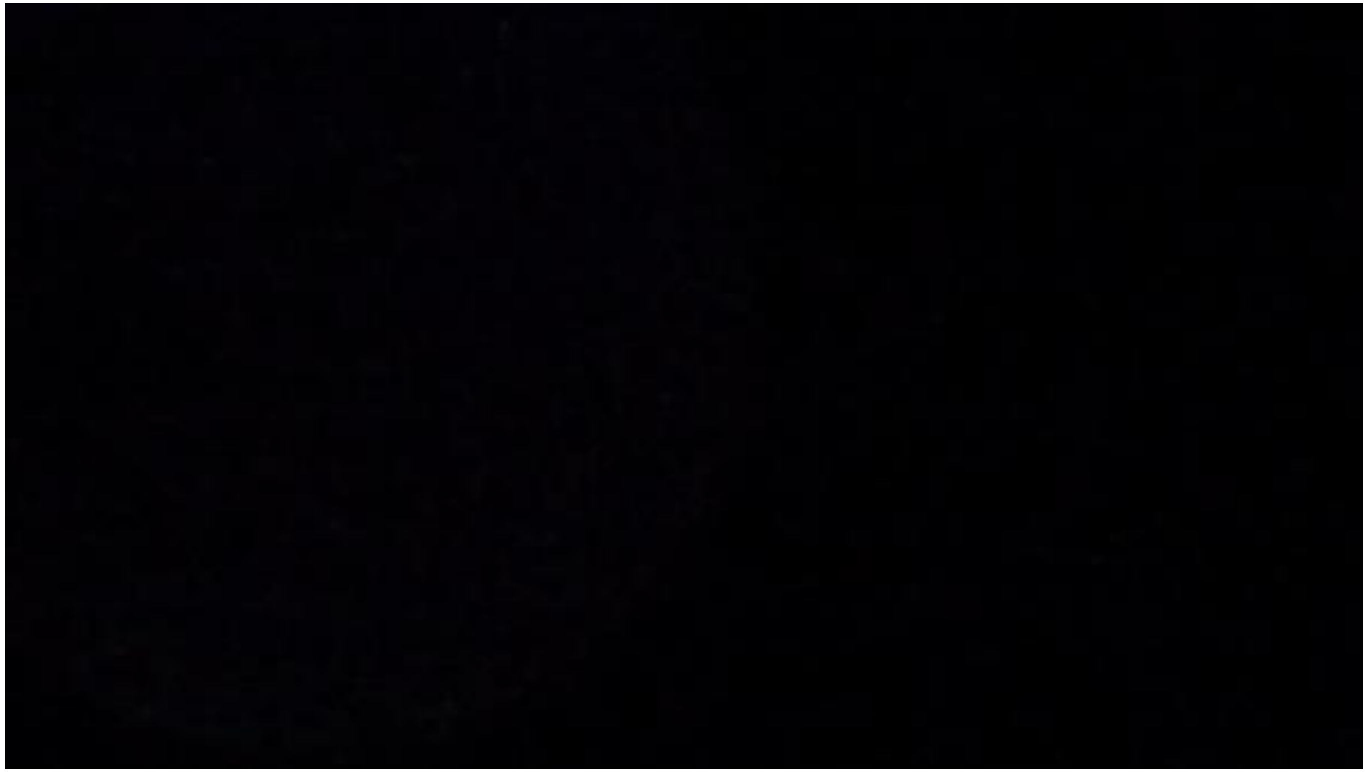
Categories of scintillation

Phenomenon
Ionospheric scintillation

Cause
Ionospheric irregularities

→

Effect
Fluctuations of the amplitude and phase of the signal



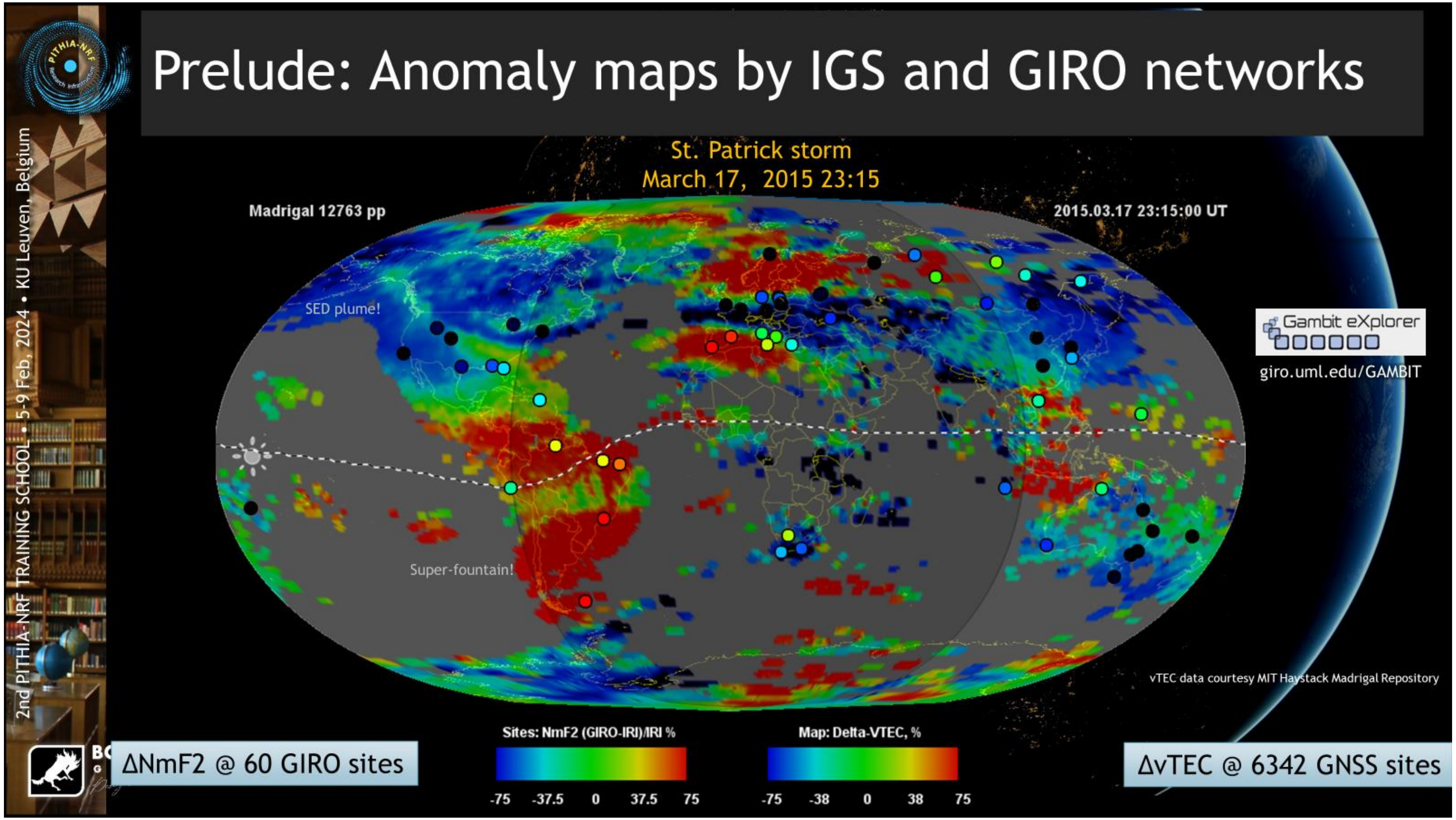
Ionospheric Scintillation

Ionospheric Scintillation

Ionospheric Irregularities

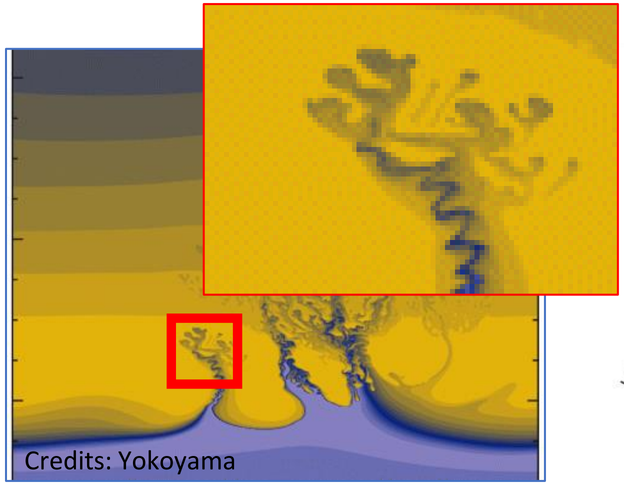
Irregularities in a nutshell

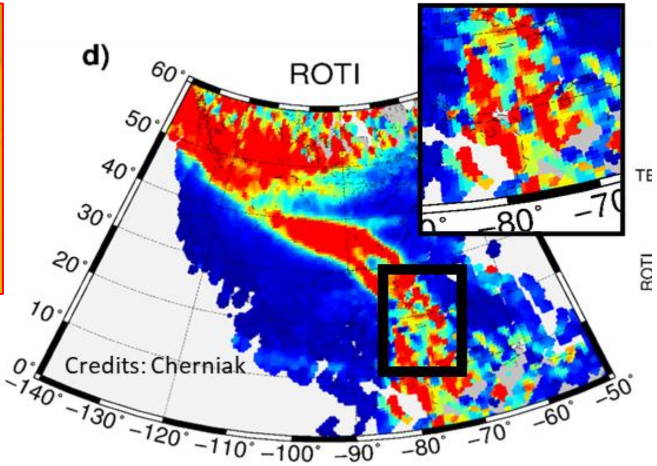
Anomalies (i.e., ± gradients) w.r.t. a background, smooth, ambient, ideal ionosphere

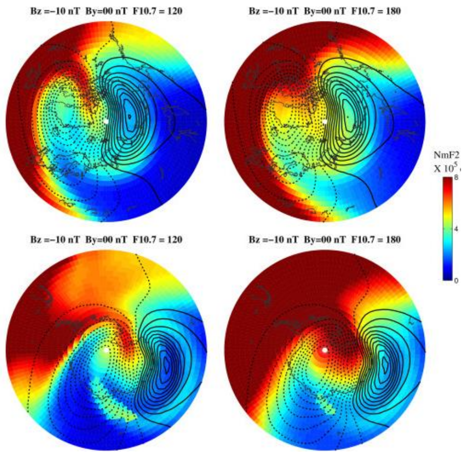


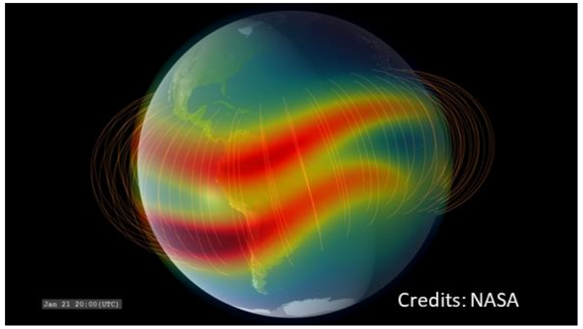
Stolen from Ivan's lesson

Irregularities* in a nutshell









100 m   1 km   10 km   100 km   1000 km

Small scale
(Fresnel's scale)

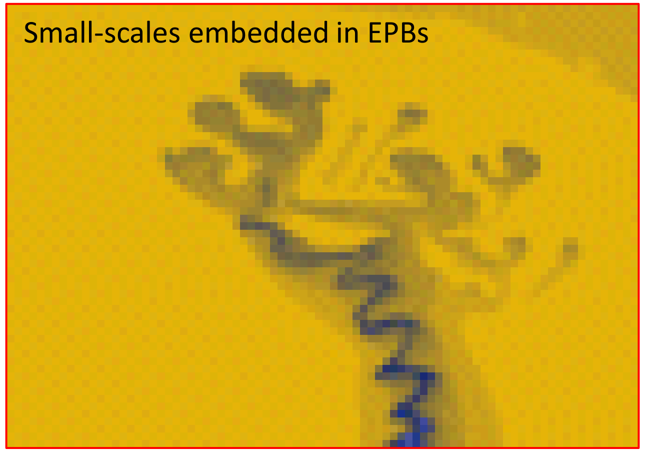
Medium scale

Large scale

*from a GNSS perspective

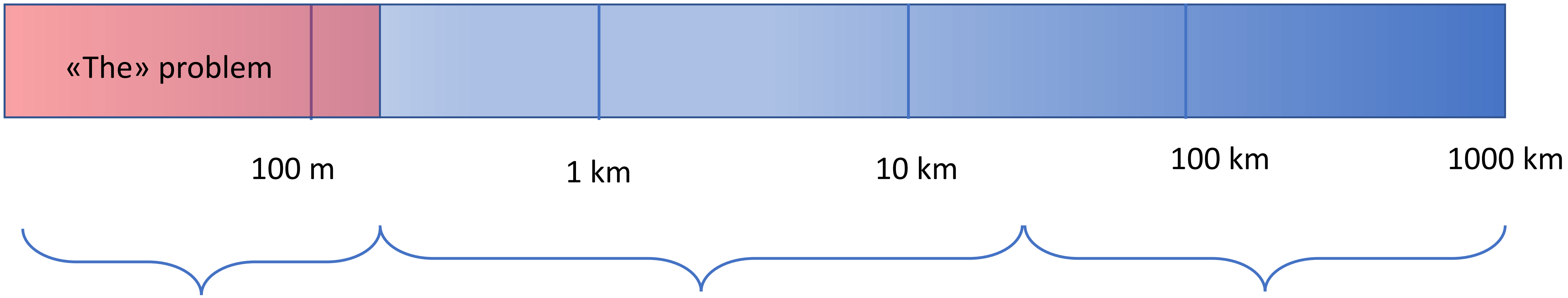
Irregularities* in a nuthsell

Growth/Decay of instabilities:



K-H and GDI at high-lat (very rare)
R-T at low-latitudes (very common)

«few hundreds of meters»



Small scale
(Fresnel's scale)

Medium scale

Large scale

*from a GNSS perspective

Irregularities* in a nutshell

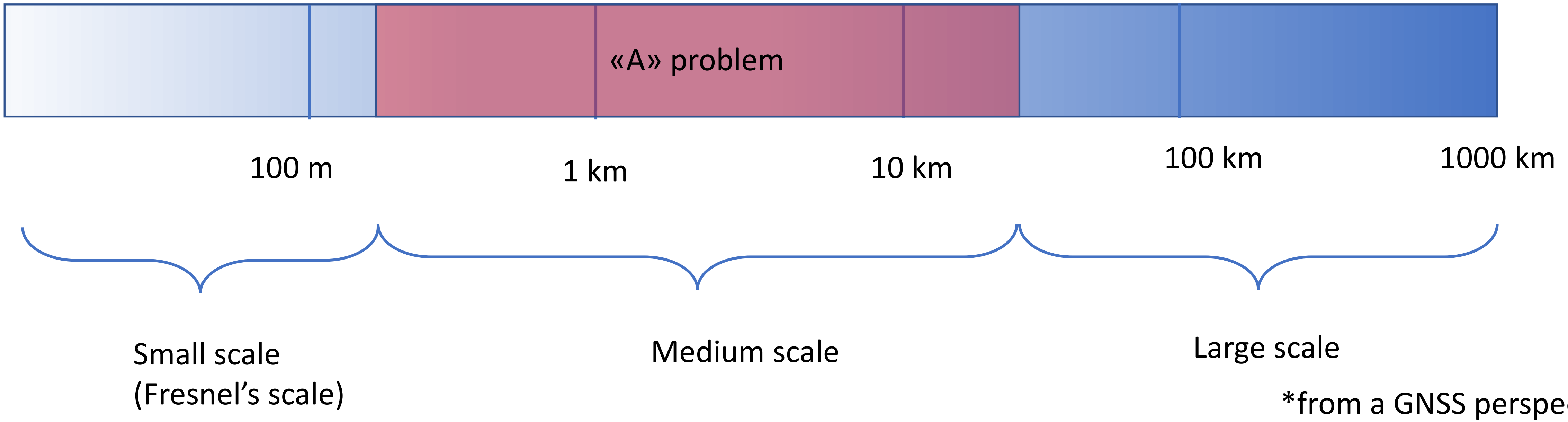
Boundaries and edges of:

Auroral oval precipitation
Polar cap patches
Auroral blobs
Storm-enhanced densities

Mostly storm-time phenomena

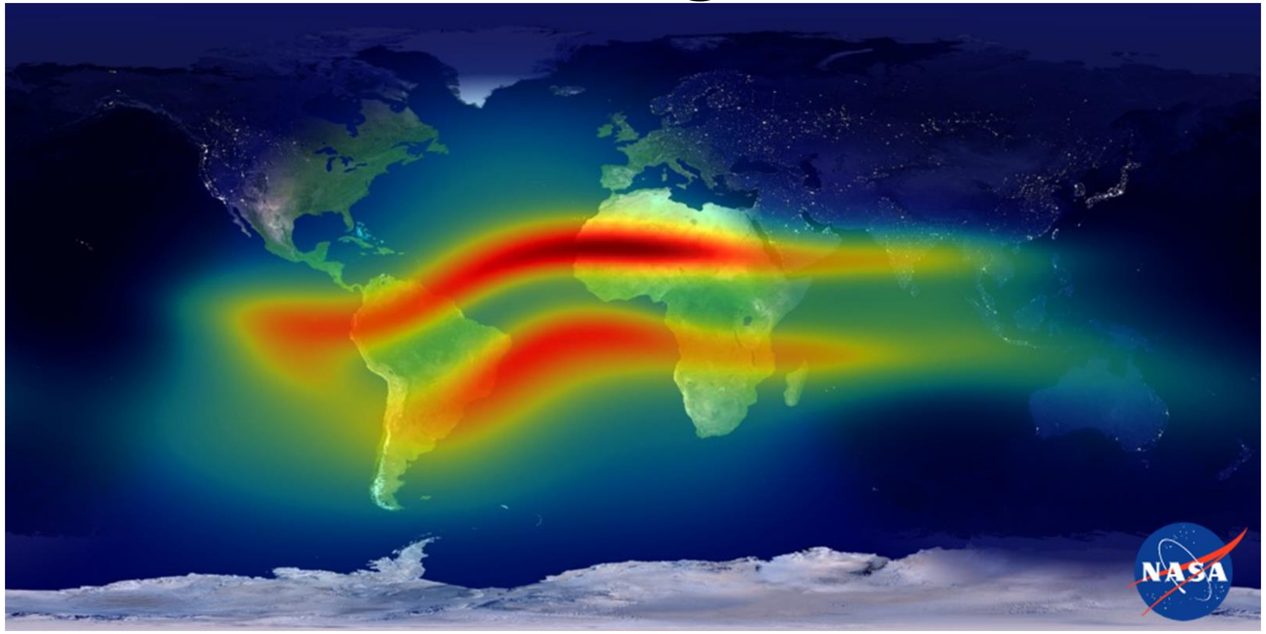
Equatorial plasma bubbles

Modulated by storm-time phenomena (electrodyamics)



*from a GNSS perspective

Irregularities* in a nuthsell



Large-scale ionospheric structures

Large-scale ionospheric structures

«No» problem

100 m

1 km

10 km

100 km

1000 km

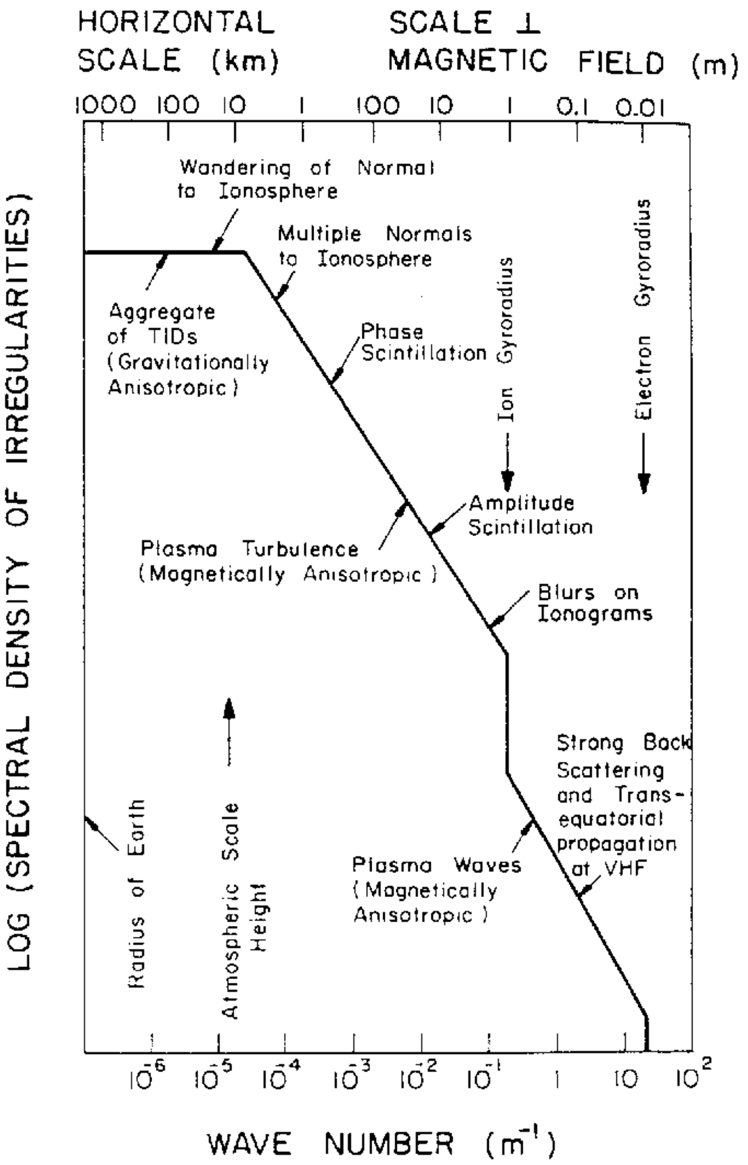
Small scale
(Fresnel's scale)

Medium scale

Large scale

*from a GNSS perspective

Irregularities in a nuthsell

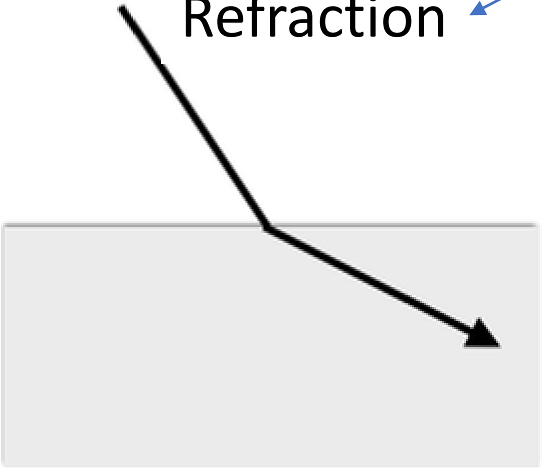


Spectra of ionosphere irregularities and their intensity as function of wave number over spatial scale sizes covering from the electron gyro-radius to the radius of the Earth (Booker, 1956).

What causes phase and amplitude fluctuations in the GNSS signals?

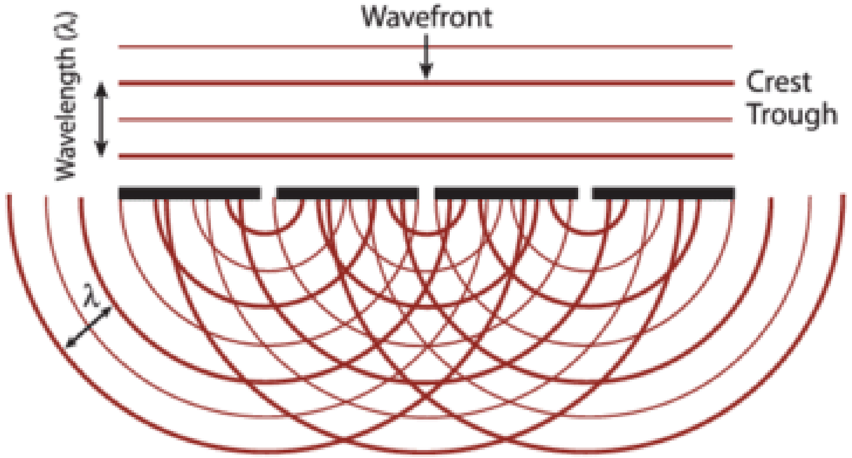
Ionospheric irregularities

Refraction



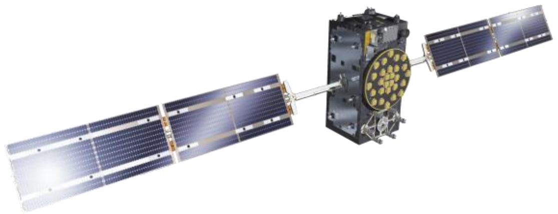
Scale size range: full ionospheric spectrum
Affects: phase
Physical mechanism: phase mixing

Diffraction



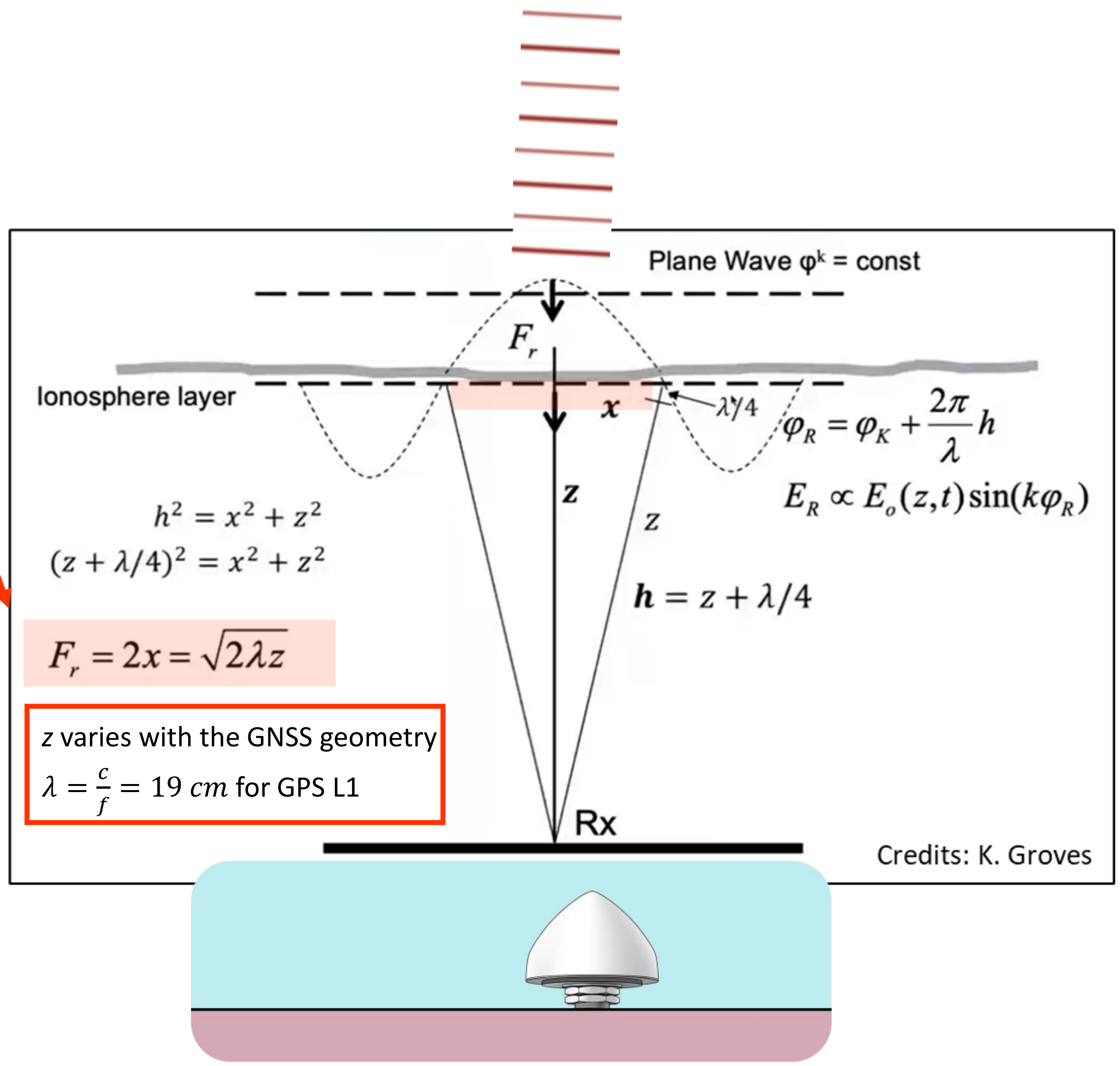
Scale size range: up to Fresnel's scale
Affects: amplitude, phase
Physical mechanism: decorrelation, interference

What causes phase and amplitude fluctuations in the GNSS signals?

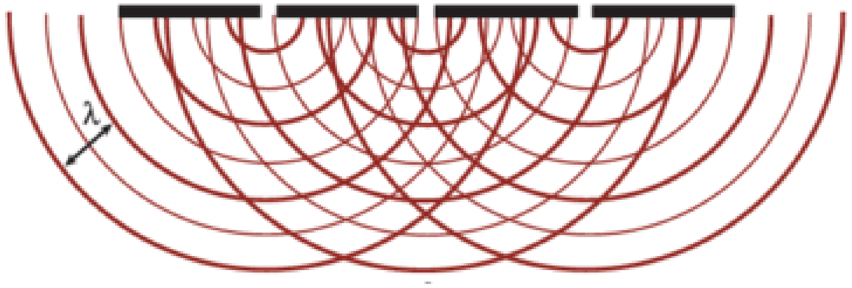


Scale size range: up to **Fresnel's scale**

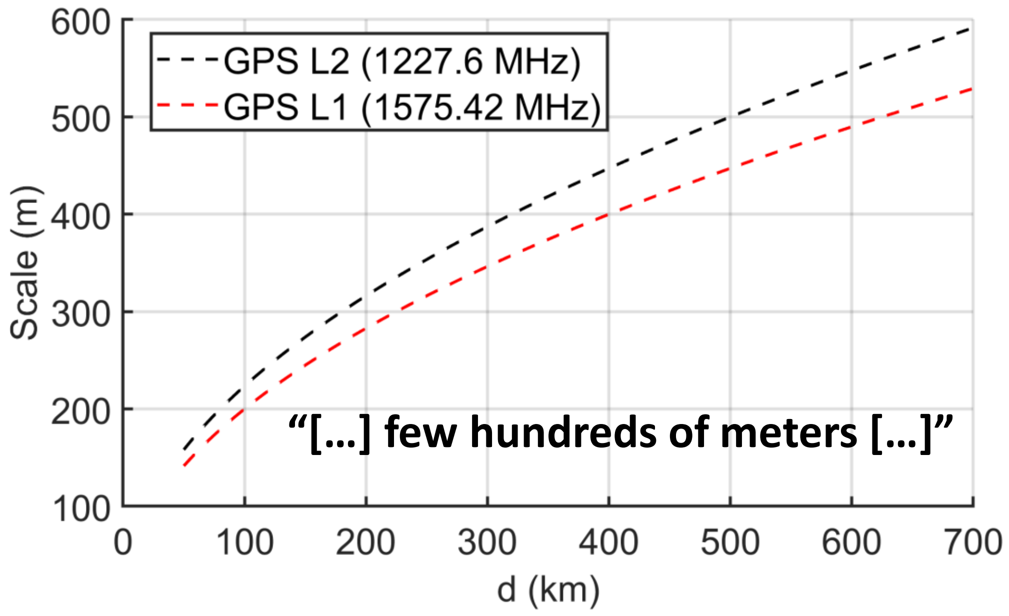
The first Fresnel zone is an elliptical region in free space which radio waves travel directly from transmission to reception without significant alterations

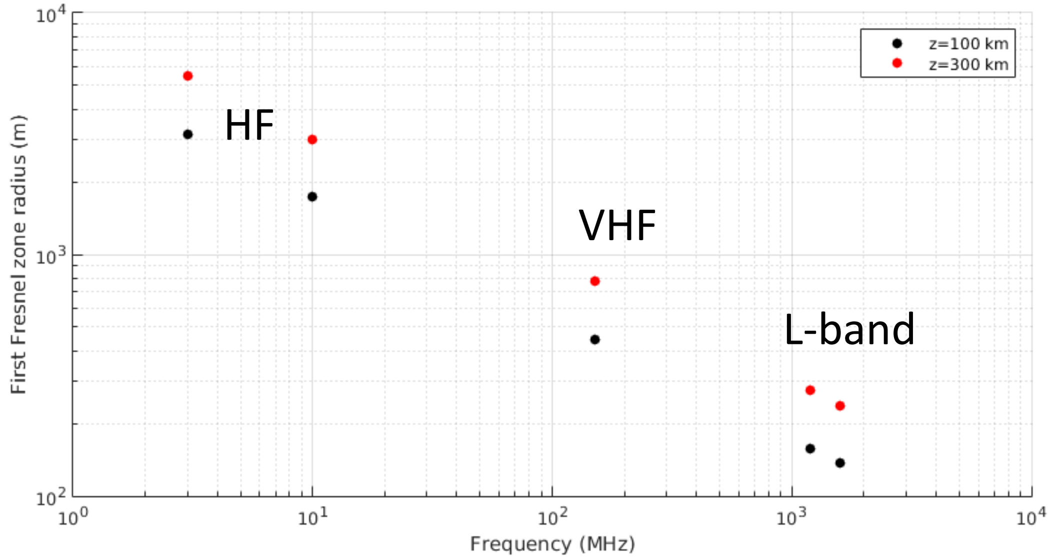


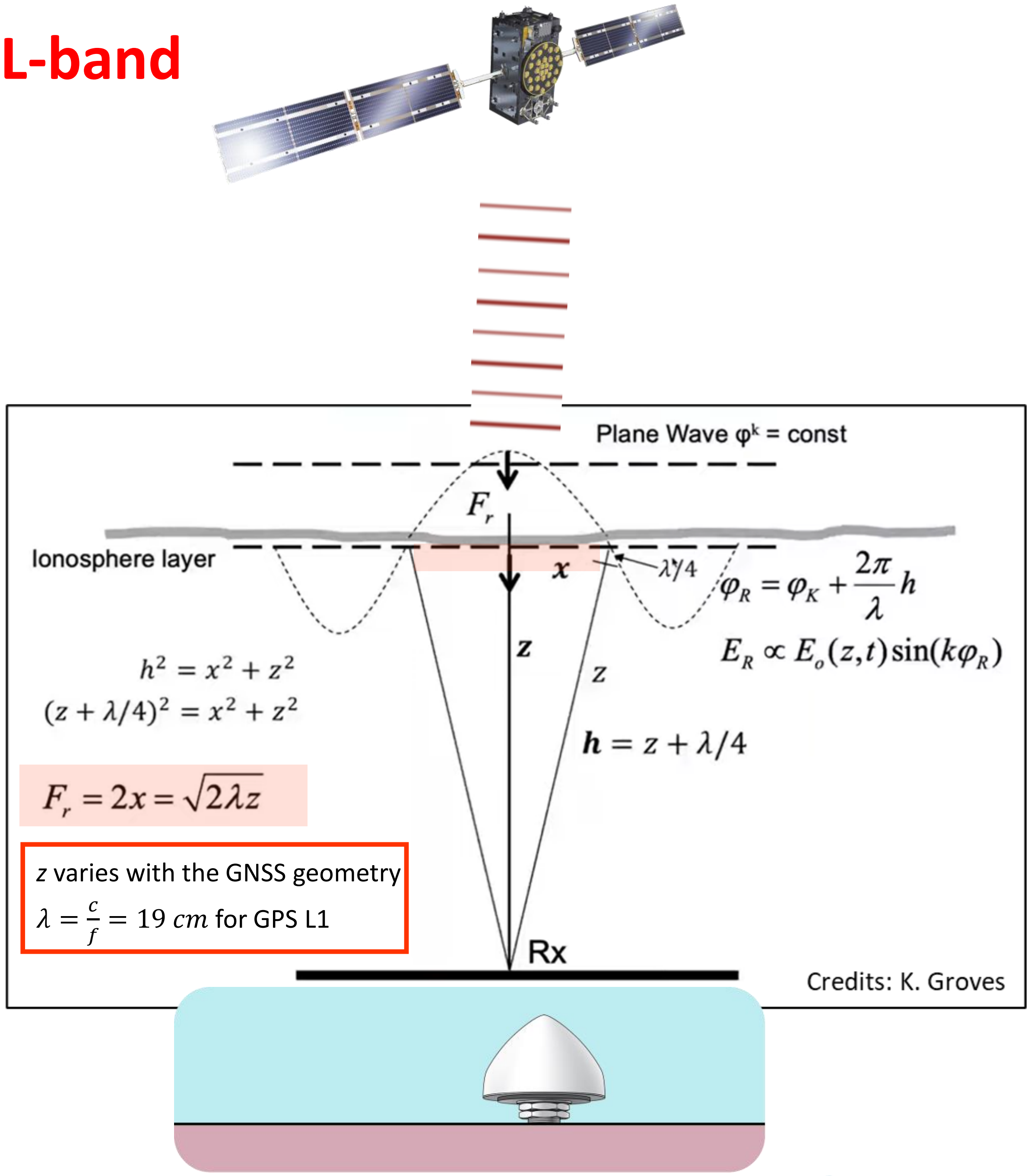
Diffraction occurs when $F_{irr} \leq F_r$



Scale size range: up to **Fresnel's scale…for L-band signals and GNSS observational geometry**







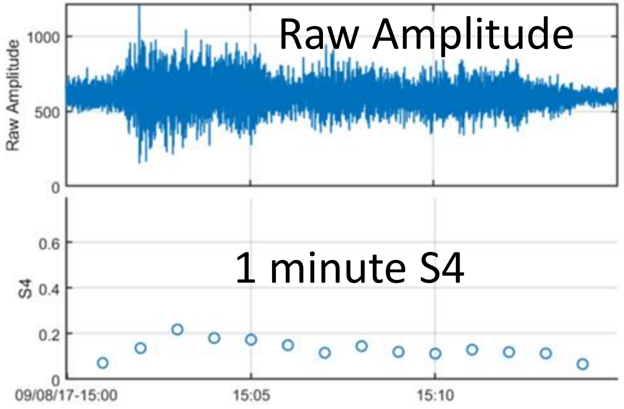
Ionospheric Scintillation

GNSS scintillation: how to measure

Ionospheric Scintillation Monitor Receivers

Features:

- High-sampling frequency (50/100 Hz)
- Low-noise oscillators
- Stable clock
- Firmware providing scintillation indices (1-min resolution)
- Output in (quasi) real-time



- Amplitude scintillation, S4 index:

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

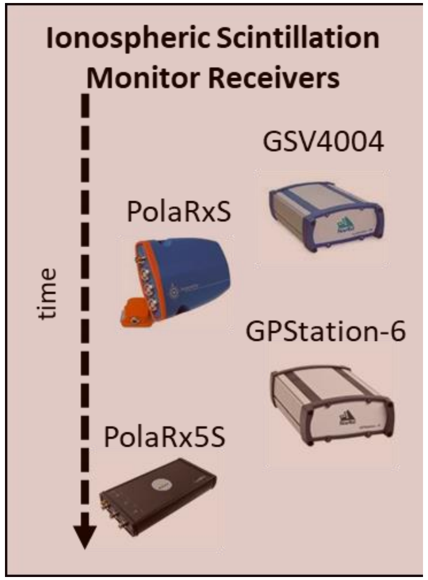
$\mathrm{I} = \mathrm{Signal\ Intensity}$

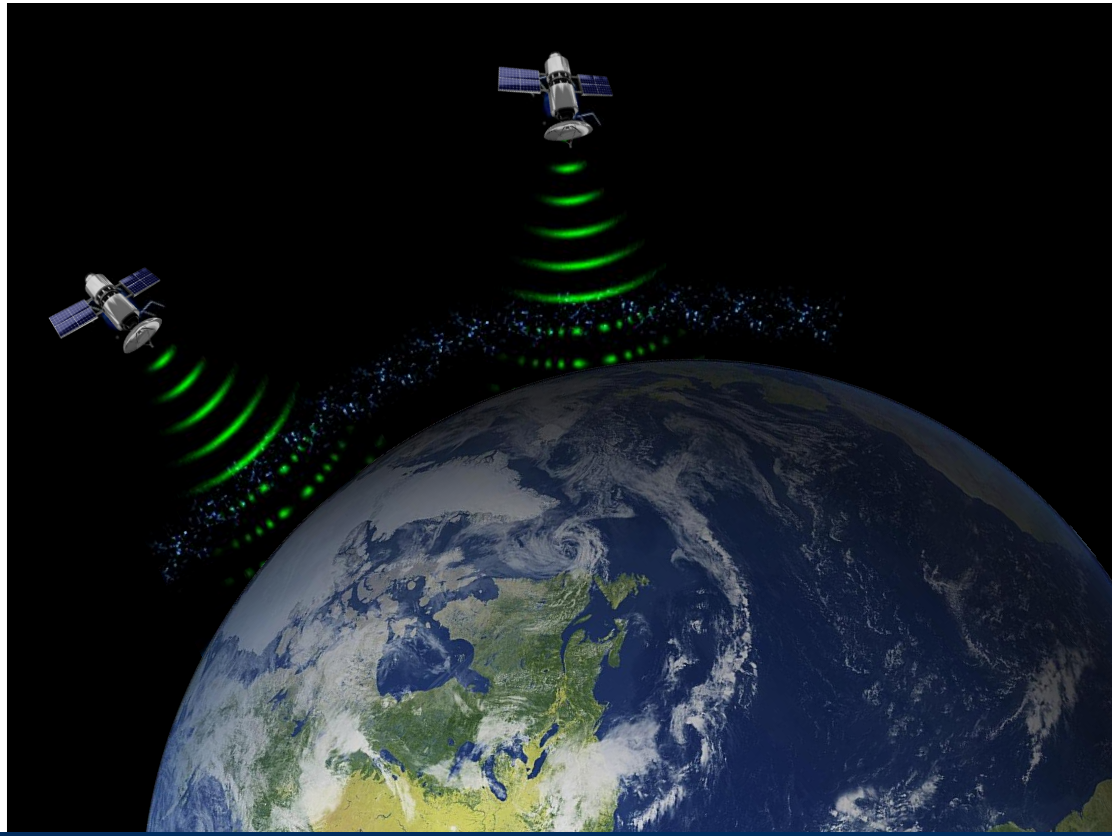
square-root of the normalized variance of signal intensity over a given interval of time.

- Phase scintillation, σ_ϕ (SigmaPhi) index:

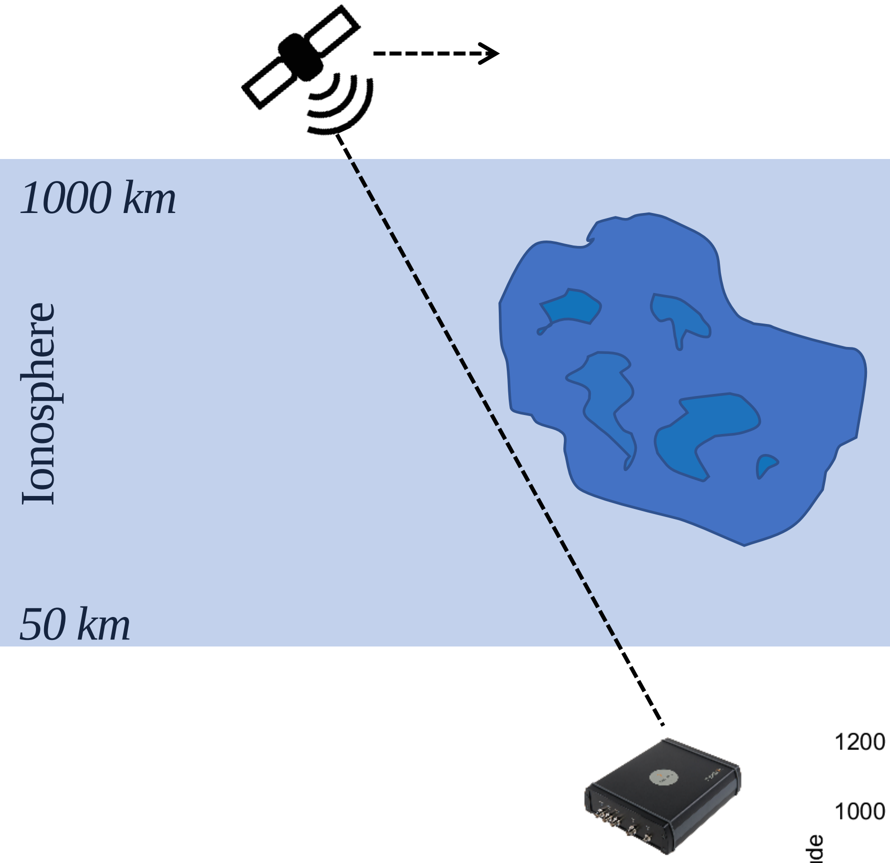
$$\sigma_\phi = \sqrt{\langle \phi^2 \rangle - \langle \phi \rangle^2}$$

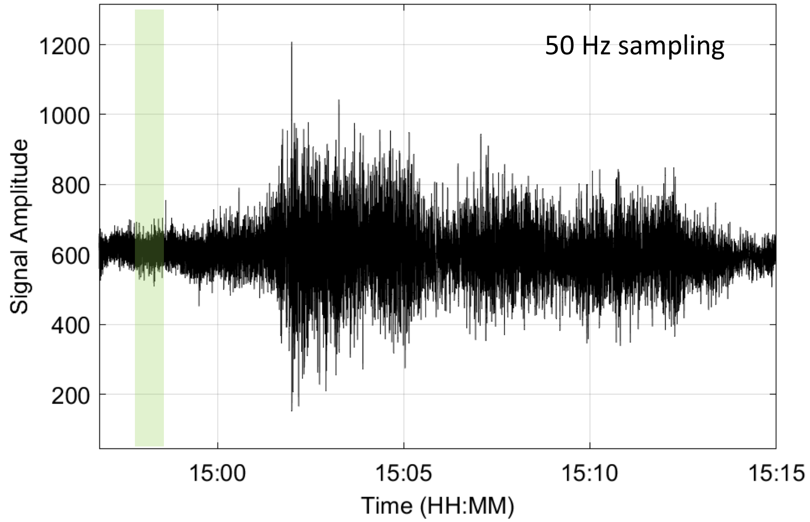
standard deviation of detrended phase measurements.





A simplified picture





Scintillation indices

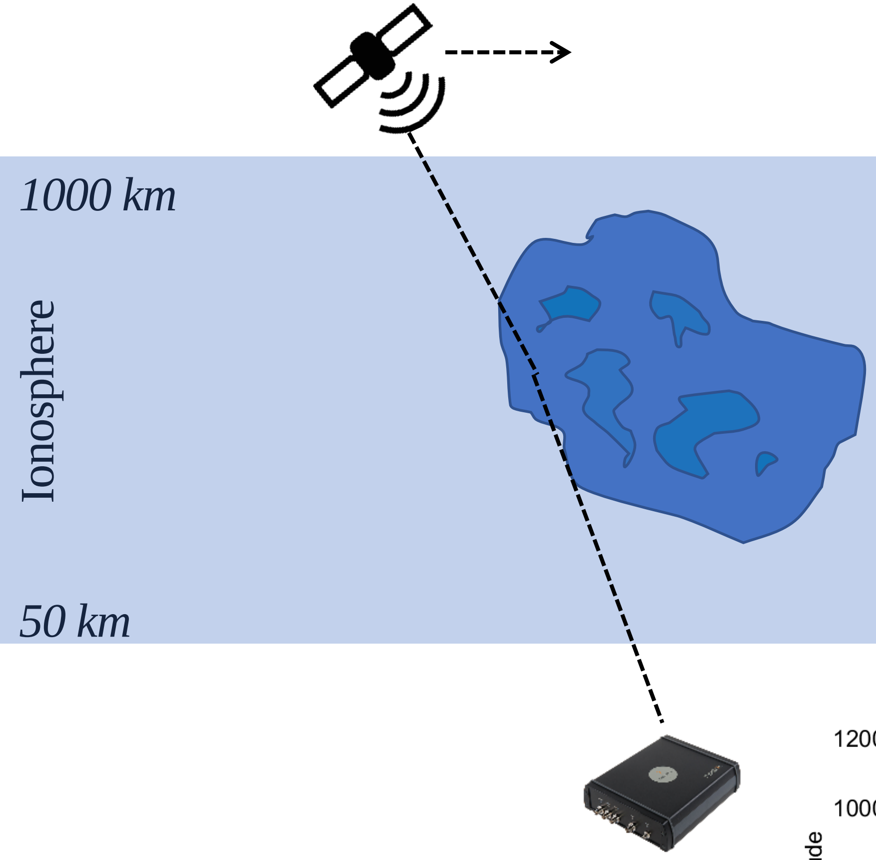
$$S_4^2 = \left(\langle I^2\rangle - \langle I\rangle^2\right)/\langle I\rangle^2.$$

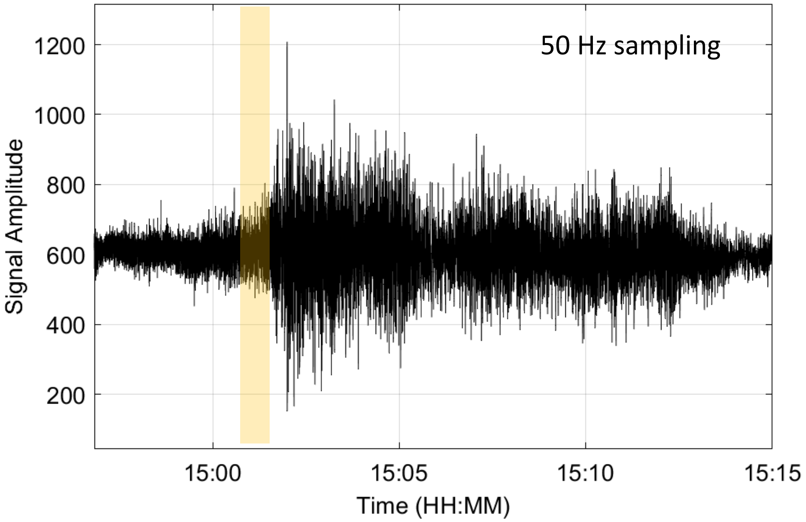
Ampl.

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

Phase

A simplified picture





Scintillation indices

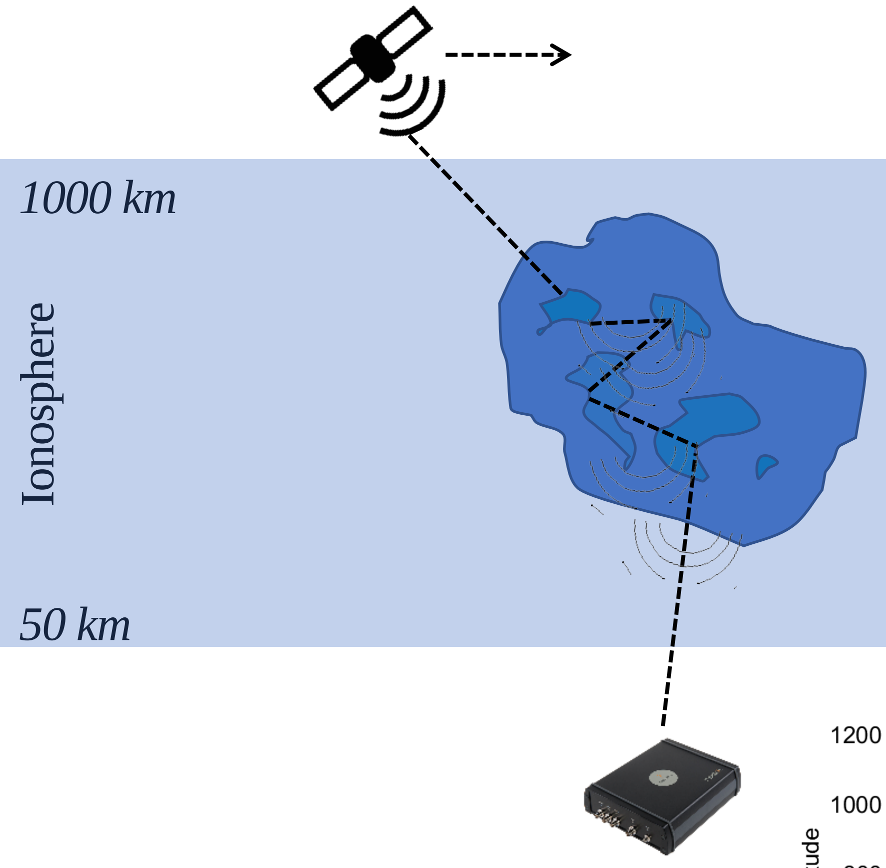
$$S_4^2 = \left(\langle I^2 \rangle - \langle I \rangle^2\right) / \langle I \rangle^2.$$

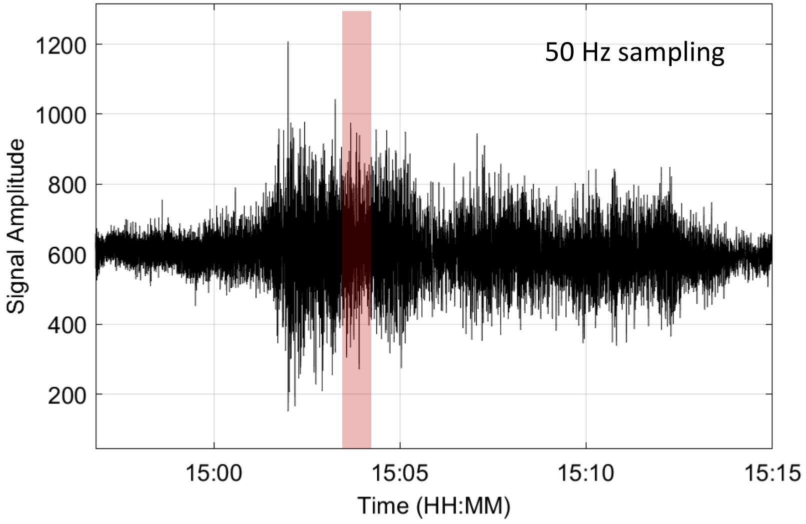
Ampl.

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

Phase

A simplified picture





Scintillation indices

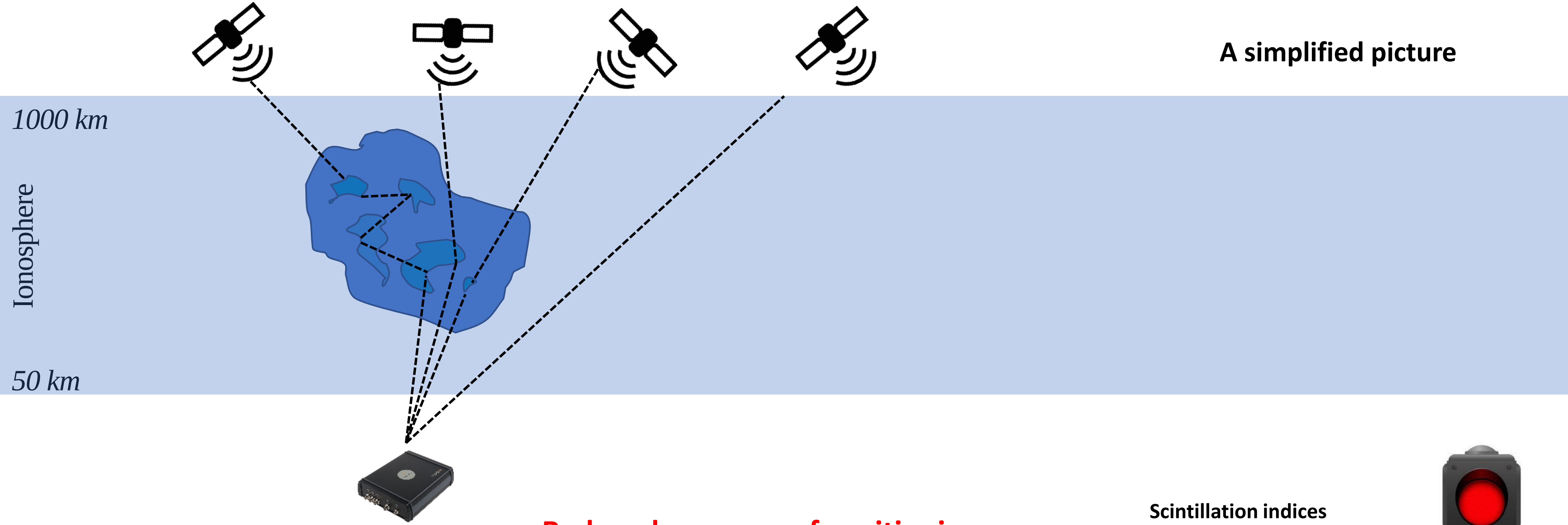
$$S_4^2 = \left(\langle I^2\rangle - \langle I\rangle^2\right)/\langle I\rangle^2.$$

Ampl.

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

Phase

A simplified picture



Reduced accuracy of positioning

Loss of lock

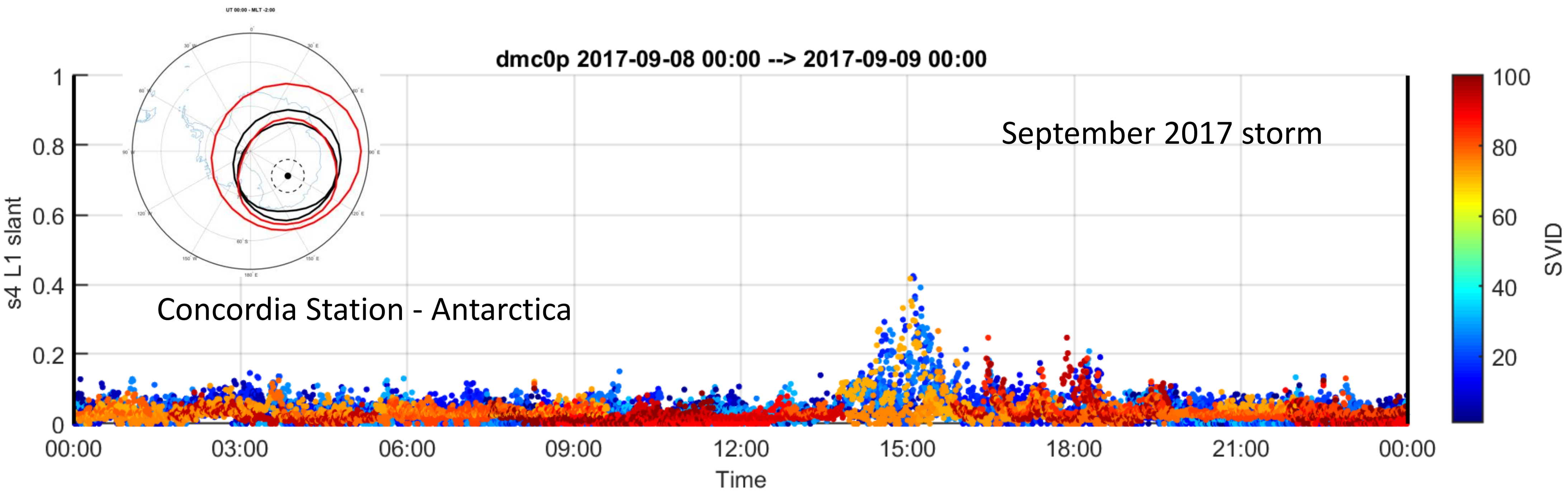
Scintillation indices

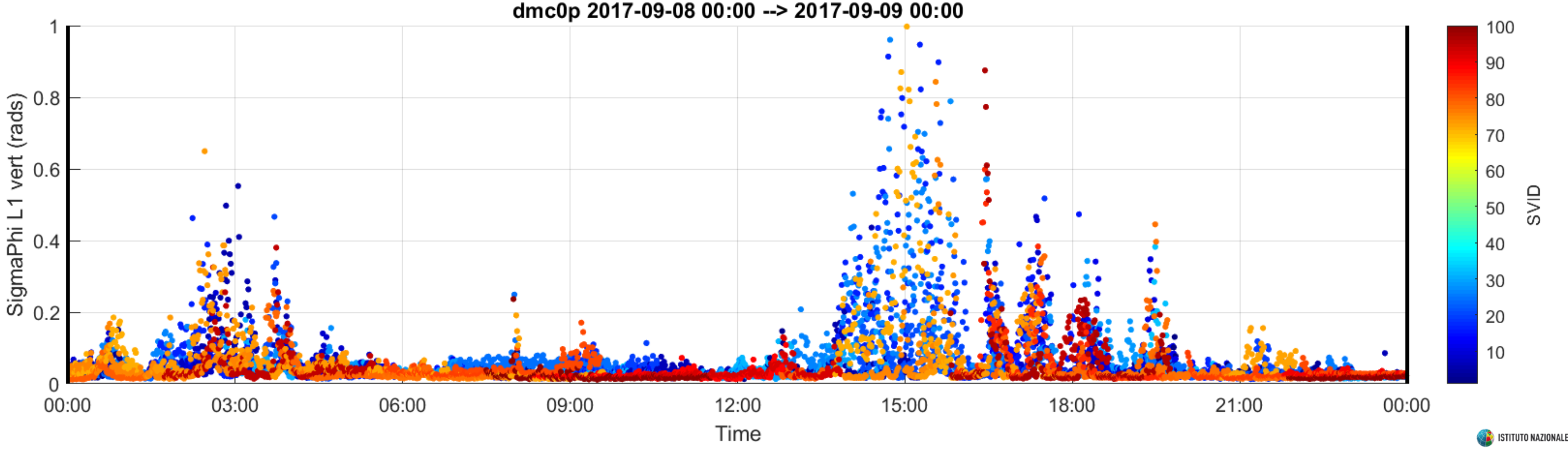
$$S_4^2 = \left(\langle I^2\rangle - \langle I\rangle^2\right)/\langle I\rangle^2.$$

Ampl.

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

Phase


dmc0p 2017-09-08 00:00 --> 2017-09-09 00:00
September 2017 storm
Concordia Station - Antarctica
s4 L1 slant
Time
SVID
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00


dmc0p 2017-09-08 00:00 --> 2017-09-09 00:00
SigmaPhi L1 vert (rads)
Time
SVID
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00

PITHIA
e-Science Centre

Home | Scientific Metadata | Space Physics Ontology

Home > All Scientific Metadata > Data Collection-related Metadata > Data Collections

Data Collections

Top-level definition of a collection of the model or measurement data, with CollectionResults pointing to its URL(s) for accessing the data. Note: data collections do not include begin and end times, please see Catalogue.

On This Page:

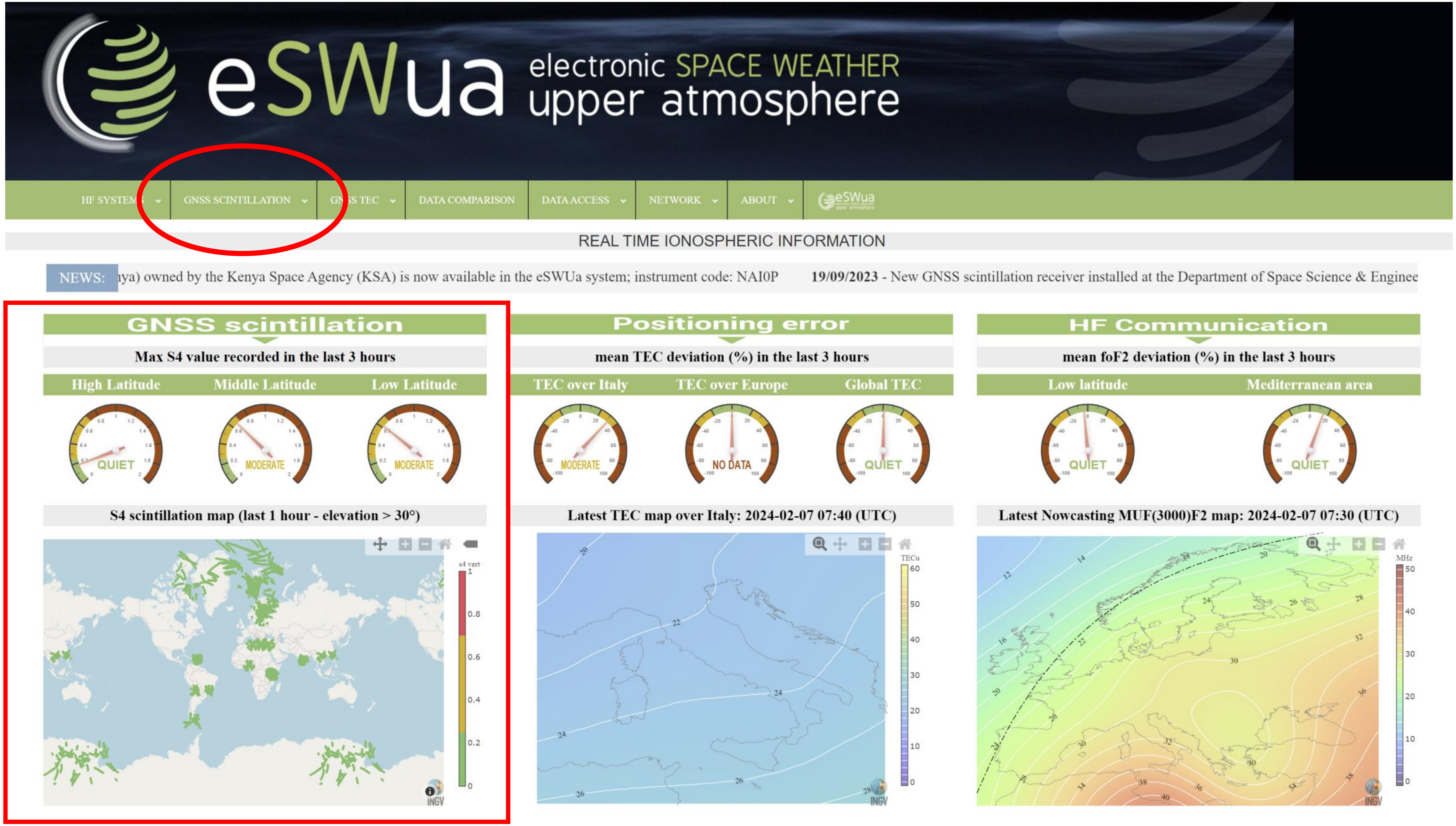
- Activity Indicators
- Sensor Measurements
- Computational Models
- Mixed
- Other

Mixed

- eSWua IONOWORD tool: Nowcasting global TEC maps
- eSWua IONOWORLD tool: Long-term forecasting global TEC maps
- eSWua: Scintillation Indices and Total Electron Content (TEC) database
- GIM: Global Ionosphere Maps
- IRTAM 3D global real-time assimilative model of ionospheric electron density
- RayTRIX-CQP: Oblique ionogram synthesizer with E, F1, F2 layer echo traces and MUF

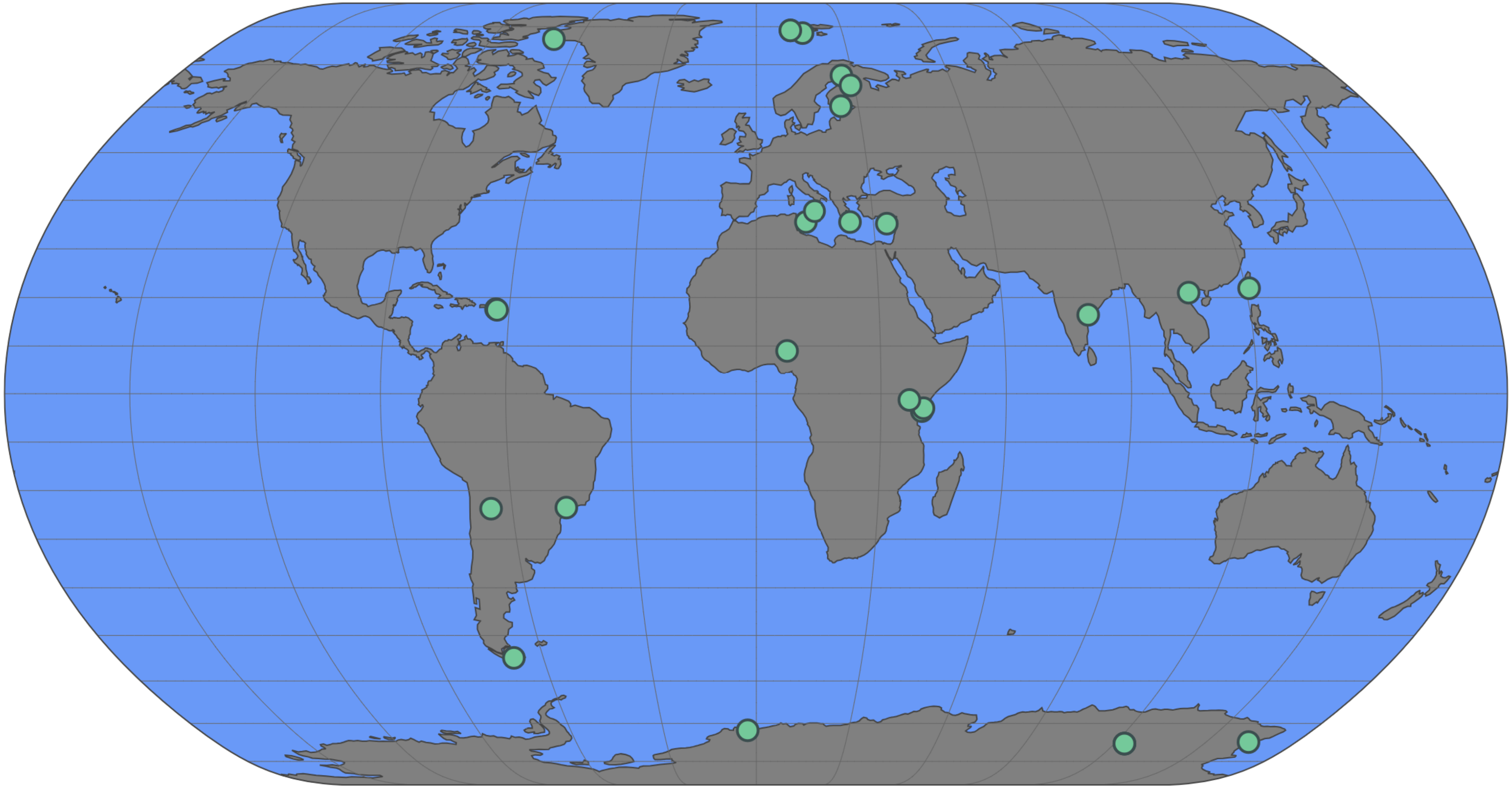
https://esc.pithia.eu/

eswua.ingv.it



eswua.ingv.it

INGV IONOSPHERIC MONITORING NETWORK

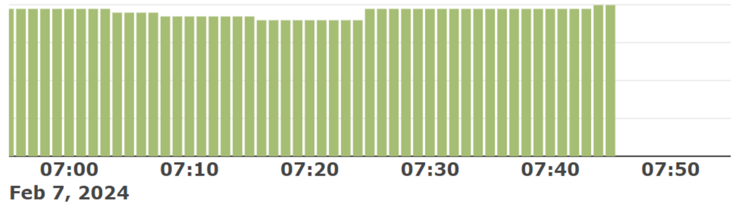


INGV

eswua.ingv.it

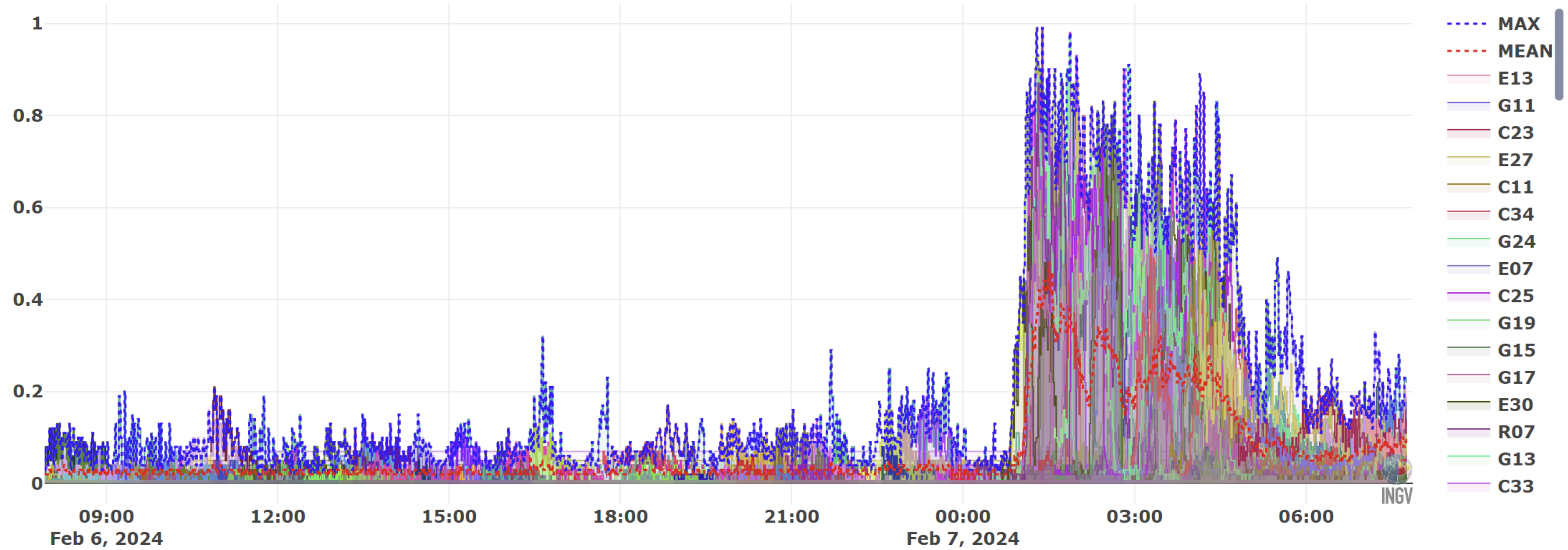
STATION CODE - LOCATION	STATION AREA:	STATION STATUS
tuc0p - Tucuman	SOUTH AMERICA LAT: -23.73° - LON: -65.23°	ACTIVE
STATION INSTRUMENT		LAST DATA RECEIVED
Septentrio PolaRx5S		10 minutes ago

HOST	DATA OWNER
UNIVERSIDAD NATIONAL DE TUCUMÁN	INGV



S4 VERTICAL INDEX

Yaxis limit: autorange



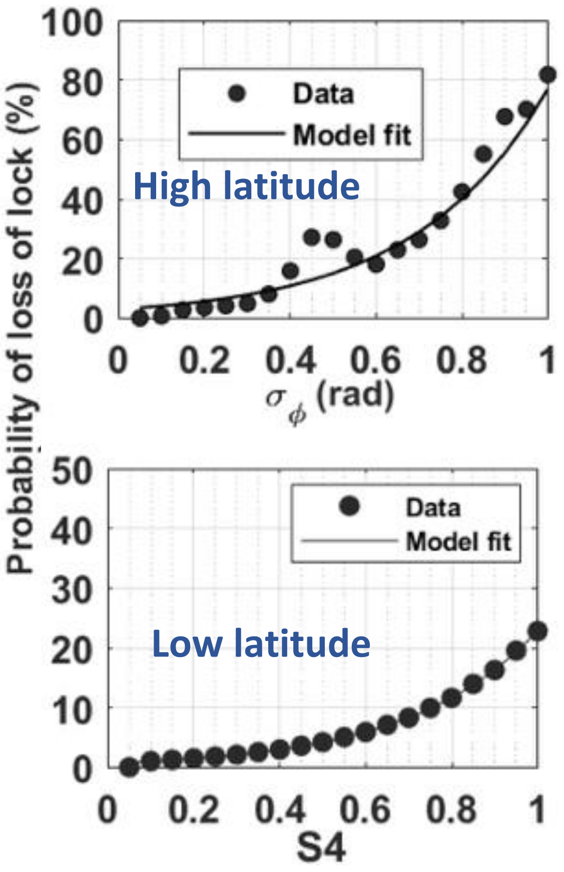
Map
Skyplot

Scale limit = 1

Impact on tracking

Occurrence of scintillation is strongly linked with Loss of Lock probability

Vadakke Veettil, S., & Aquino, M. (2021). *GPS Solutions*, *25*(2), 1-12.



$$Prob\ lol_{scint}^{highlat}(\%) = \left[0.02955.\exp\left(3.26.\sigma_{\varphi}\right)\right].100$$

$$Prob\ lol_{scint}^{lowlat}(\%) = \left[0.00797.\exp(3.36.S4)\right].100$$

X. Luo et al. / Advances in Space Research 60 (2017) 1039–1053 1045

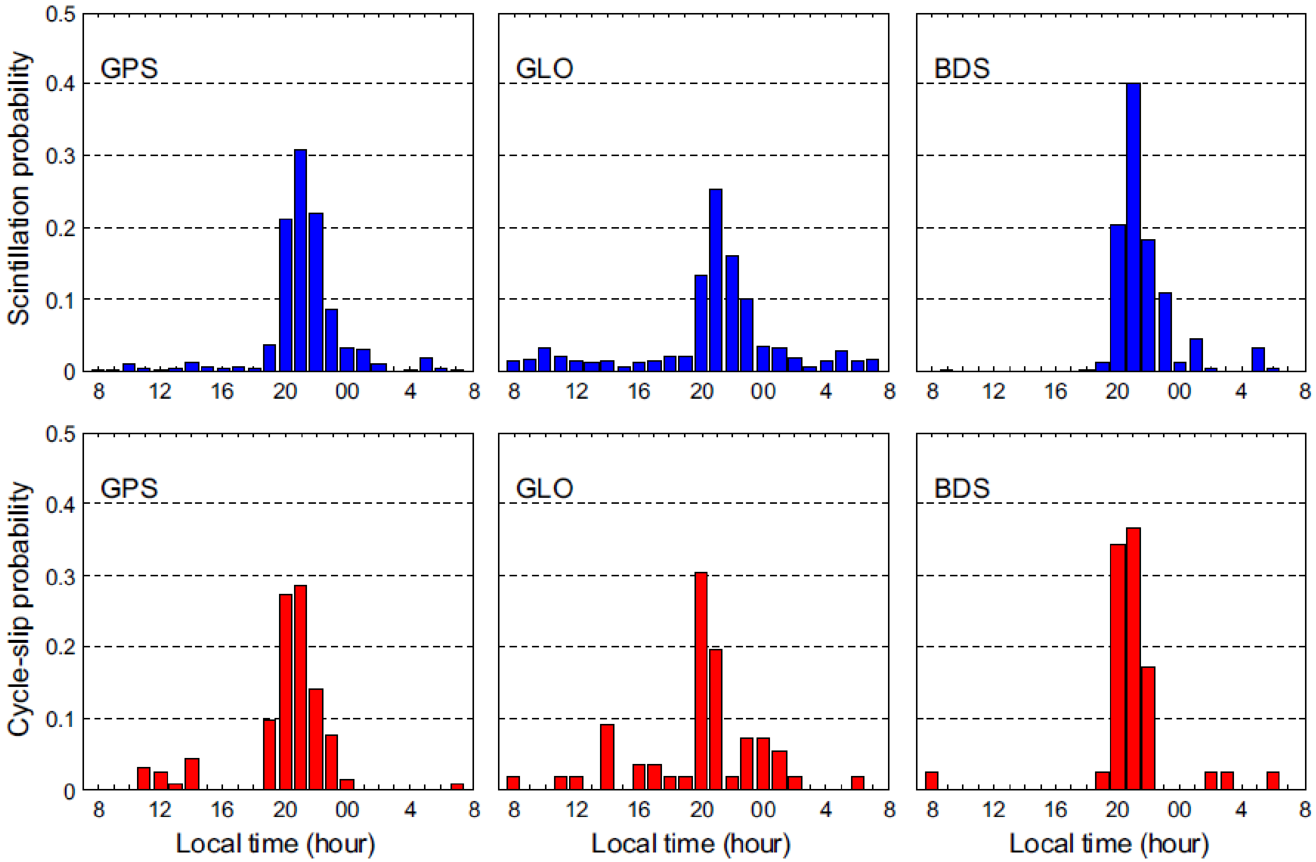


Fig. 5. Hourly occurrence probability of scintillation events and cycle-slips for GPS, GLONASS, and BDS satellites data collected at Sha Tin station from 6 October 2015 to 31 December 2016.

Impact on positioning

K.S. Jacobsen and Y.L. Andalsvik: 2015 St. Patrick's day storm in Norway

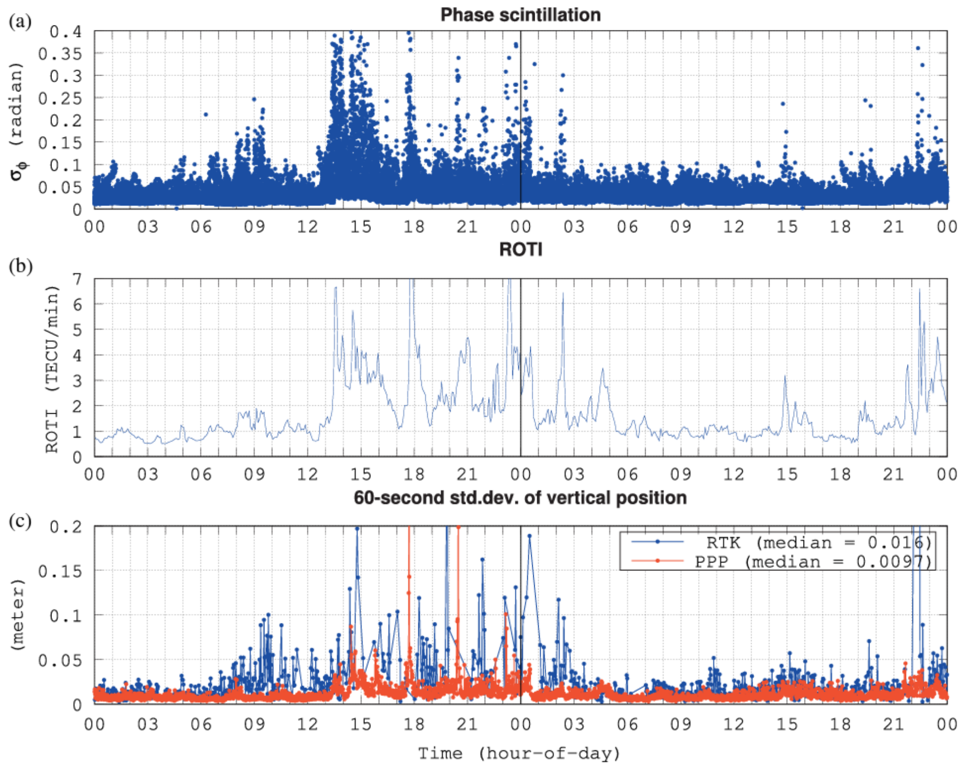
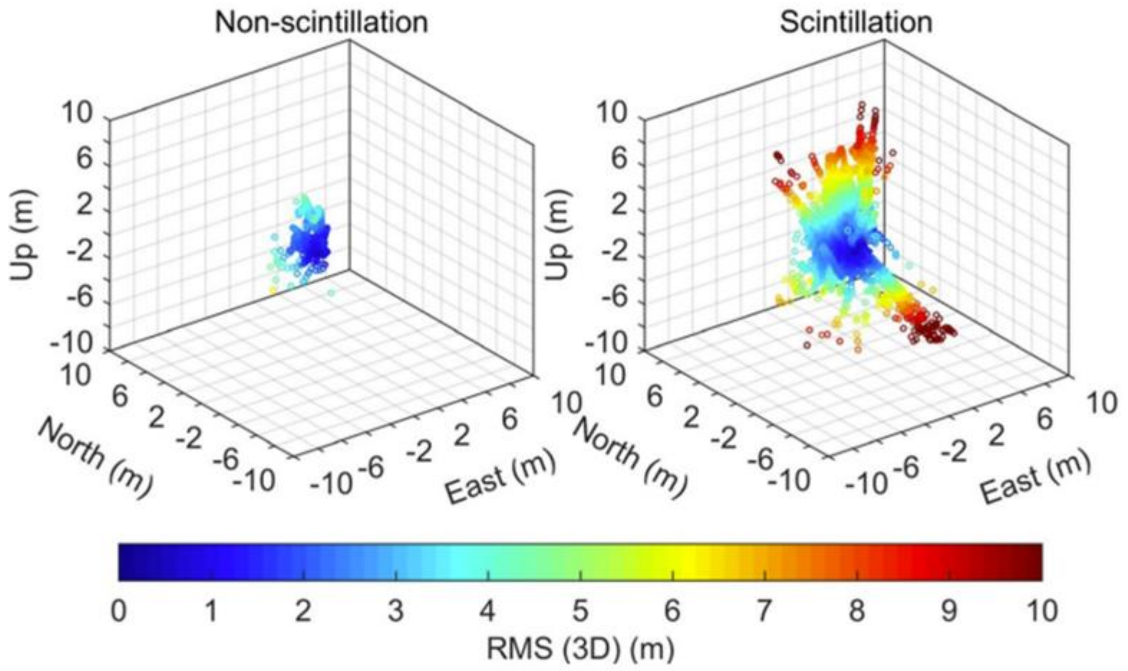


Fig. 8. Data for 2015-03-17 and 2015-03-18. (a) Phase scintillation index for all GPS and GLONASS satellites, from the scintillation receiver in Vega. (b) ROTI@Rec for the receiver VEGS. (c) Position errors for Steinkjer (RTK) and Vega (PPP) (receivers MSTE & VEGS). Blue line is RTK, red line is PPP.



Distribution of positioning errors in the East, North and Up directions

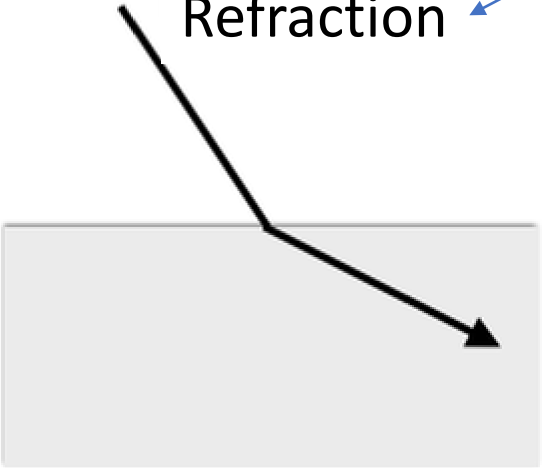
Luo et al. (2018). Investigation of ionospheric scintillation effects on BDS precise point positioning at low-latitude regions. GPS solutions, 22(3), 1-12.

Occurrence of scintillation decreases GNSS performance

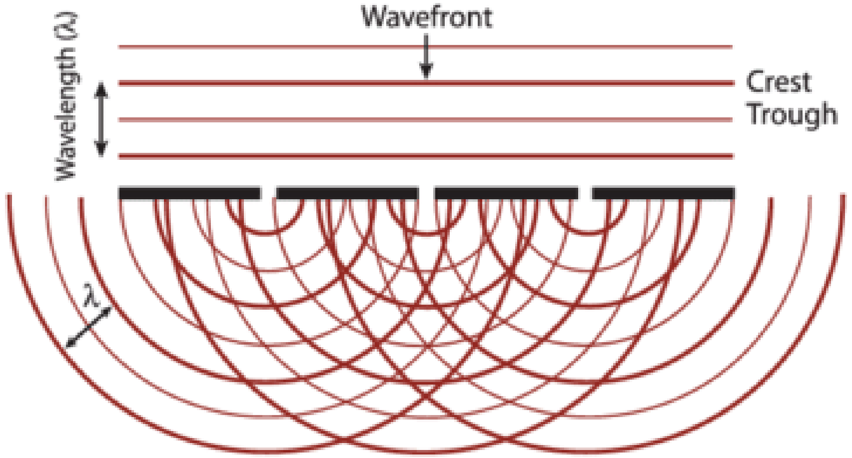
What causes phase and amplitude fluctuations in the GNSS signals?

Ionospheric irregularities

Refraction



Diffraction



Scale size range: full ionospheric spectrum
Affects: phase
Physical mechanism: phase mixing
Effect: deterministic fluctuations
Mitigation: IFLC (1st ionospheric order)
Positioning issues: Cycle Slips, Losses and Lock, Phase Noise, 2nd order ionospheric effect (fraction of cm), etc.

Scale size range: up to Fresnel's scale
Affects: amplitude, phase
Physical mechanism: decorrelation, interference
Effect: stochastic fluctuations
Mitigation: e.g., Conker et al., Aquino et al., etc., de-weighting methods.
Positioning issues: stochastic nature is challenging, TEC cannot be calculated

What is scintillation?

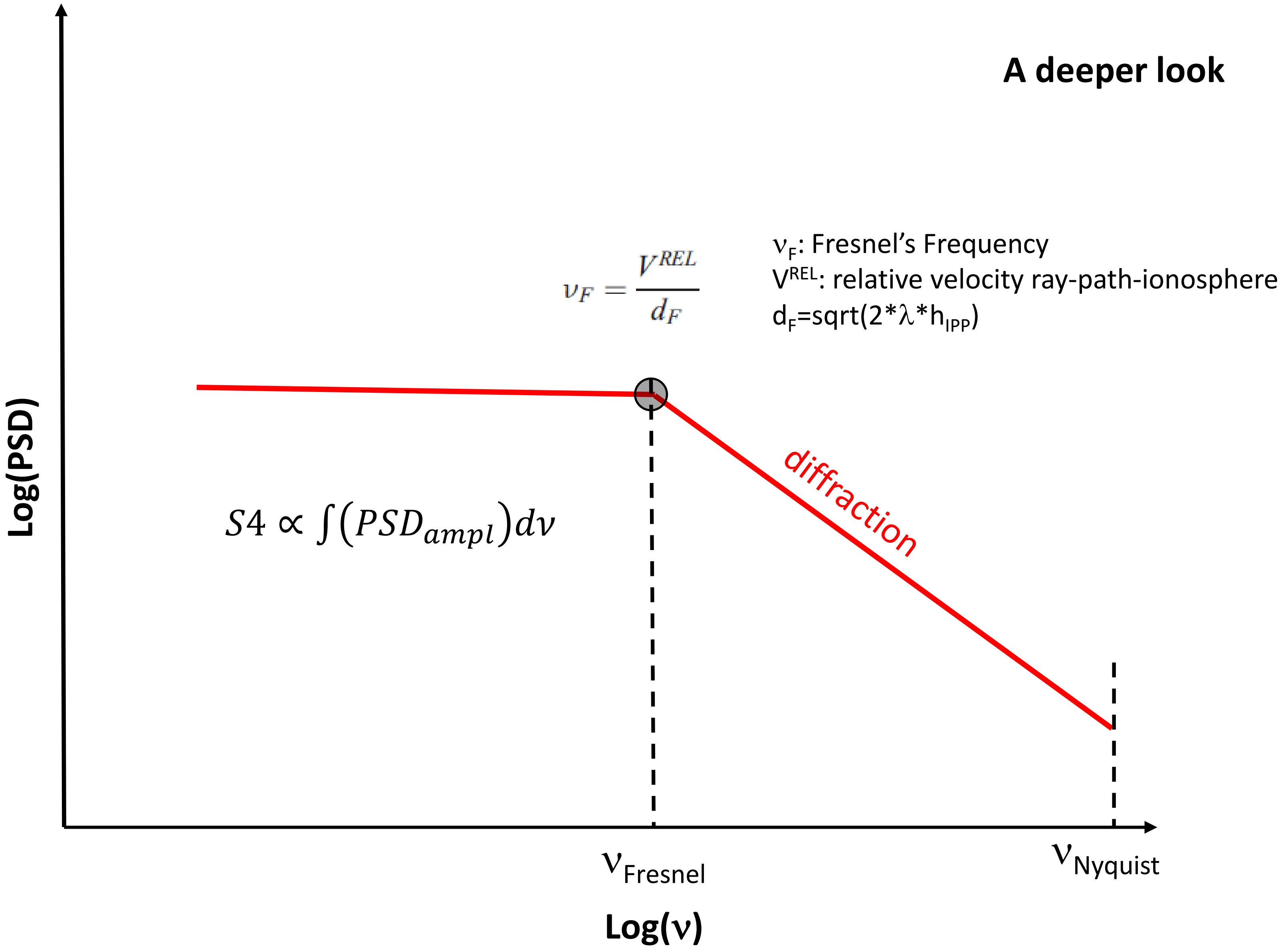
A deeper look

Amplitude scintillation:

1 mechanism:
diffraction triggered by small-scale irregularities

Stochastic effect

Stochastic effects are the most threating for GNSS positioning



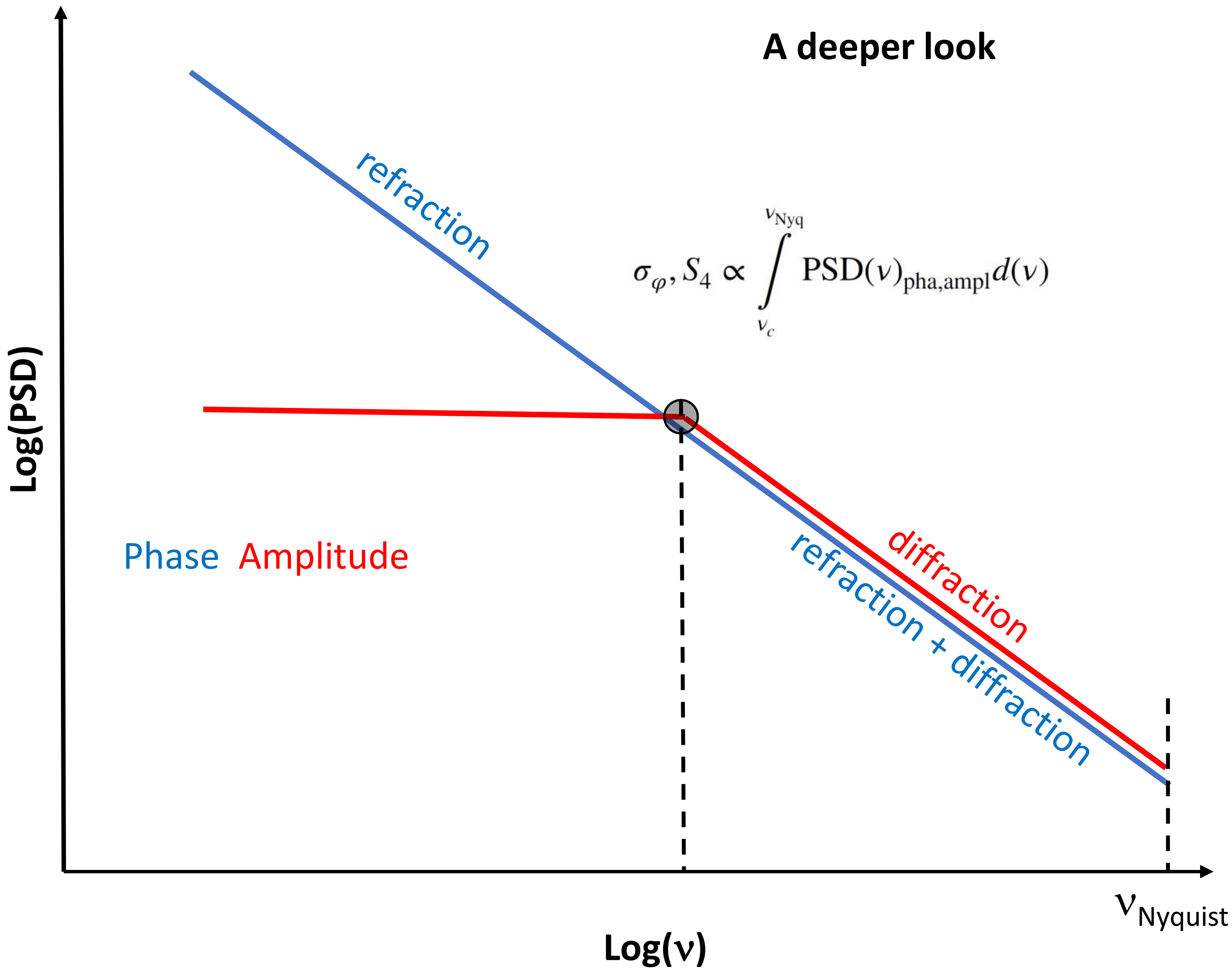
What is scintillation?

Phase "fluctuations":

2 mechanisms:
-**diffraction** (small-scale irregularities)
-refraction (all scale range and scaling with 1/f)

Stochastic and deterministic effects

A deeper look



What is scintillation?

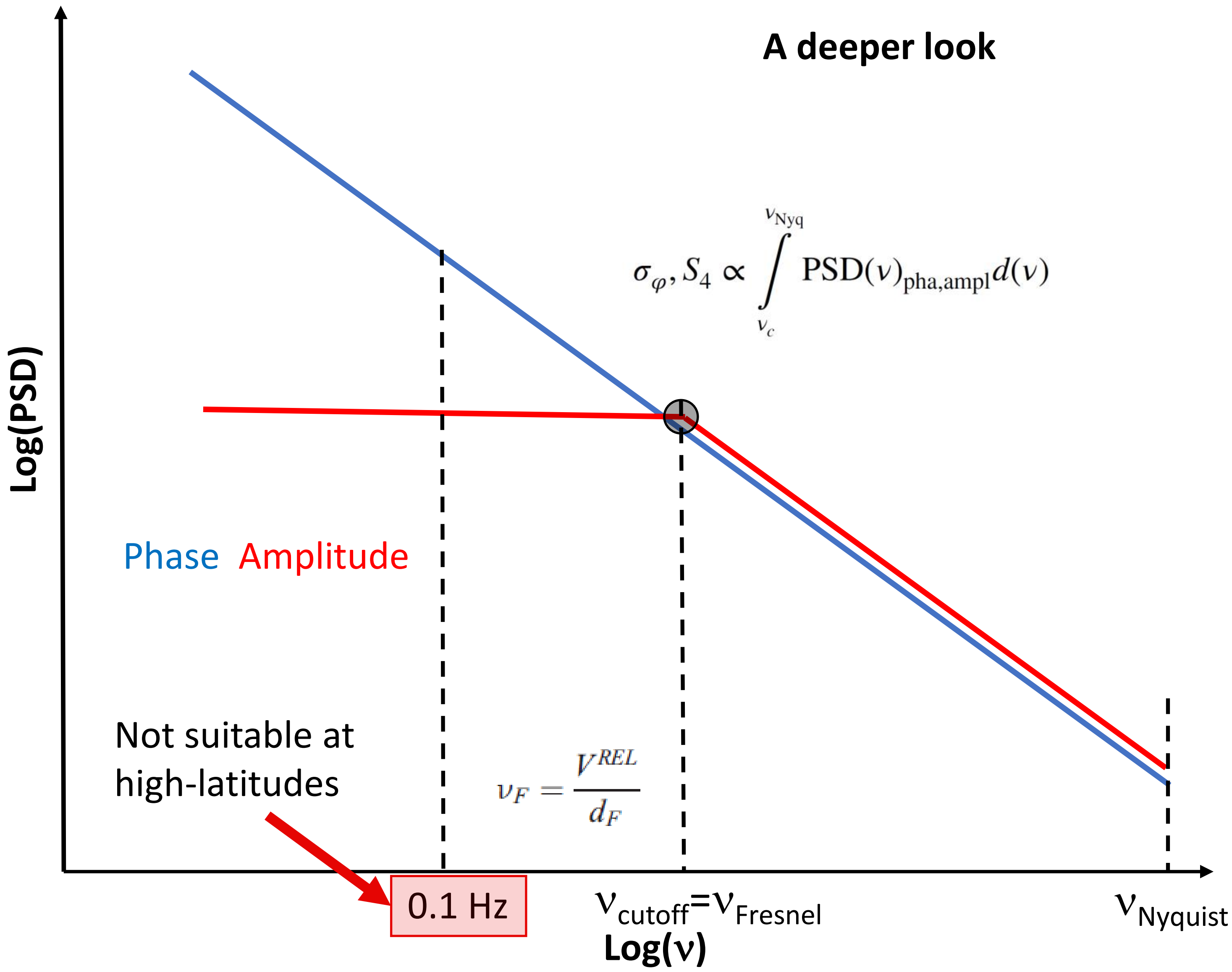
Phase "fluctuations":

2 mechanisms:
-**diffraction** (small-scale irregularities)
-refraction (all scale range and scaling with 1/f)

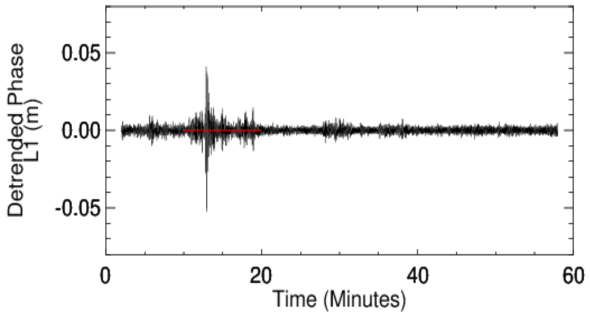
Stochastic and deterministic effects

If cutoff frequency is "wrong" (ususally fixed at 0.1 Hz), detrending is wrong, σ_Φ value includes mainly phase fluctuations due to refraction, i.e., mostly deterministic effects.
Overestimated σ_Φ

A deeper look



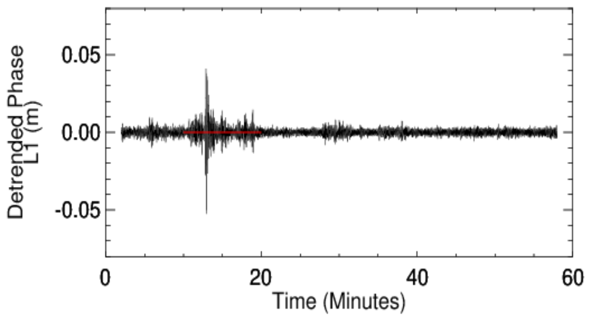
What is scintillation?



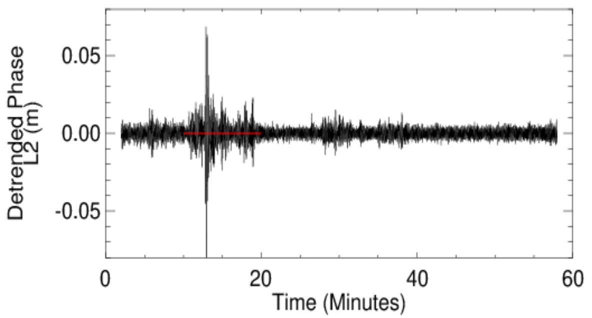
Scintillation on L1?

*adapted from a slide by Jayachandran (UNB)

What is scintillation?



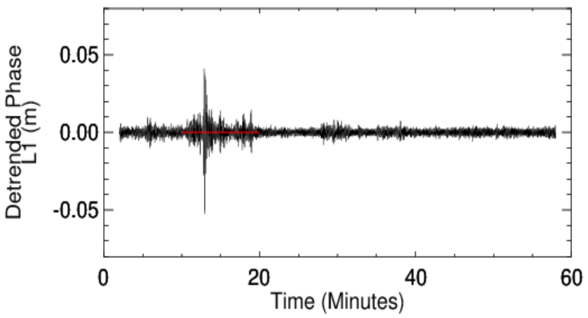
Scintillation on L1?



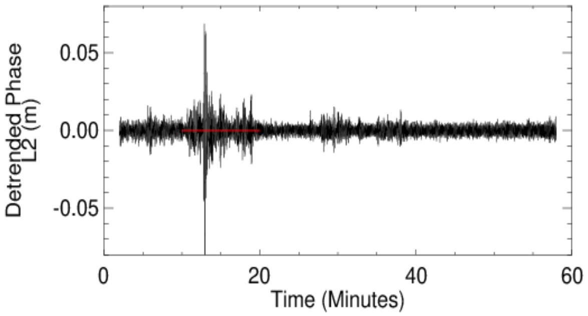
Scintillation on L2?

*adapted from a slide by Jayachandran (UNB)

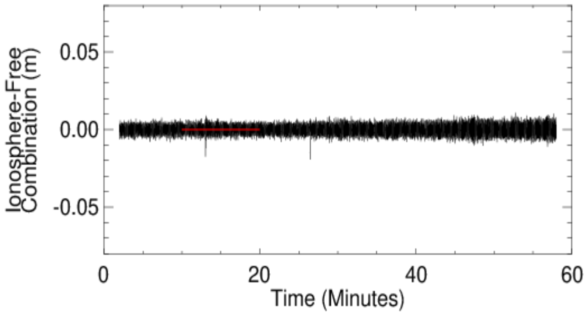
What is scintillation?



Scintillation on L1?



Scintillation on L2?

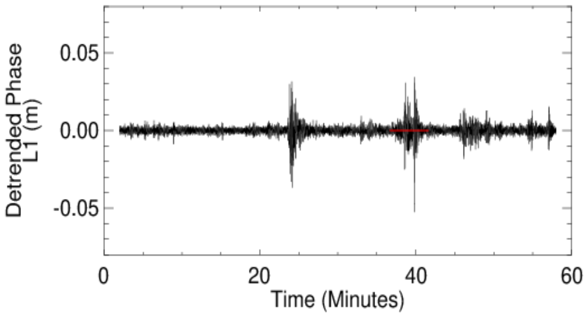


NO! Ionosphere-Free Linear Combination says NO!

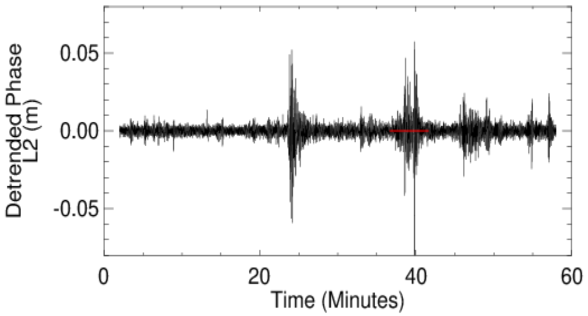
$$IFLC = \frac{\Phi_1 f_1^2 - \Phi_2 f_2^2}{f_1^2 - f_2^2}$$

*adapted from a slide by Jayachandran (UNB)

What is scintillation?



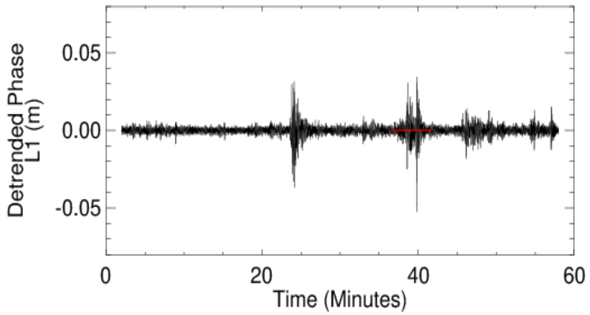
Scintillation on L1?



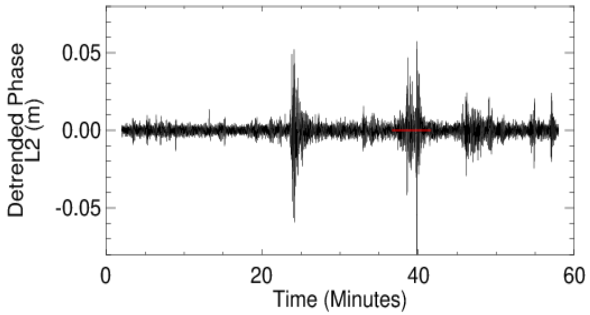
Scintillation on L2?

*adapted from a slide by Jayachandran (UNB)

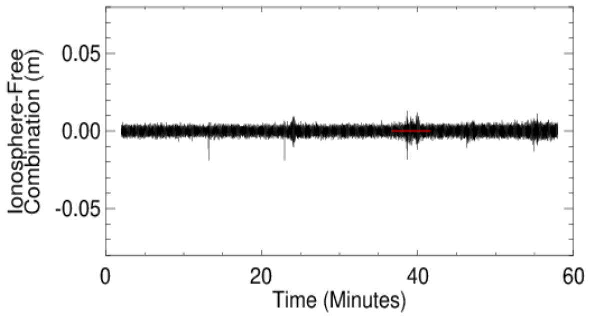
What is scintillation?



Scintillation on L1?



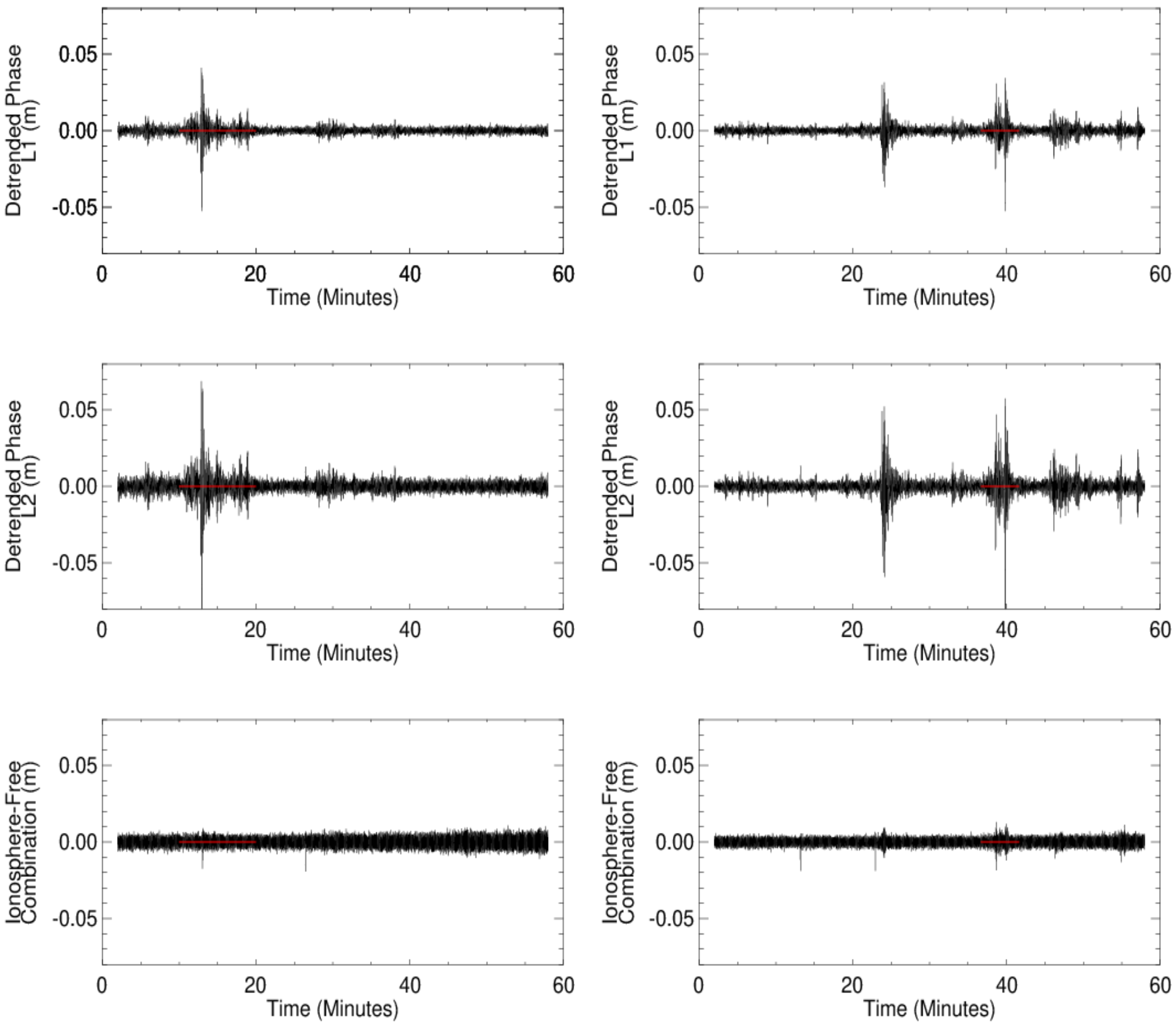
Scintillation on L2?



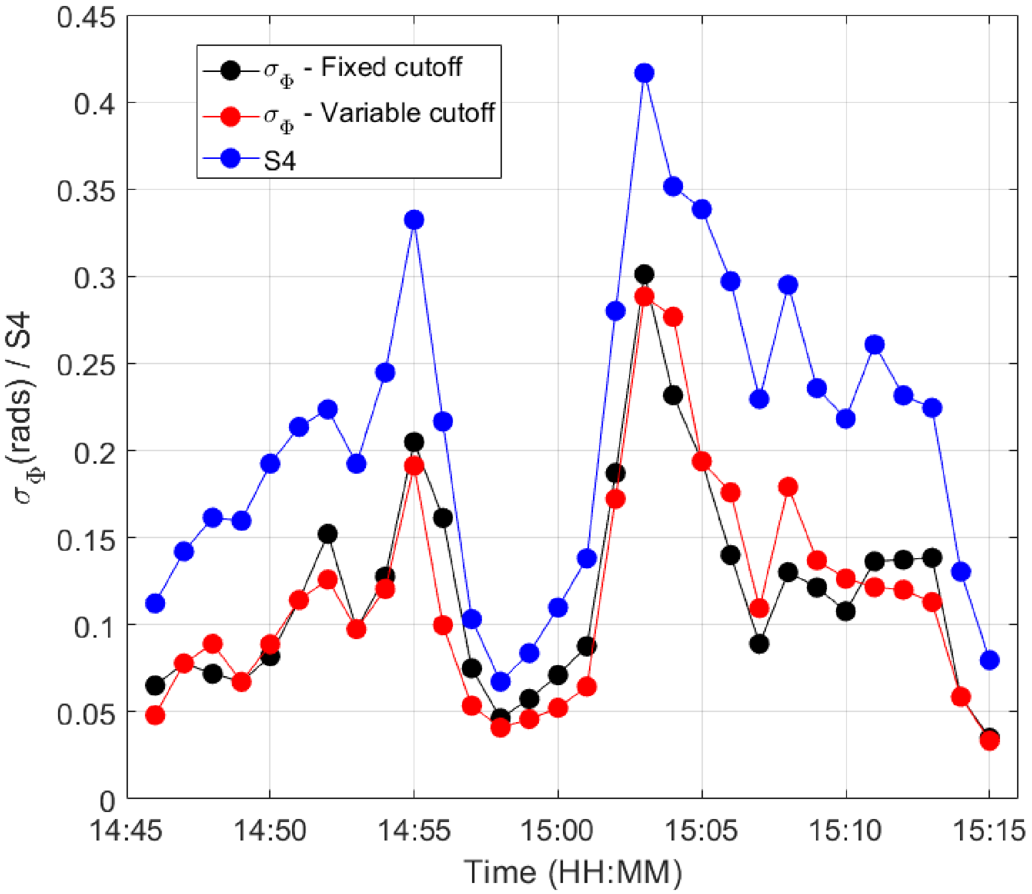
YES! Ionosphere-Free Linear Combination doesn’t account for all fluctuations

*adapted from a slide by Jayachandran (UNB)

What is scintillation?



Courtesy of Jayachandran (UNB)

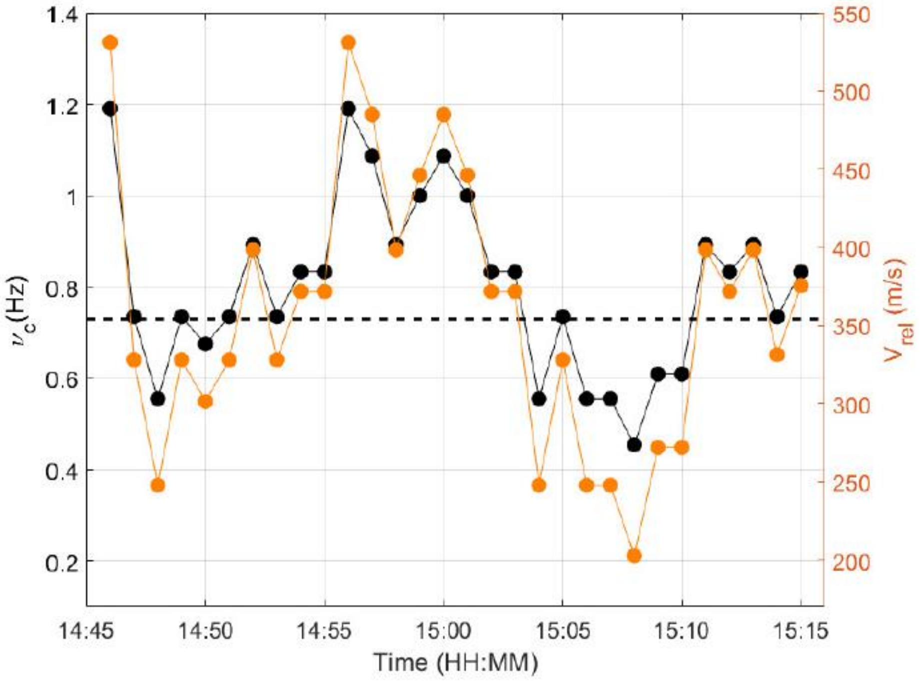


If properly detrended, SigmaPhi has almost the same information content of S4

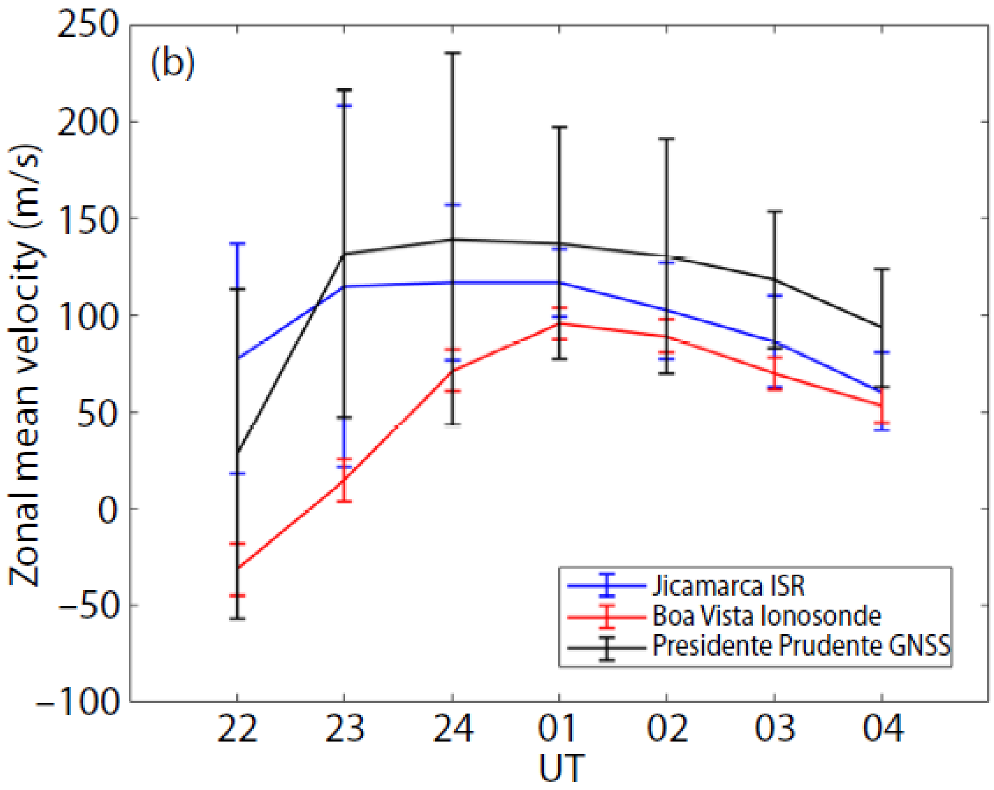
Ghobadi et al. (2020). *GPS Solutions*

Spogli et al. (2021). *IEEE Geoscience and Remote Sensing Letters*.

This is an issue for high-latitude only, where plasma convection is way larger



$$\nu_F = \frac{V^{REL}}{d_F}$$

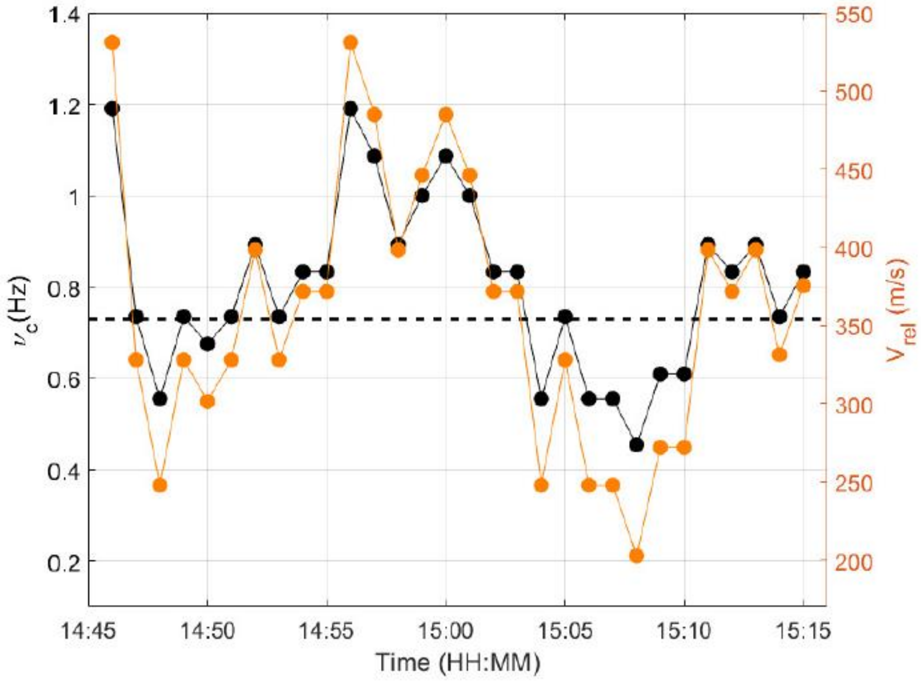


Spogli et al. (2021).
IEEE Geoscience and Remote Sensing Letters.

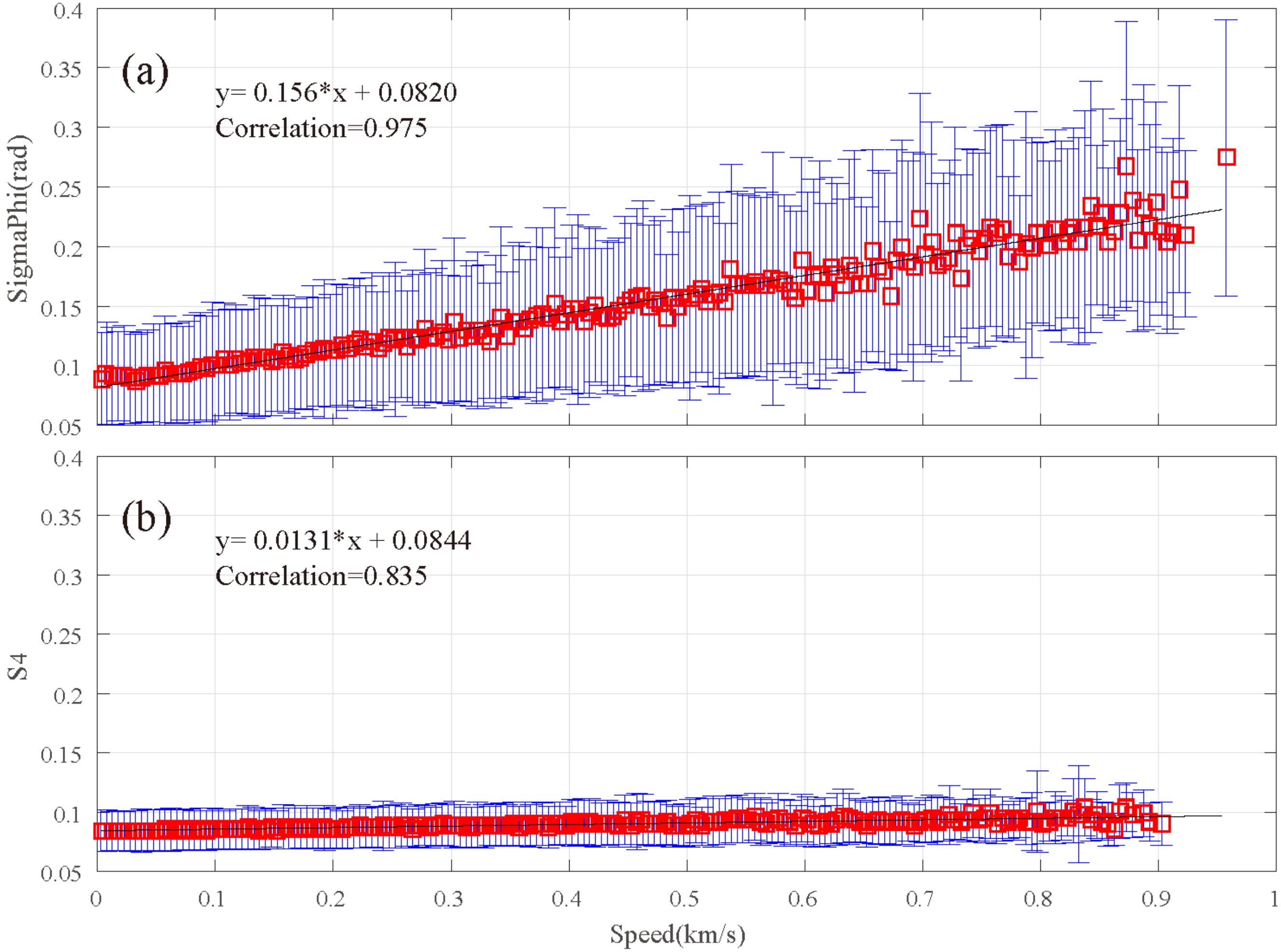
Cesaroni et al. (2021).
Earth and Planetary Physics

0.1 Hz cutoff is not that bad at low latitudes…

Cutoff frequency depends (-- > σ_Φ) on plasma drift velocty

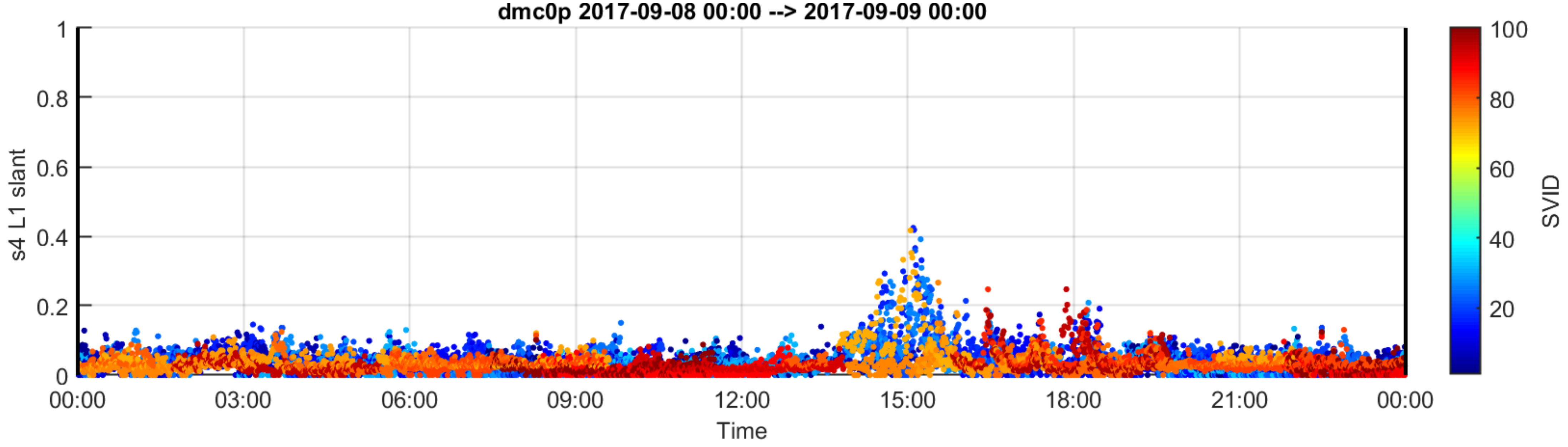


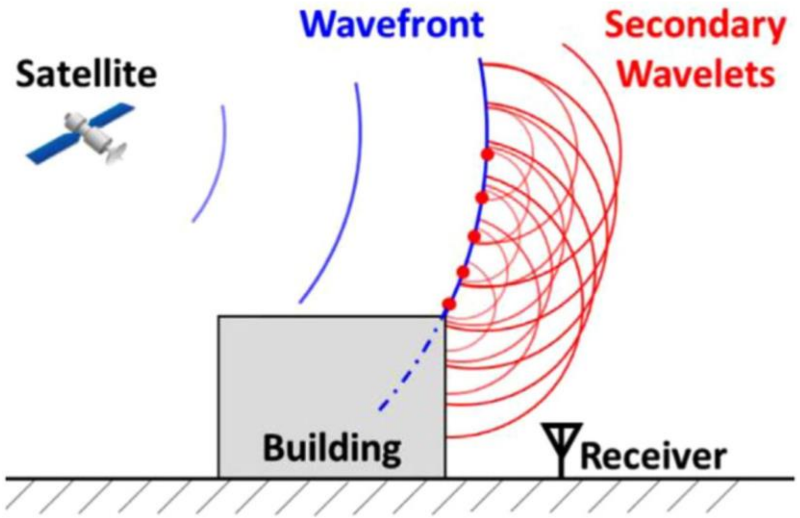
Spogli et al. (2021).
IEEE Geoscience and Remote Sensing Letters.



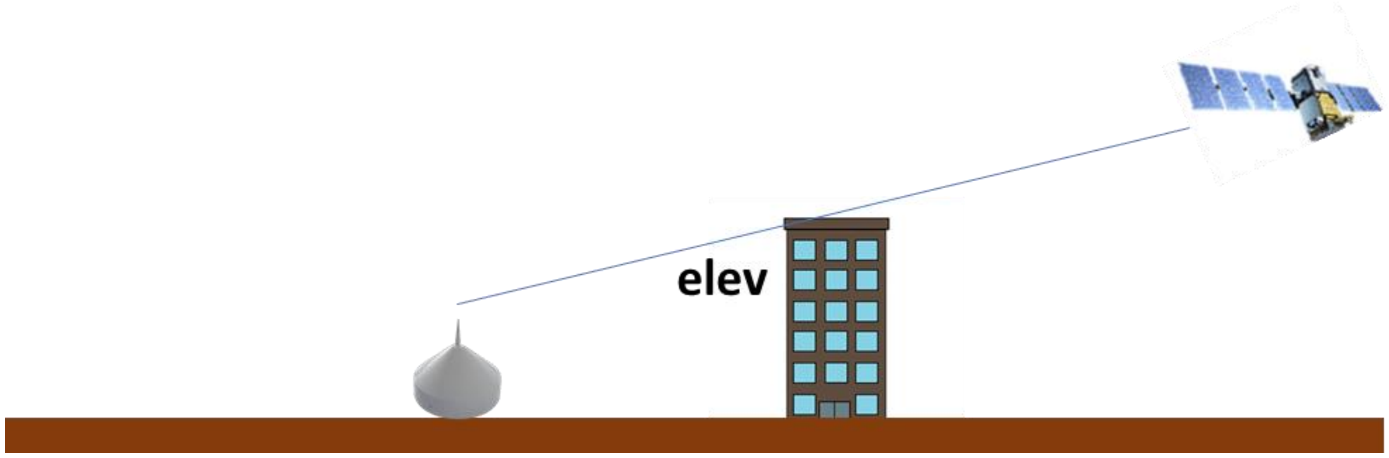
Wang et al. (2018)
Journal of Geophysical Research: Space Physics

What can mimic scintillation?

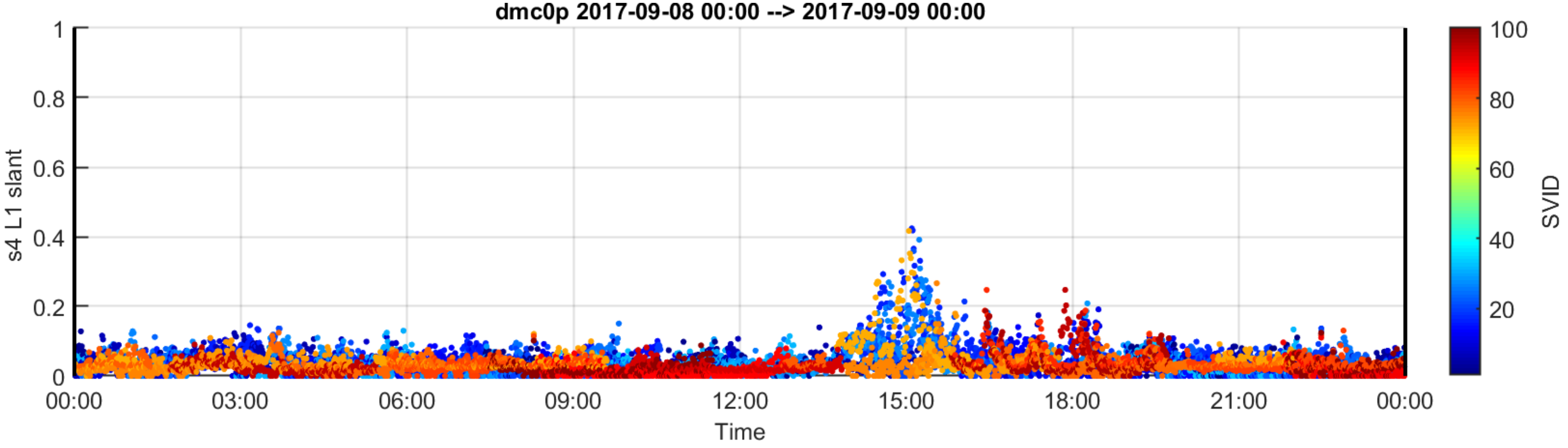




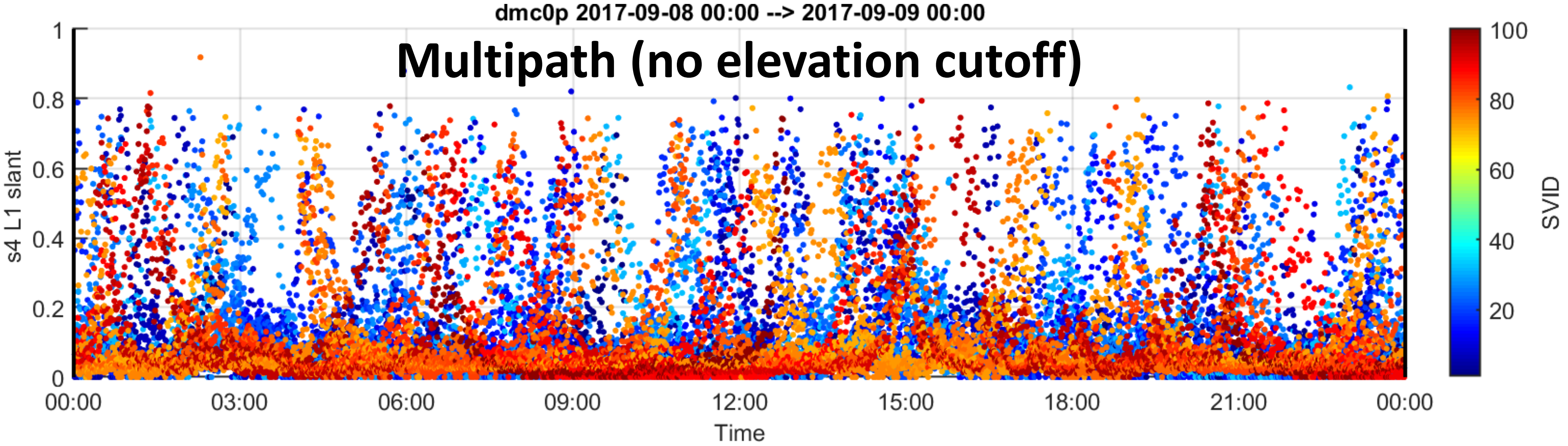
Zhang et al., 2021, https://doi.org/10.1002/navi.417



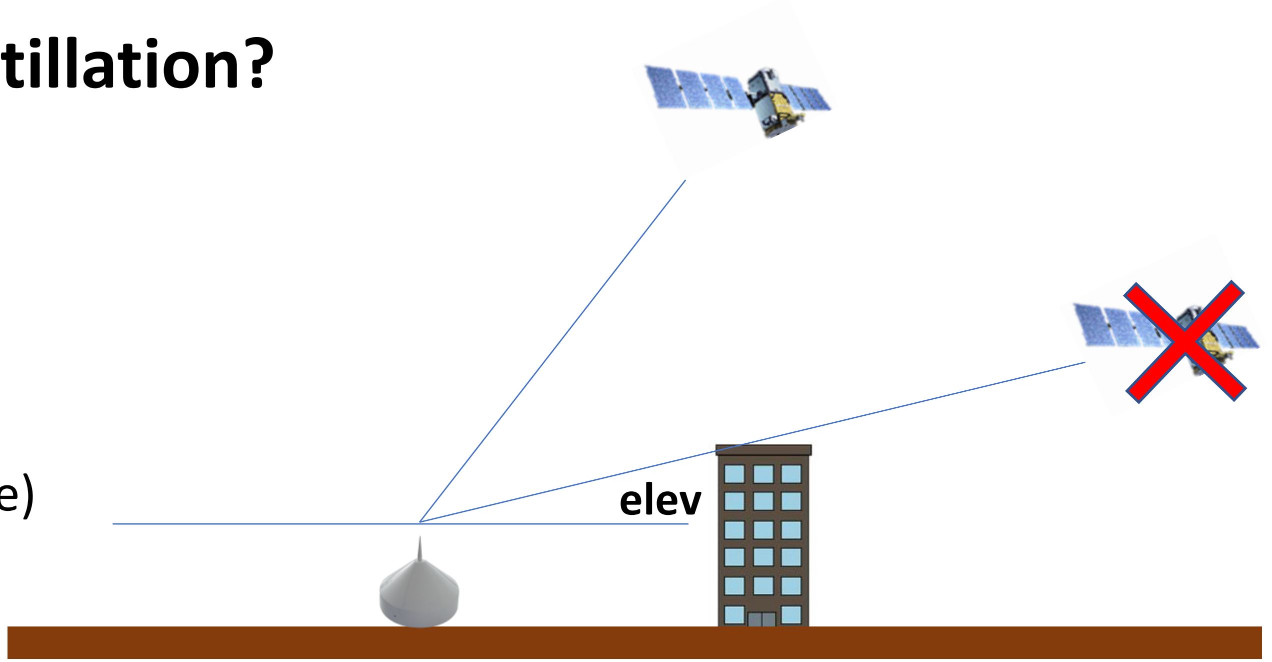
What can mimic scintillation?



Multipath (no elevation cutoff)

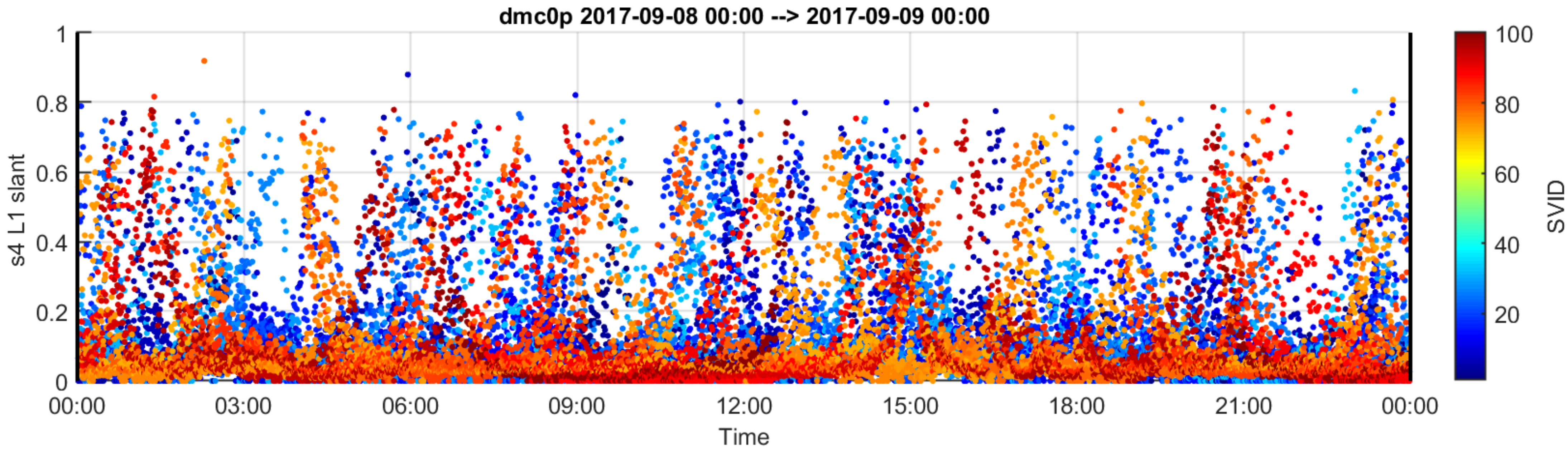


What can mimic scintillation?



How to mitigate?

Cutting the elevation angle (typically 30°)
Sidereal rejection (every day, 4 minutes time advance)

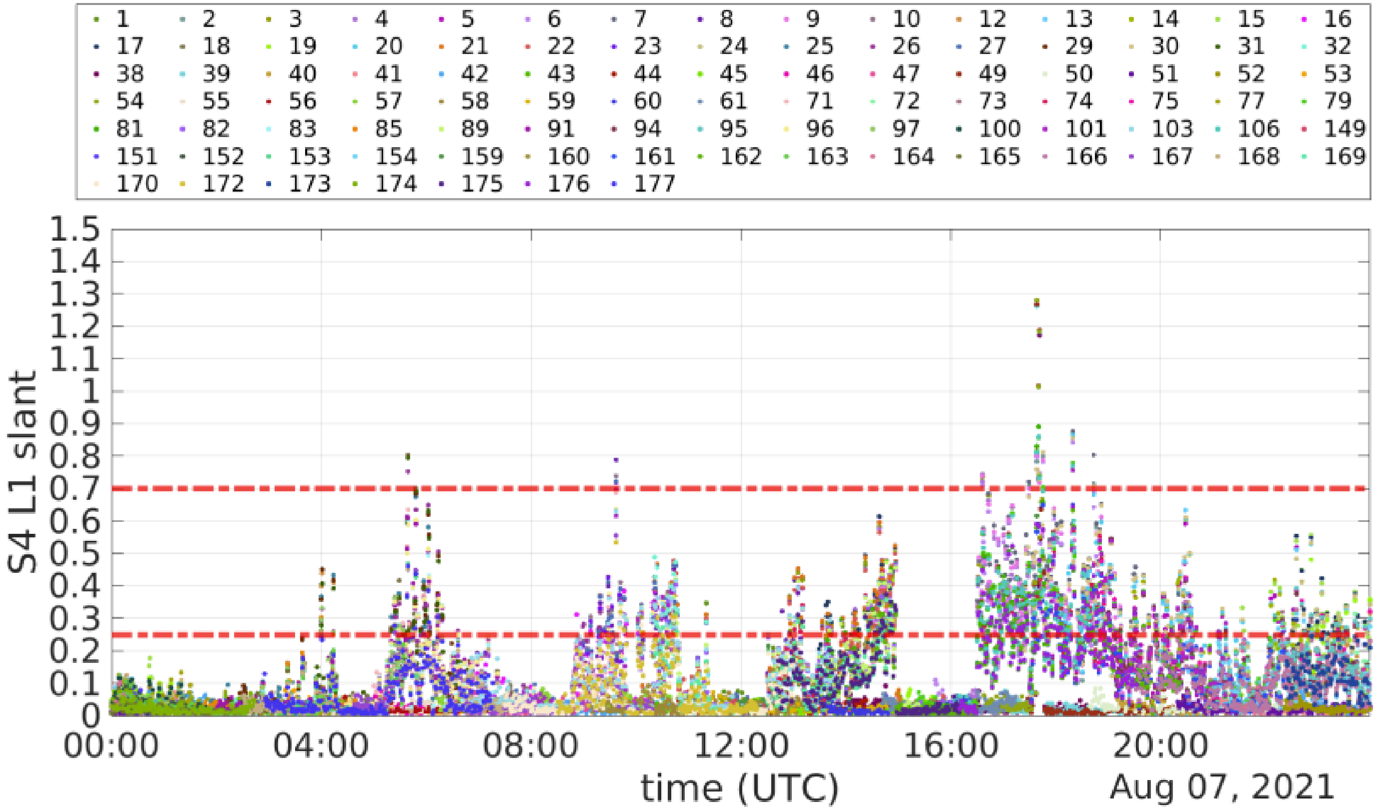


ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

What can mimic scintillation?

Radio Frequency Interference

Artificial RFI reported in Lampedusa (Sicily, Italy) island



Pica et al. (2023) *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*.

Mitigation is not trivial!

What can support the identification of the scale sizes?

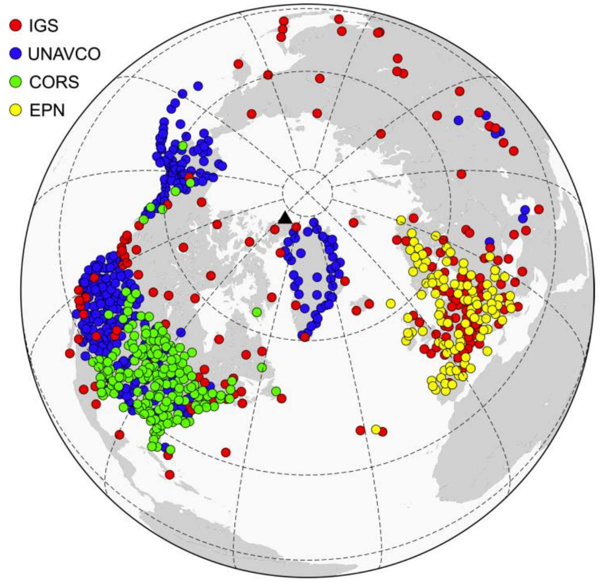
- Rate of TEC index, ROTI

$$ROT = \frac{\Delta TEC}{\Delta t}, \text{ e.g. 5 minutes}$$

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

ROTI can provide valuable information about **phase fluctuations due to irregularities at about few to few tens km scale**

It depends on the Nyquist frequency of ROT sampling, usually $(2*30s)^{-1}$

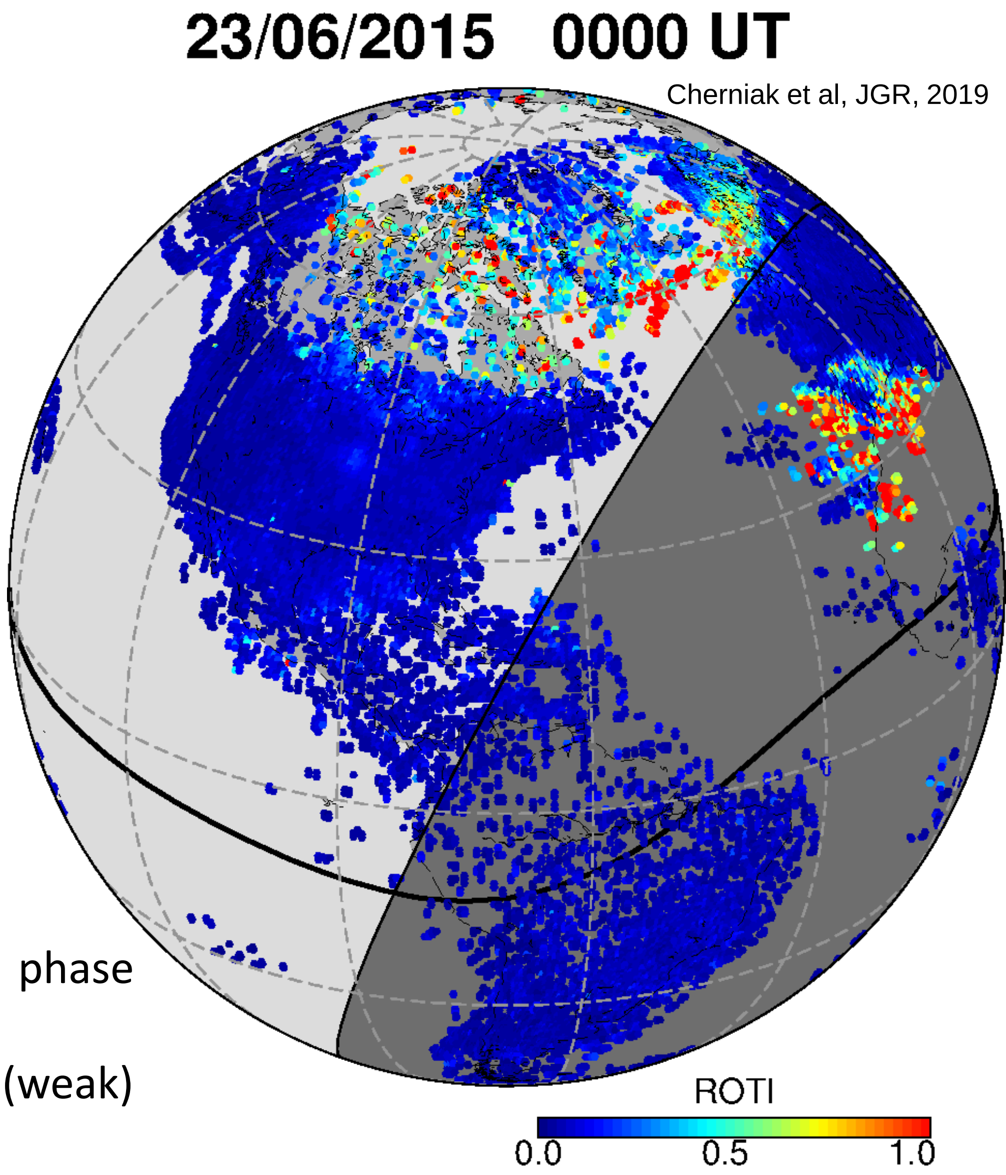


Cherniak et al., 2018

<u>ROTI is not Scintillation!</u>

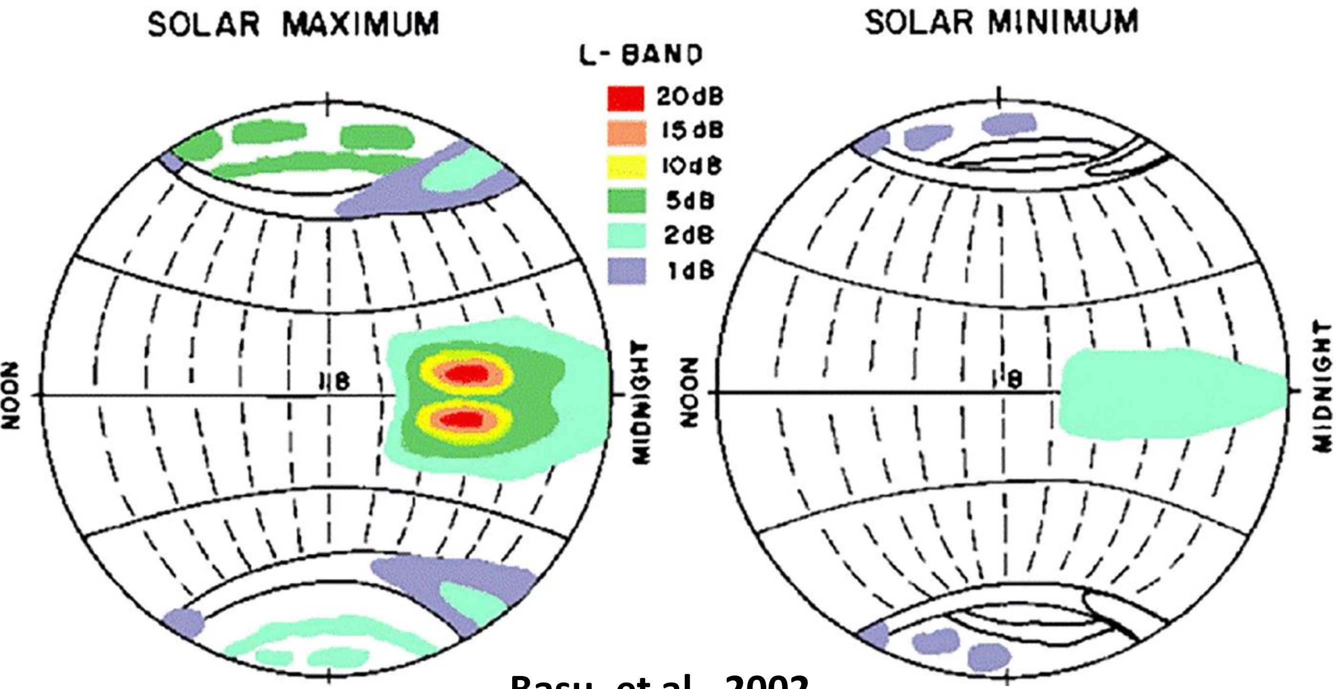
But:

- it is very useful (measures phase fluctuations)
- It can be (not easily) rescaled to (weak) scintillation (Carrano et al., 2019)



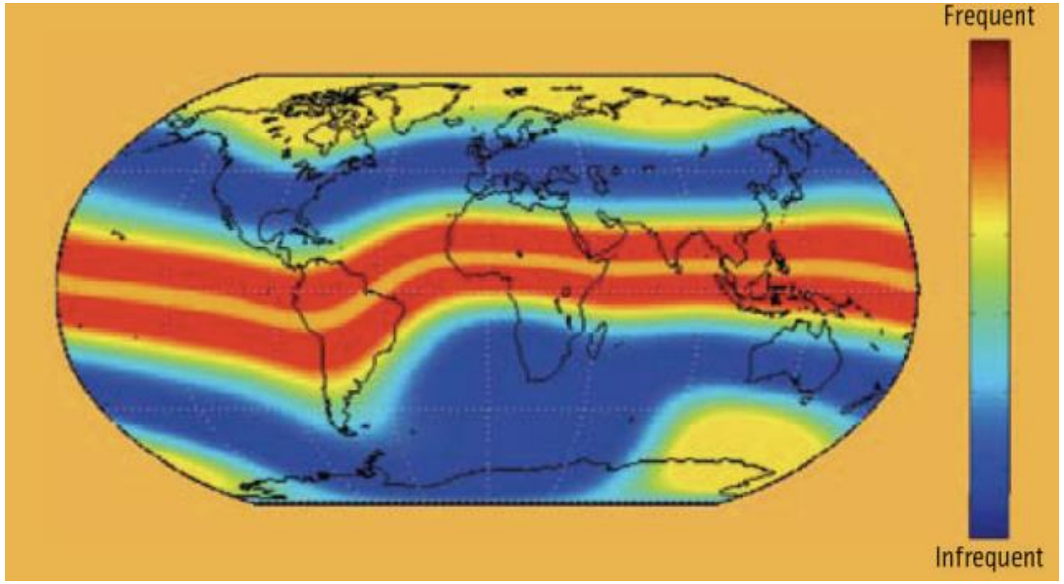
Cherniak et al, JGR, 2019

GNSS signal fading due to scintillation



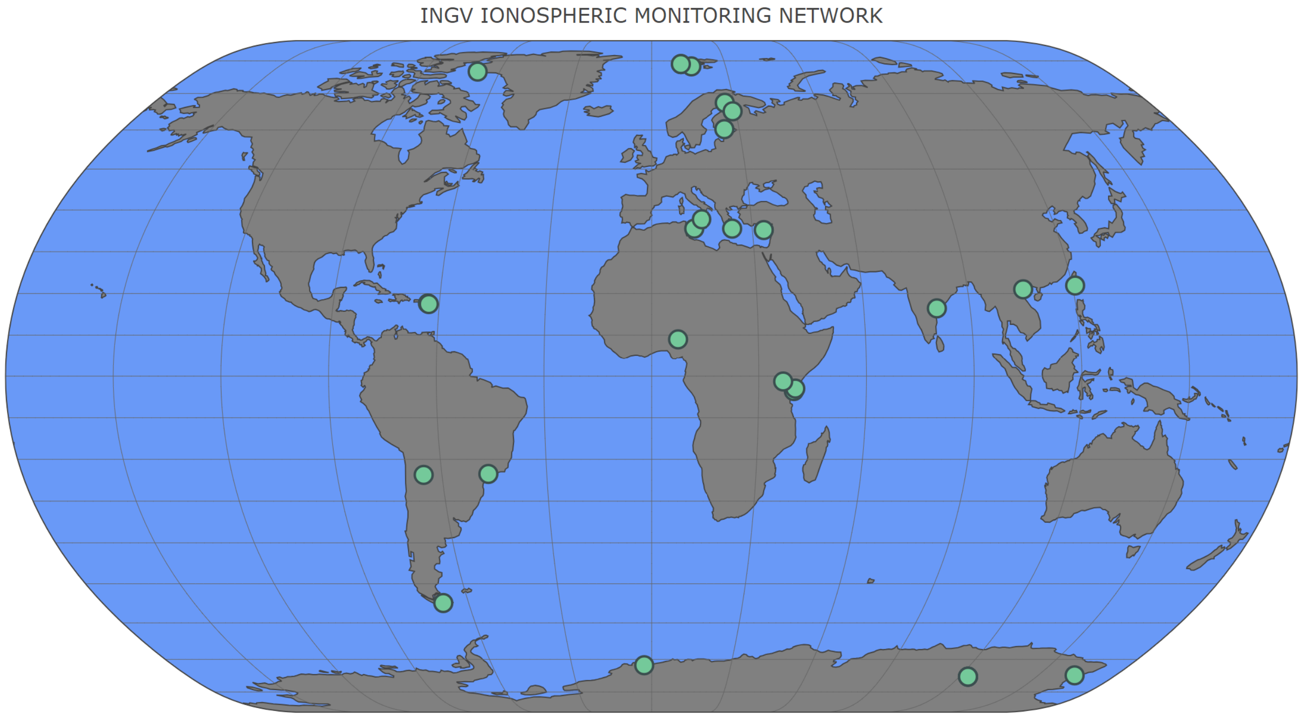
Basu. et al., 2002

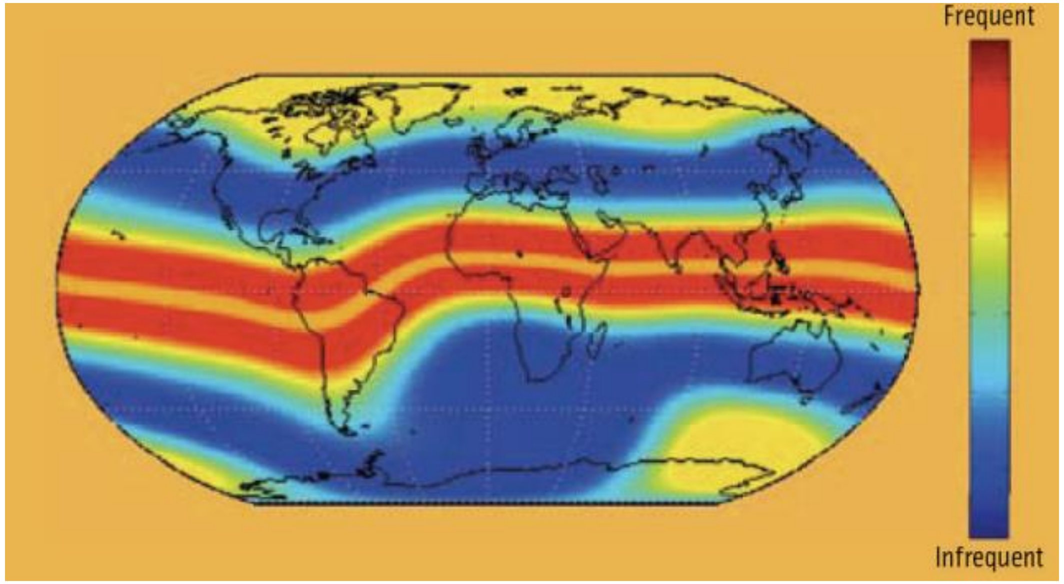
Frequency of the GNSS scintillation



Kintner at al., 2009

Among the most known pictures of climatological modelling of scintillation





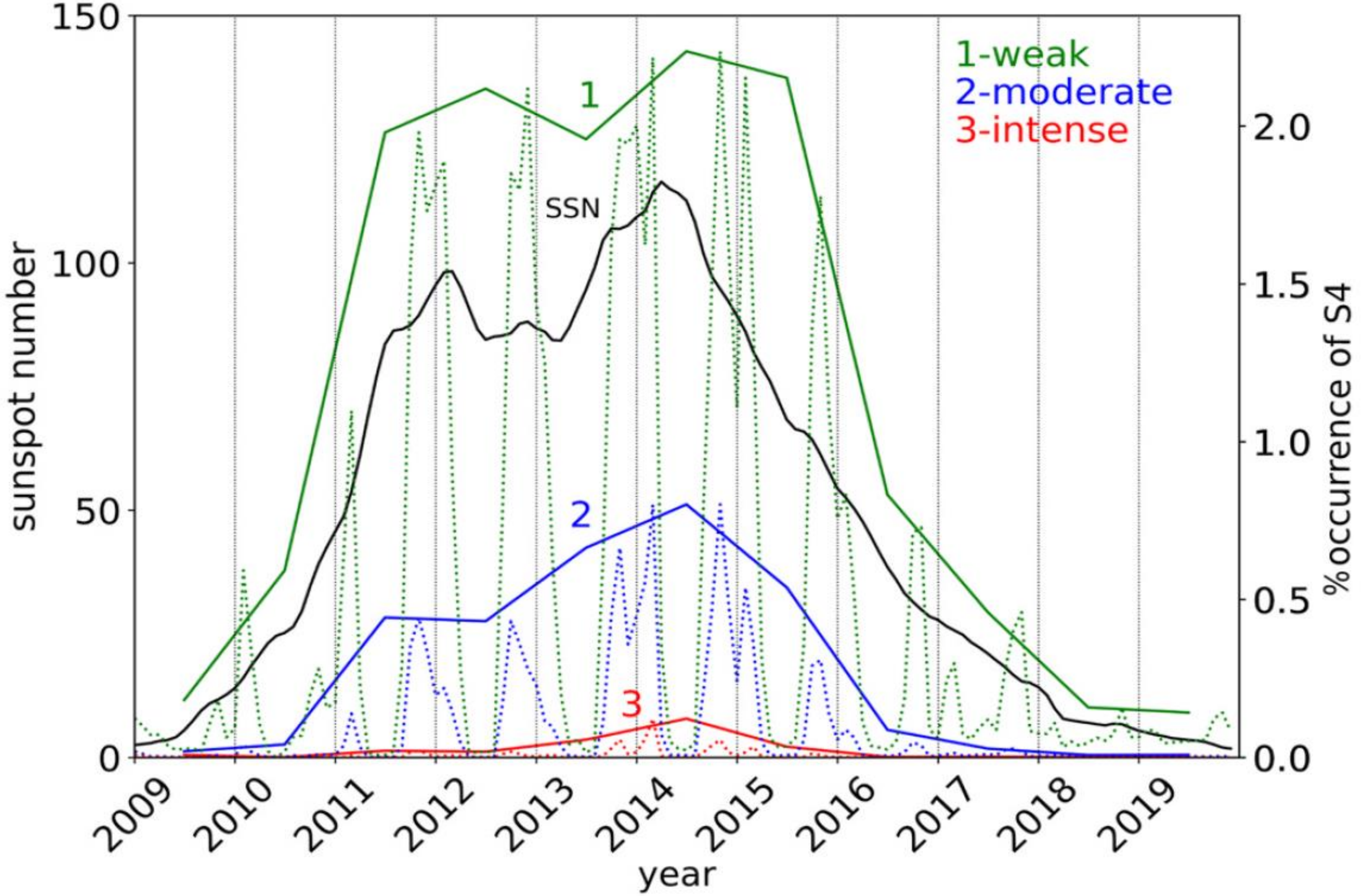
INGV

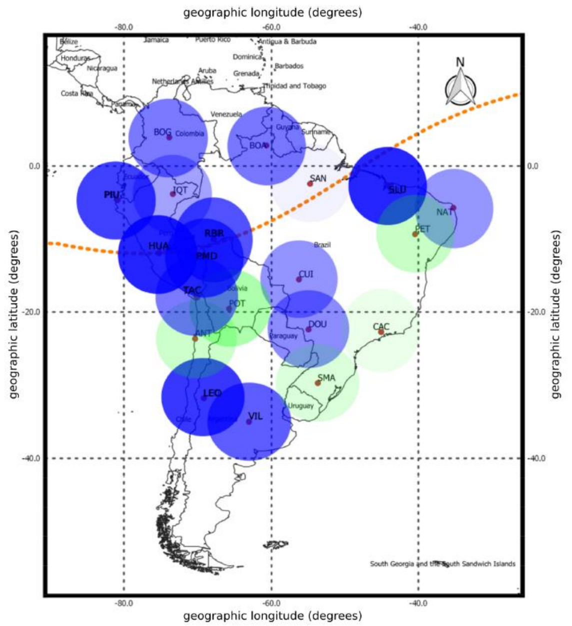
Kintner at al., 2009

Among the most known pictures of climatological modelling of scintillation

Scintillation climatology at low latitudes

Highlights from Climatology: Solar Cycle dependence of EPB-related scintillation

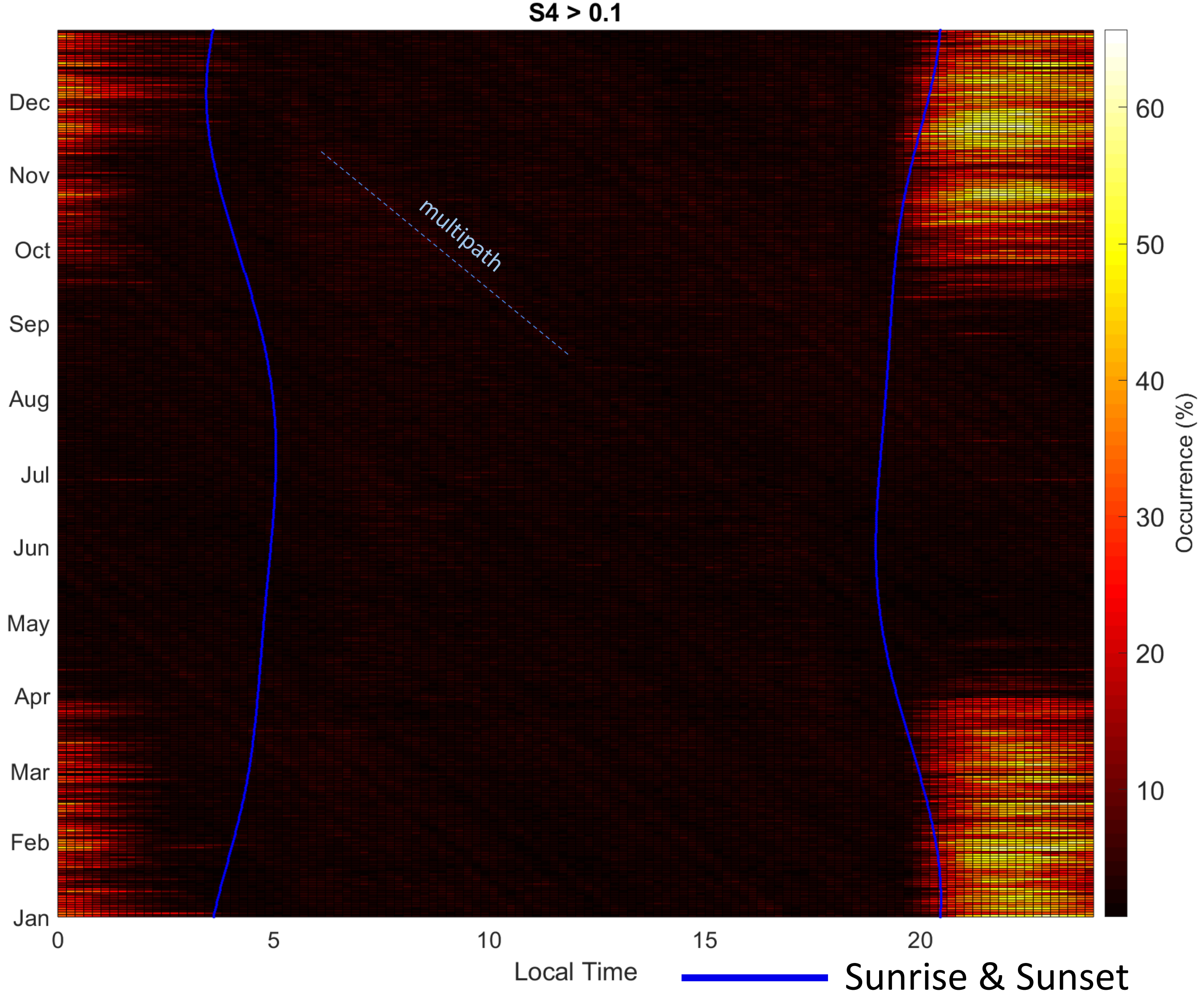




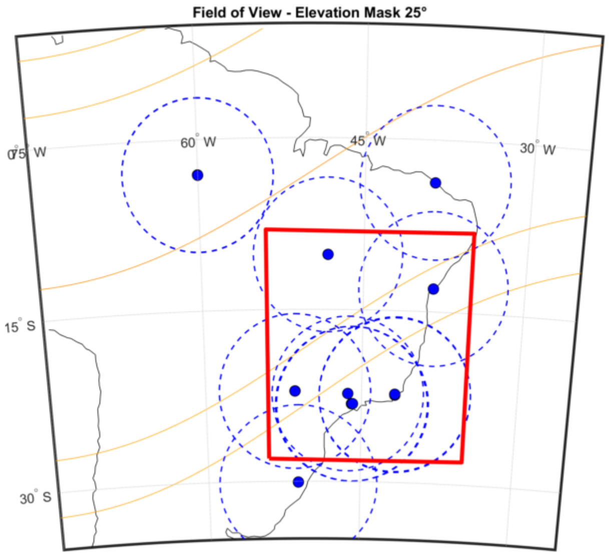
Data available at http://lisn.igp.gob.pe/

Macho, E. P., Correia, E., Spogli, L., & Muella, M. T. D. A. H. (2022). Climatology of ionospheric amplitude scintillation on GNSS signals at south American sector during solar cycle 24. *JASTP*.

Highlights from Climatology: LT and season



Ground-based GNSS for scintillation
CIGALA/CALIBRA network



PolaRxS

Period: 2013-2015

Occurrence above **weak to strong** threshold

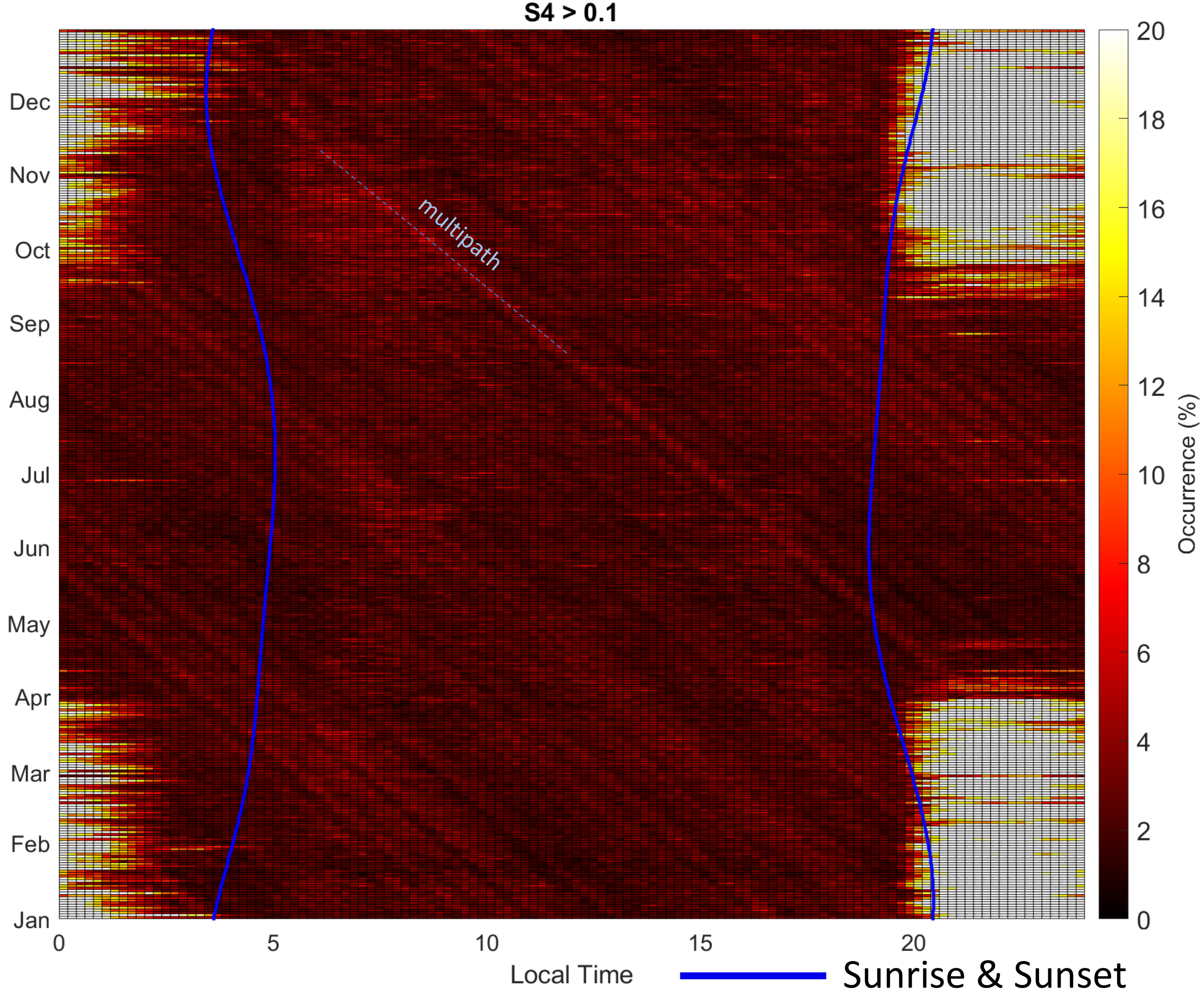
Post-sunset scintillation maximizes between sunset and sunrise

Occurrence maximizes between September and April

Residual multipath effects (streaks in the occurrence) → elevation cutoff at 25° in not suitable

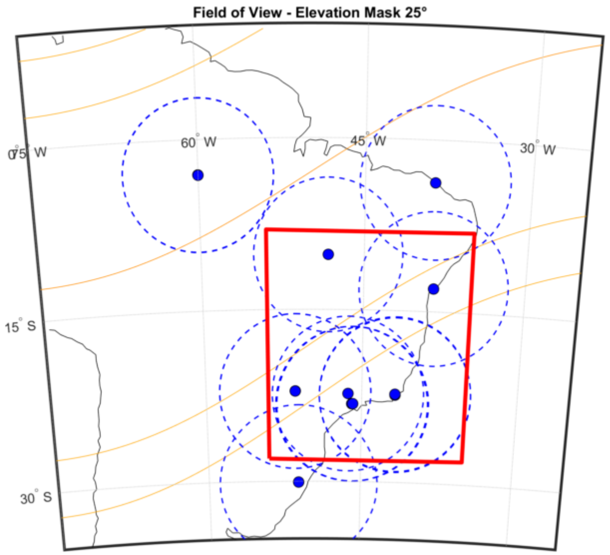
Data available at http://is-cigala-calibra.fct.unesp.br

Highlights from Climatology: LT and season



Ground-based GNSS for scintillation

CIGALA/CALIBRA network



PolaRxS

Period: 2013-2015

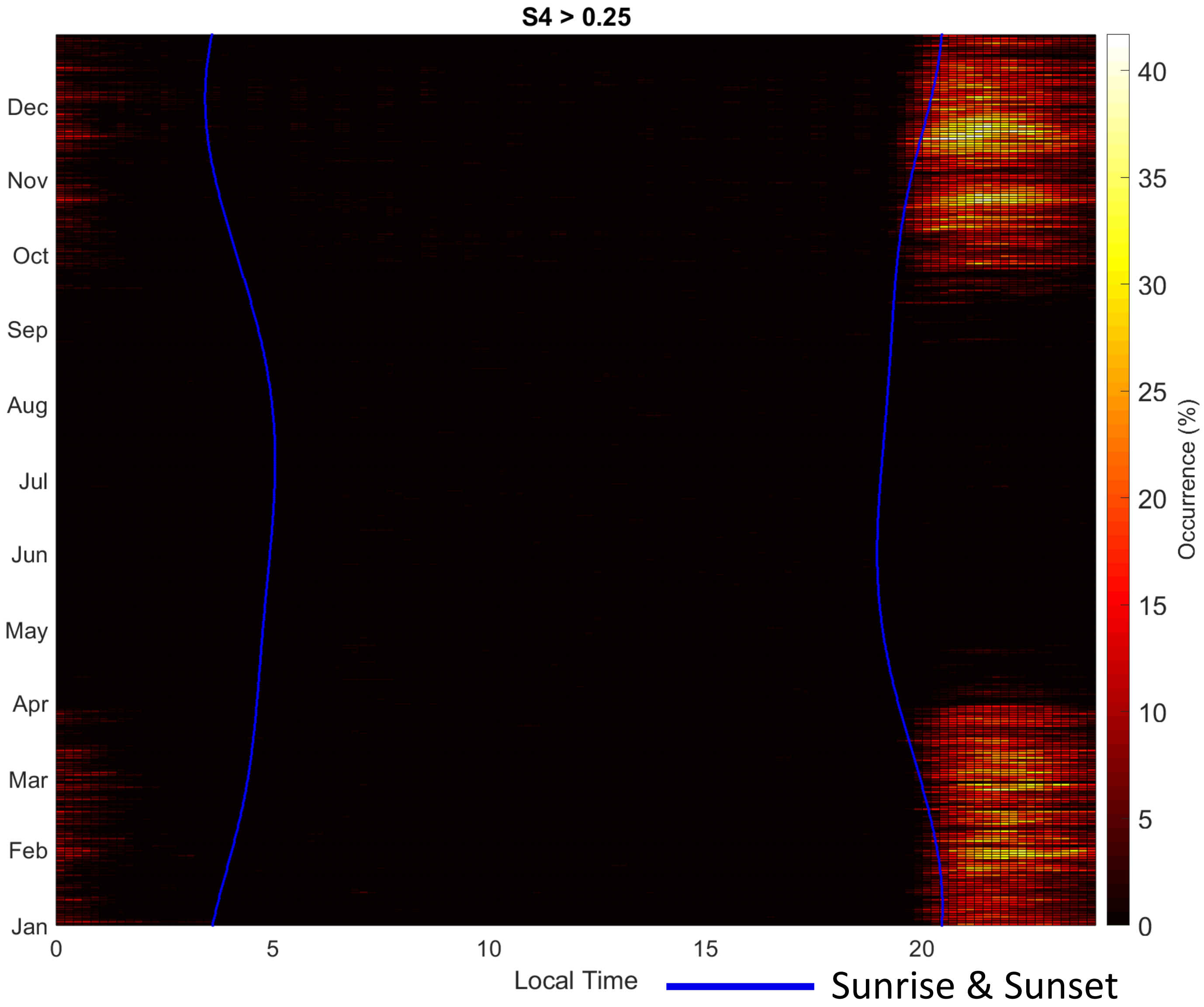
Occurrence above **weak to strong** threshold

Post-sunset scintillation maximizes between sunset and sunrise

Occurrence maximizes between September and April

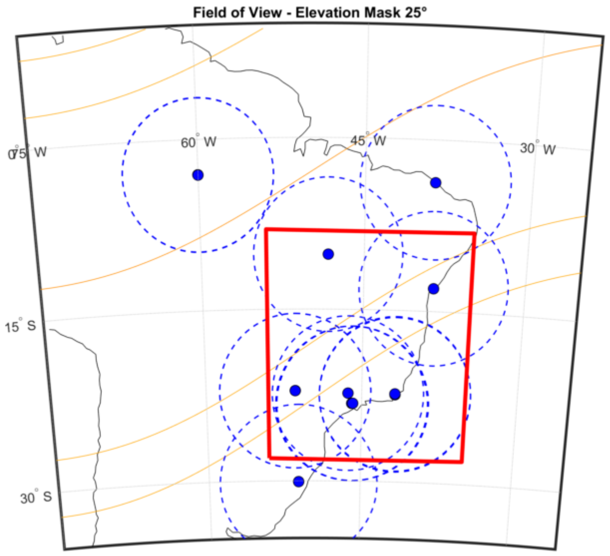
Residual multipath effects (streaks in the occurrence) → elevation cutoff at 25° in not suitable

Highlights from Climatology: LT and season



Ground-based GNSS for scintillation

CIGALA/CALIBRA network



PolaRxS

Period: 2013-2015

Occurrence above **moderate to strong** threshold

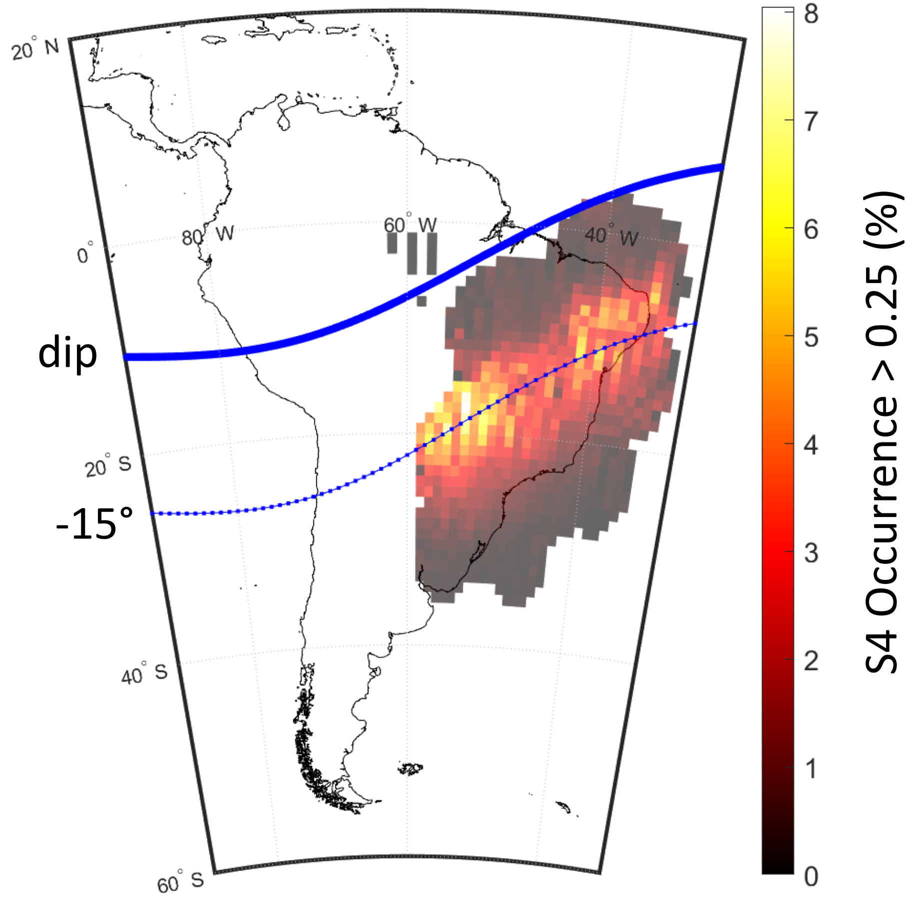
Post-sunset scintillation maximizes between sunset and sunrise

Occurrence maximizes between September and April

No multipath (30° elevation cutoff is suitable to identify moderate to strong scintillation regimes)

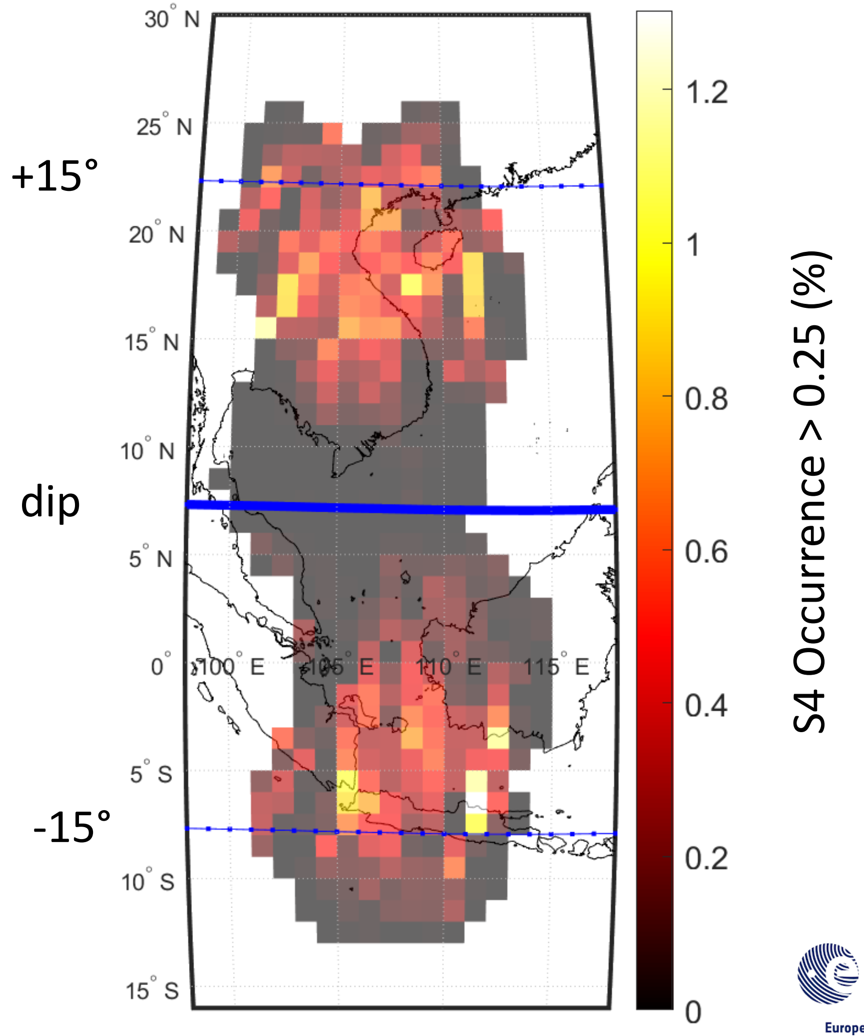
Highlights from Climatology: geographical distribution

Period: 2013-2015



CIGALA/CALIBRA network

Mar-Oct 2015

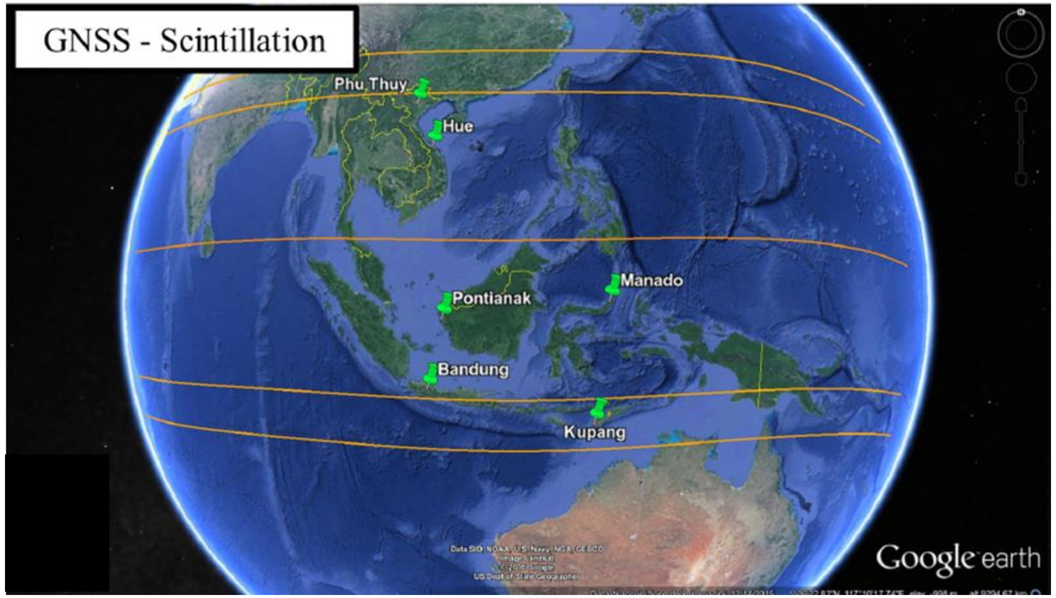


ERICA - EquatoRial Ionosphere Characterization in Asia

European Space Agency

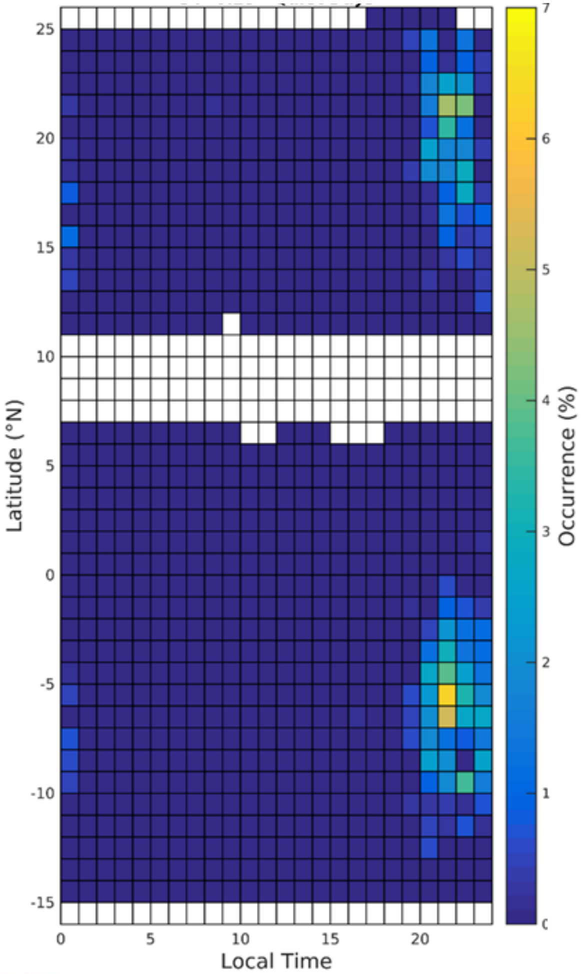
Highlights from Climatology: Scintillation inhibition/enhancement

GPS L1 - Novatel GSV4004B – Station6 - Period March 2015

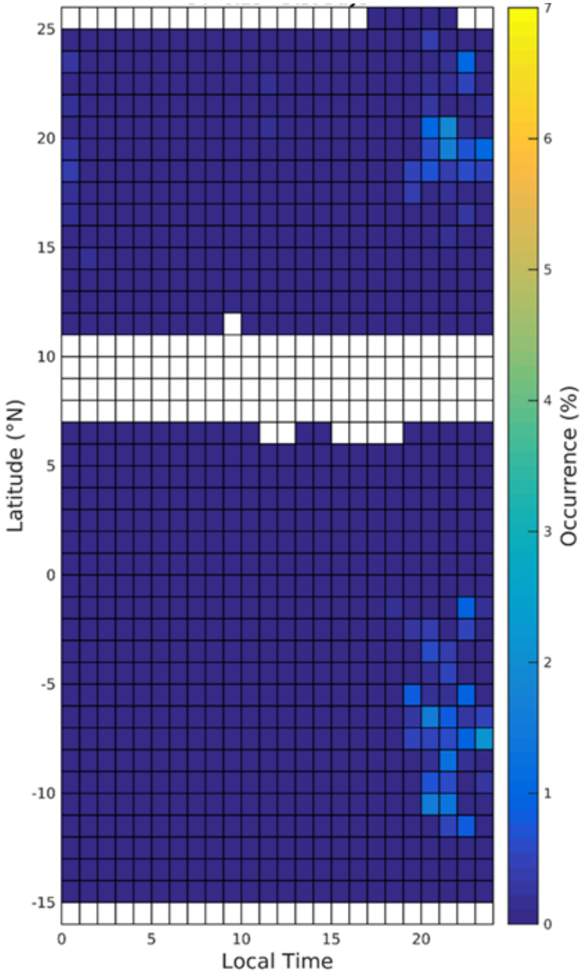


S4 occurrence > 0.1

Quiet days



Disturbed days

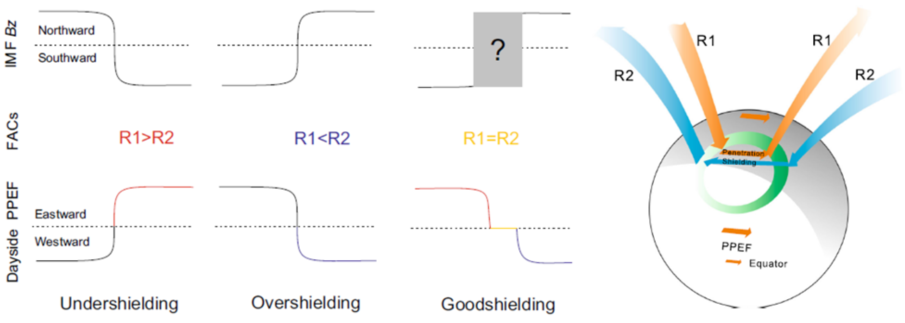


Spogli et al. (2016). *Journal of Geophysical Research: Space Physics*, *121*(12).

Highlights from Climatology: Scintillation inhibition/enhancement

In case of a geoffective Space Weather event, the low latitude electrodynamics is altered

Equatorial zonal electric field **E**, eastward in dayside and westward in nightside, is modified and the mechanisms ruling out the formation of EIA and EPB is altered.

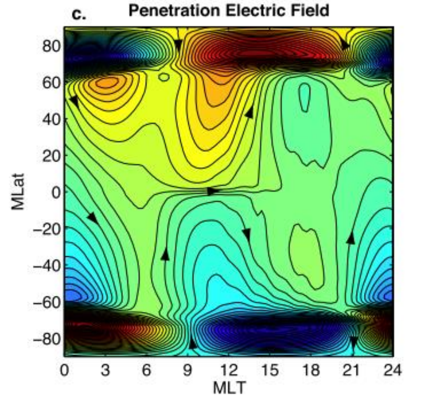


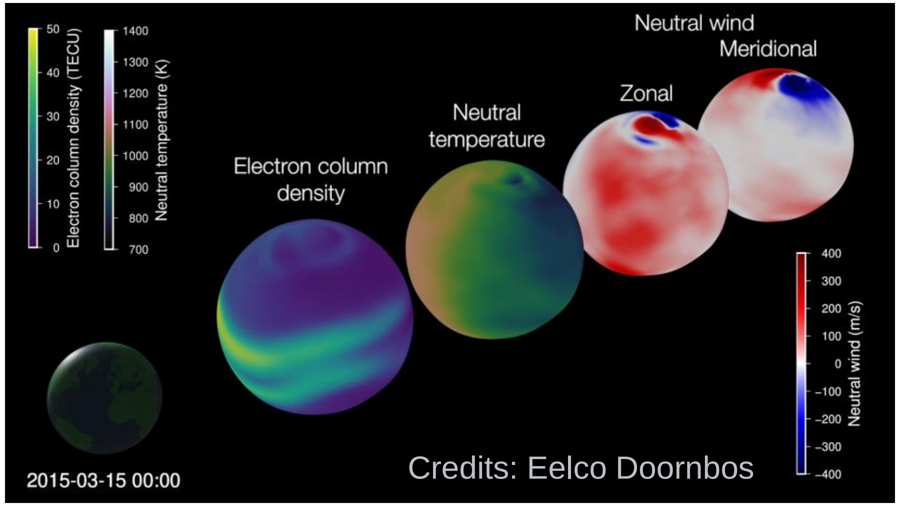
Wei et al. (2015). Science bulletin, 60(8), 748-761.

Prompt Penetration Electric Fields (PPEF)

Penetration of Electric Field from Interplanetary Electric Field. Prompt effect, perturbations in the zonal electric field for shorter durations of **about 30 min to 2 h**

Involved parameter/index: IMF-Bz, IEF-Ey

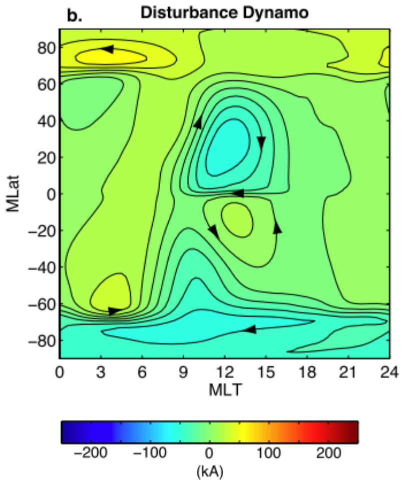




Disturbance Dynamo Electric Fields (DDEF)

Cross-equatorial winds due to thermospheric changes induced by heating at high latitude (often with LSTID). Delayed effect, non-uniform time delays at different latitudes and lasts for **few hours to more than a day**

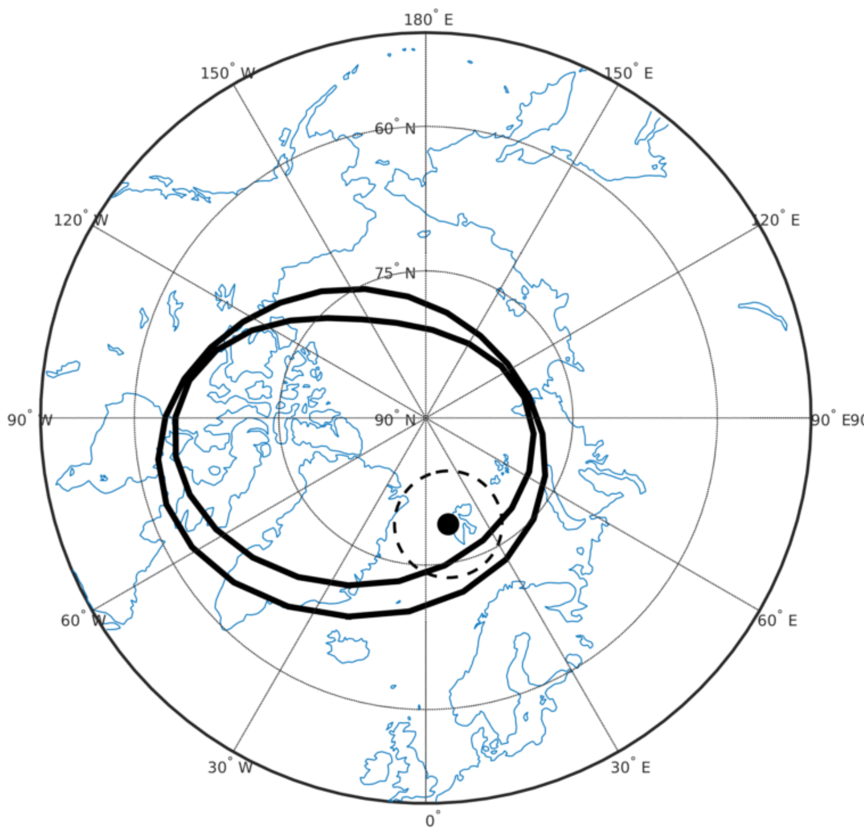
Involved parameter/index: AE, Joule heating



Scintillation climatology at high-latitude

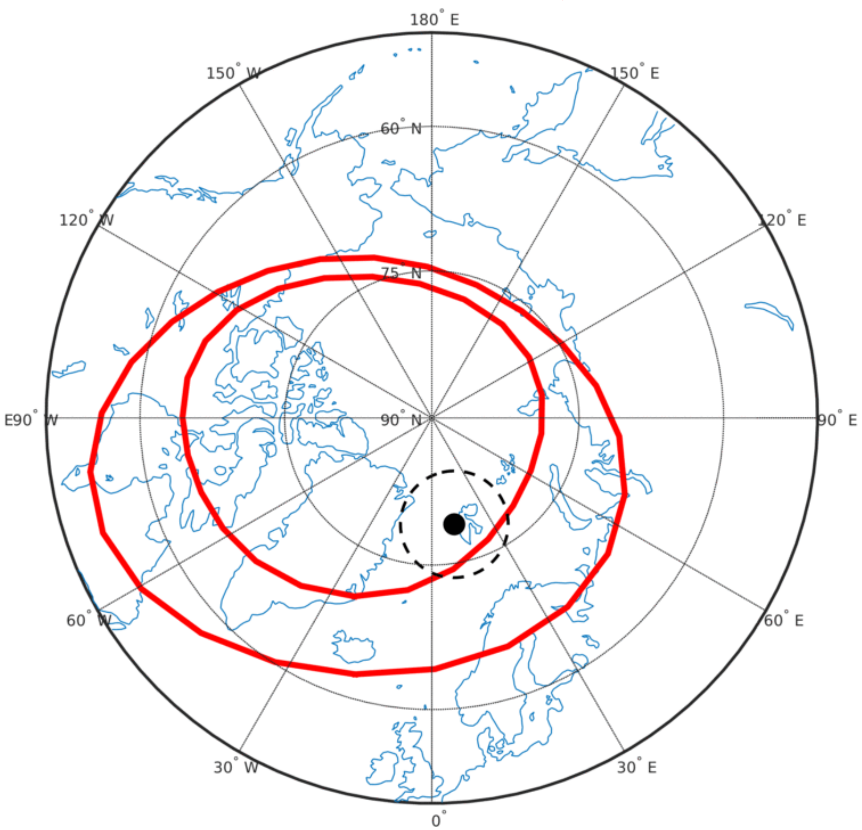
Climatology over (more than) 1 solar-cycle!

UT 00:00 - MLT 03:00



UT 00:00 - MLT 03:00

Disturbed conditions IQ = 6



September 2003

November 2015

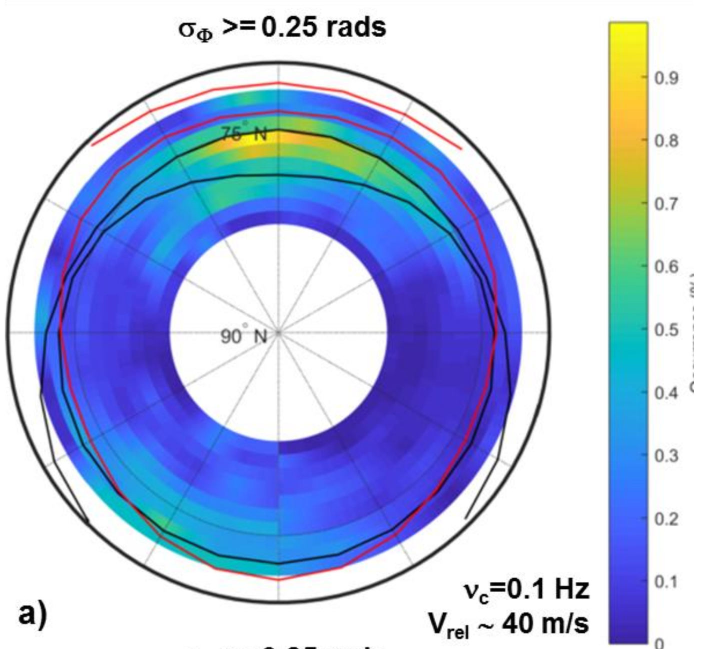
January 2020

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

De Franceschi et al., Sci.Rep, 2019

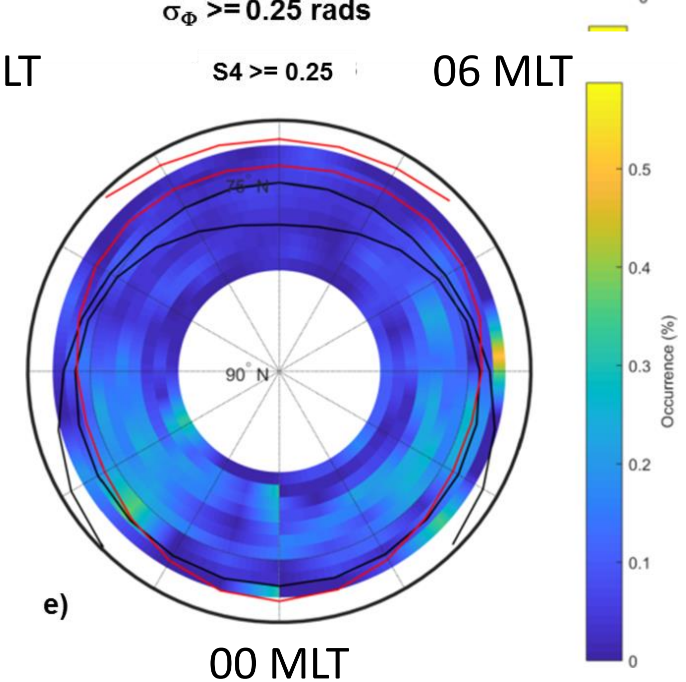
ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

12 MLT

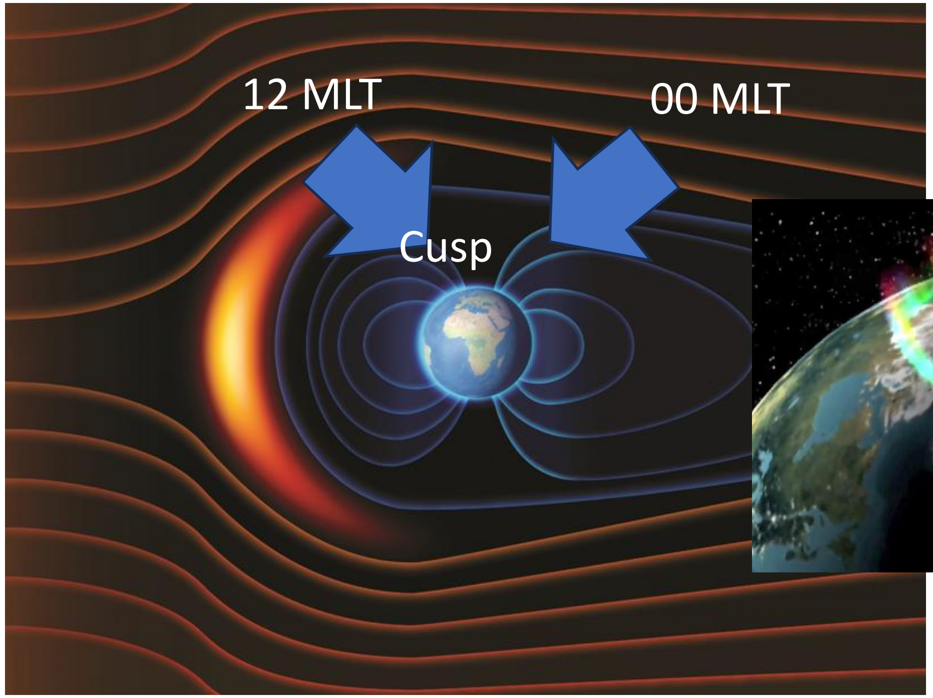


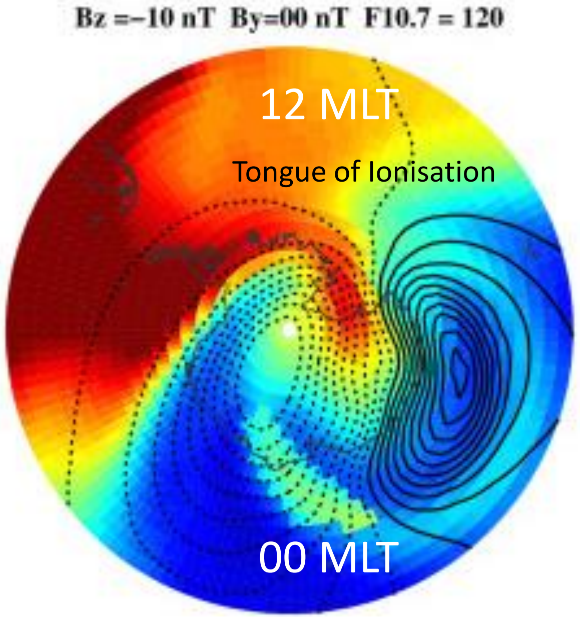
18 MLT

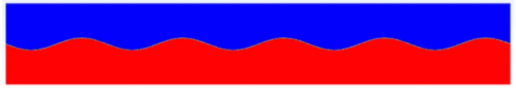
06 MLT



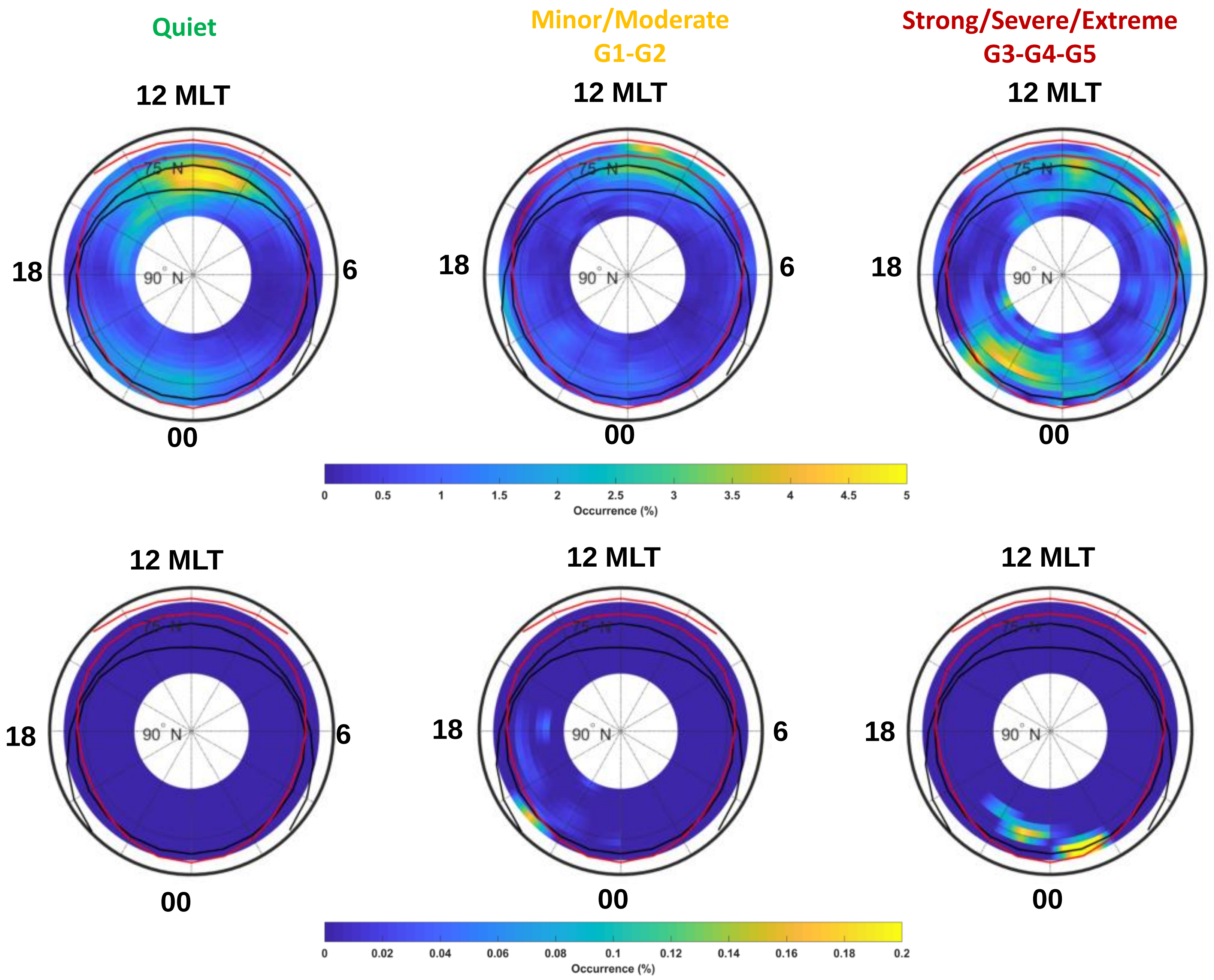
00 MLT







Kelvin-Helmotz Instability



Occurrence according to different space weather conditions.

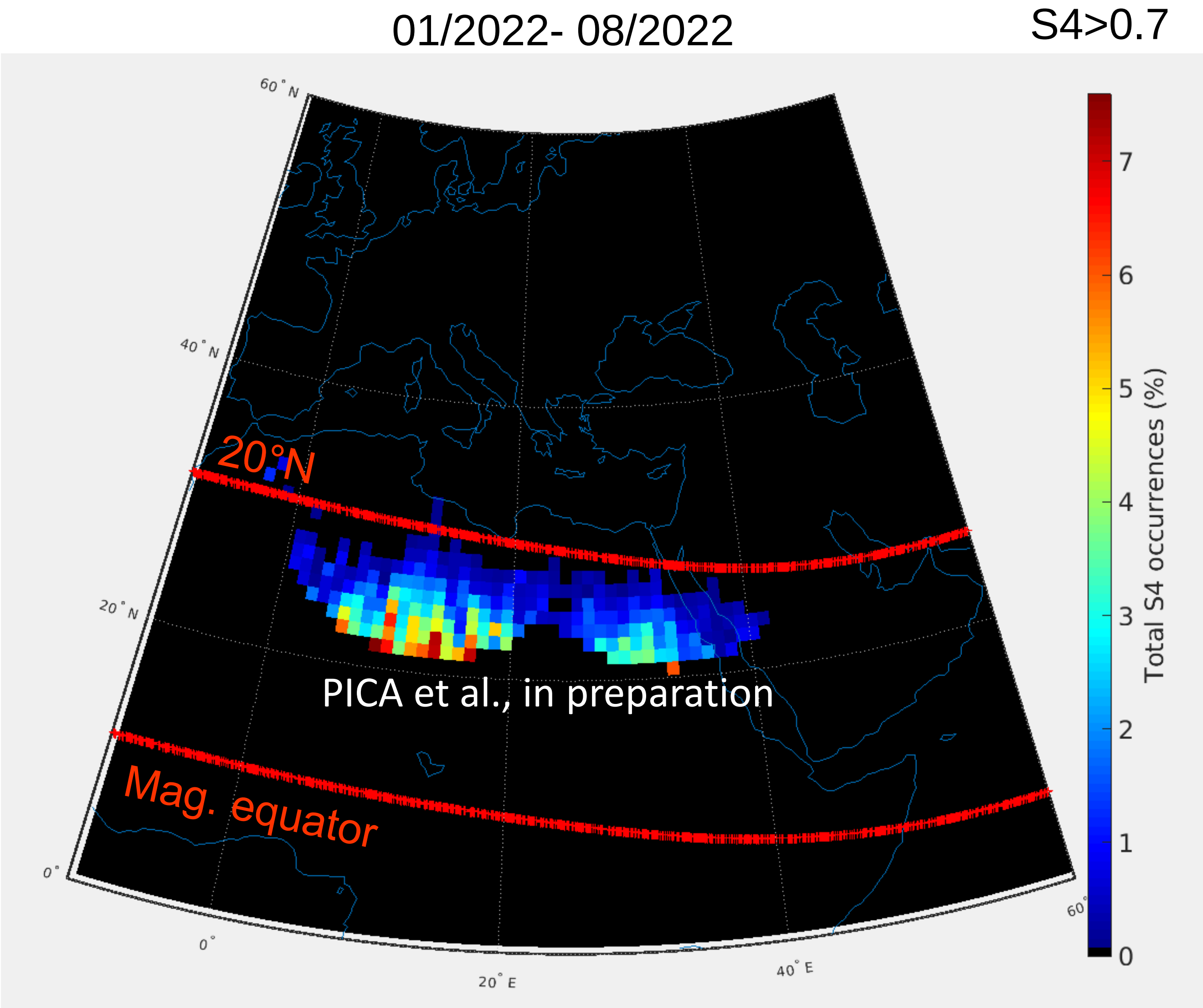
$\sigma_{\Phi} \geq 0.25$ rad

Comparing climatology of amplitude and phase scintillation occurrence to learn about irregularities scale size and dynamics

$S_4 \geq 0.25$

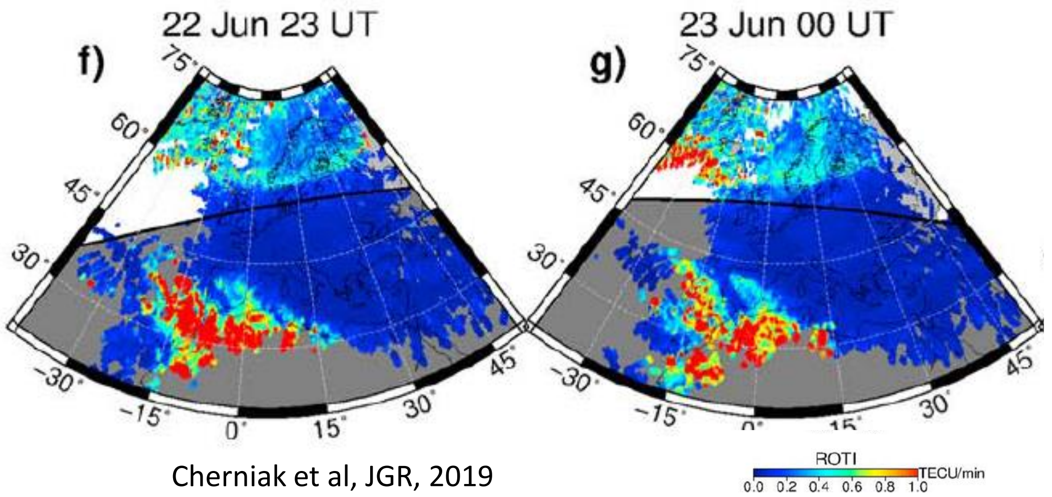
$\nu_{cut\text{-}off}$ **= 0.1 Hz**

What about mid-latitudes?



ISMR in Lampedusa and Nicosia climatologically see EPBs

PPEF and DDEF can cause the spill-over of very intense equatorial plasma bubbles



Cherniak et al, JGR, 2019

Takehome messages

- Irregularities in the ionosphere cause (on GNSS signals)
  (i) phase fluctuations and
  (ii) phase/amplitude scintillation
- These cause tracking (phase fluctuation) and positioning (scintillation) issues
- S4 and σ_Φ are routinely provided on a 1-minute basis by Ionospheric Scintillation Monitor Receivers
- They must be used wisely
- High- and low-latitude ionosphere are featured by scintillation and phase fluctuations
  - High-lat: forcing from geospace. Auroral oval, polar cap patches, auroral blobs,
  - Low-lat: EPB are quasi-regular phenomenon, modulate by geospace forcing and neutral dynamics
  - Mid-lat: spill-over from high- and low-latitudes – SED (not show)
- Climatological modelling reveals the overall features of GNSS scintillation

Thanks for your attention!

ISTITUTO NAZIONALE
DI GEOFISICA E VULCANOLOGIA

luca.spogli@ingv.it

Acknowledgments: Giorgiana De Franceschi, Lucilla Alfonsi, Vincenzo Romano, Claudio Cesaroni, Carlo Marcocci, Emanuele Pica

Ionospheric irregularities & scintillations