The role of the ionosphere in the space weather

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INGV

Thanks to Luca Spogli (INGV) and Jayachandran (UNB)

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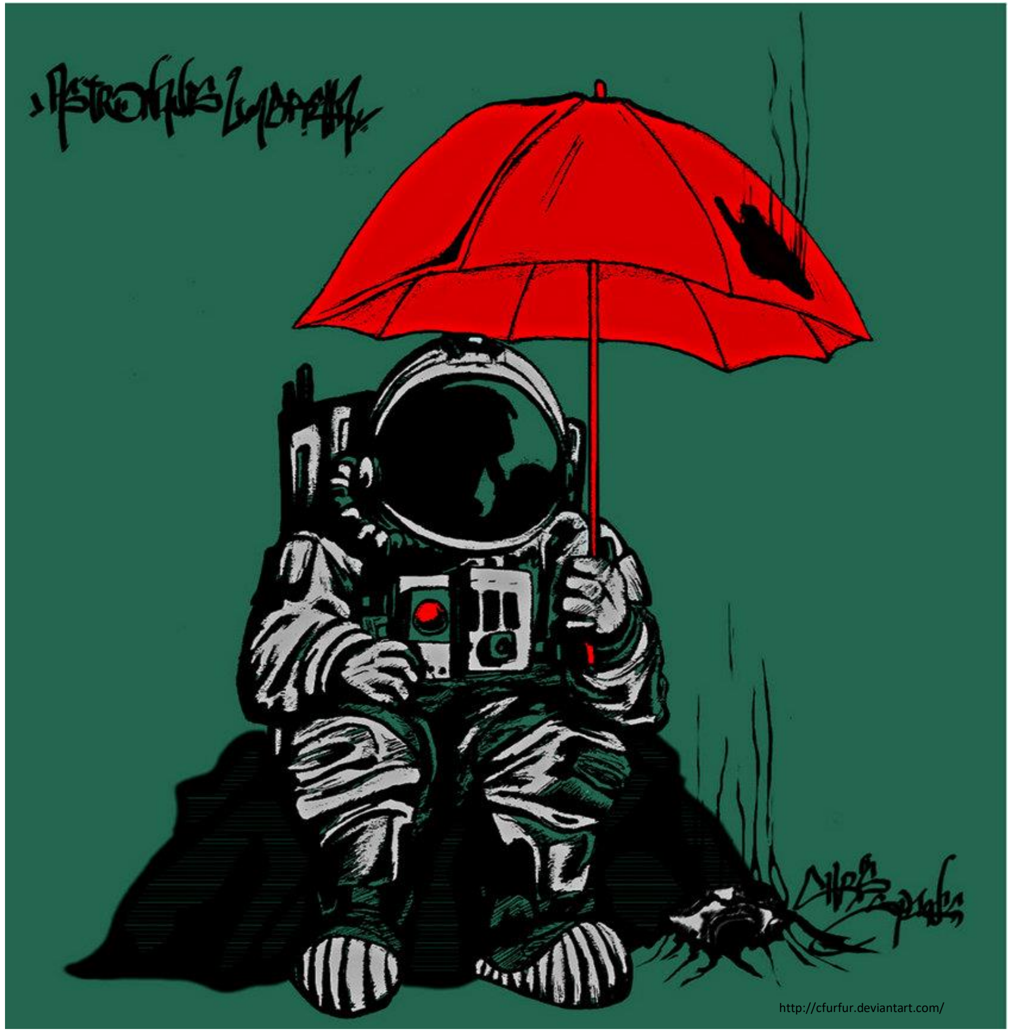
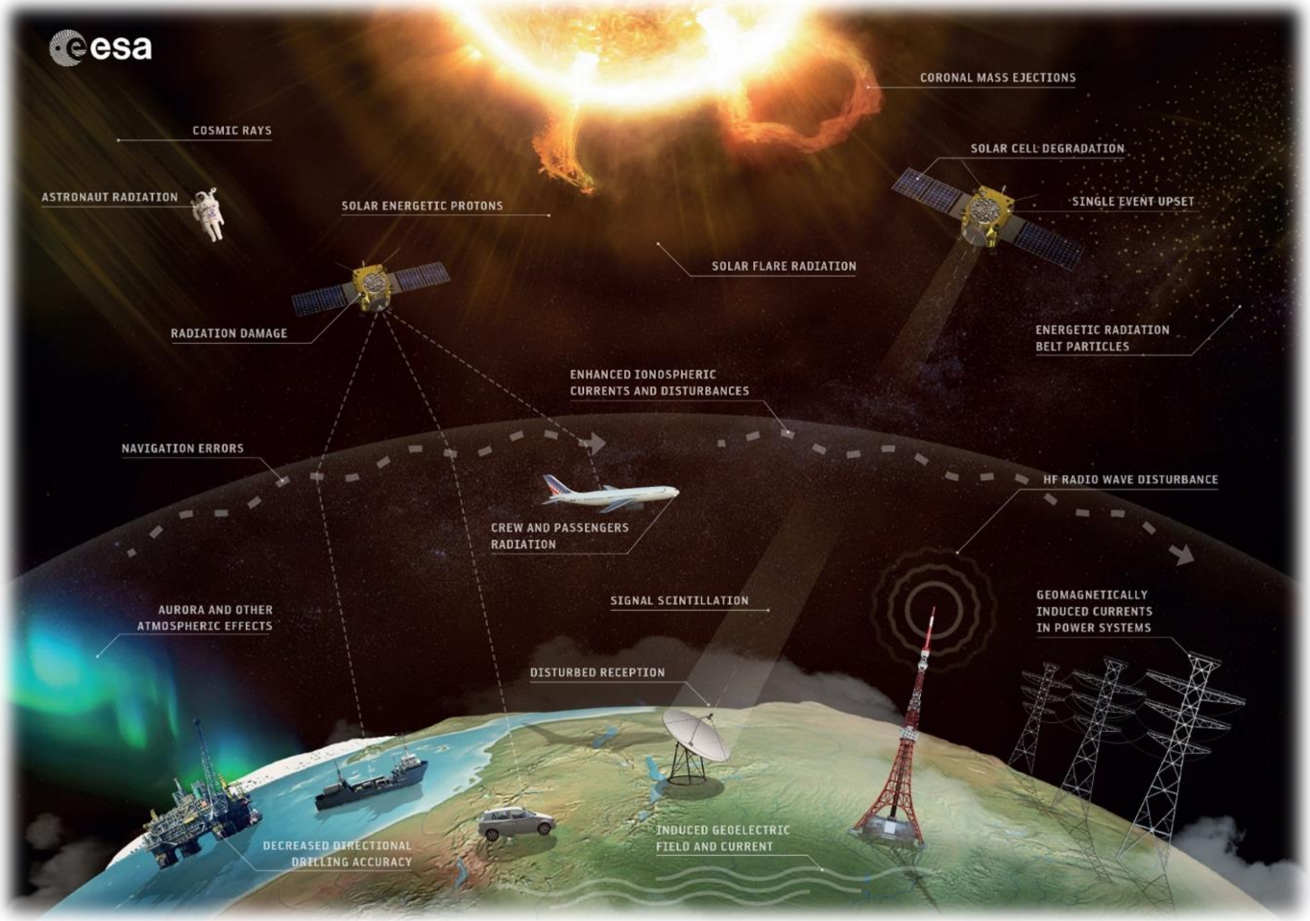
INTERNATIONAL SPACE WEATHER INITIATIVE ISWI

Space Weather

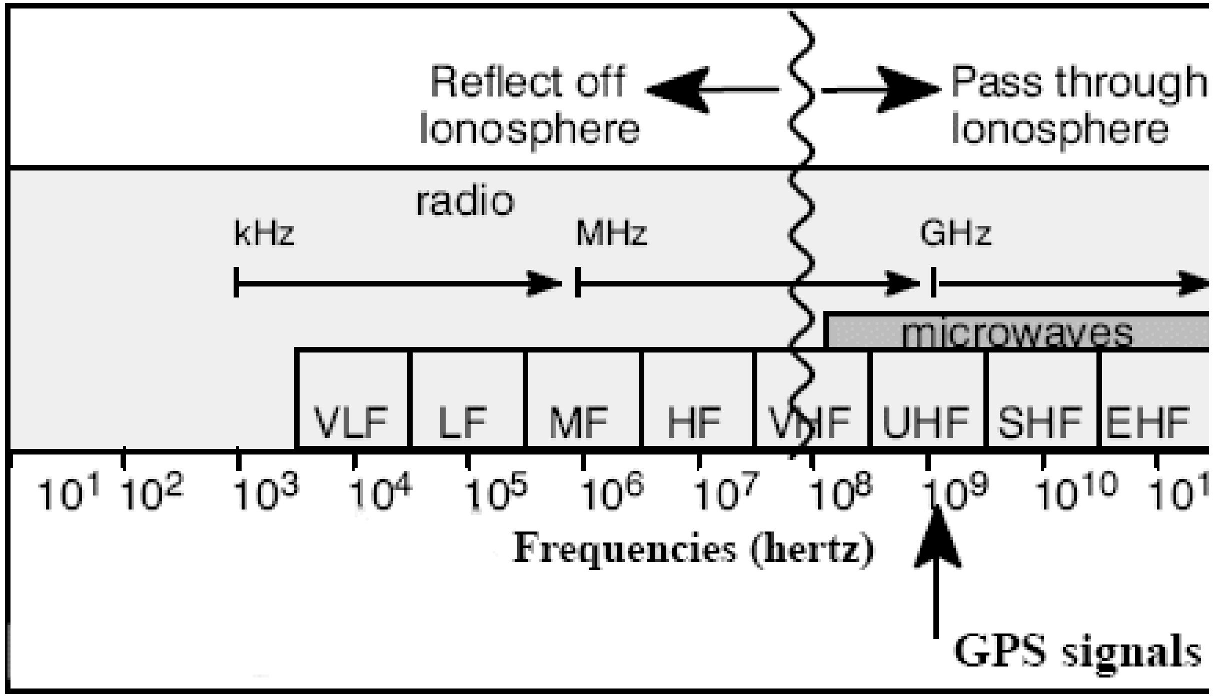
Space weather refers to the environmental conditions in Earth's <u>magnetosphere</u>, <u>ionosphere</u> and <u>thermosphere</u> due to the <u>Sun</u> and the <u>solar wind</u> that can influence the functioning and reliability of spaceborne and ground-based <u>systems</u> and <u>services</u> or endanger property or human <u>health</u>.
[European Space Agency]

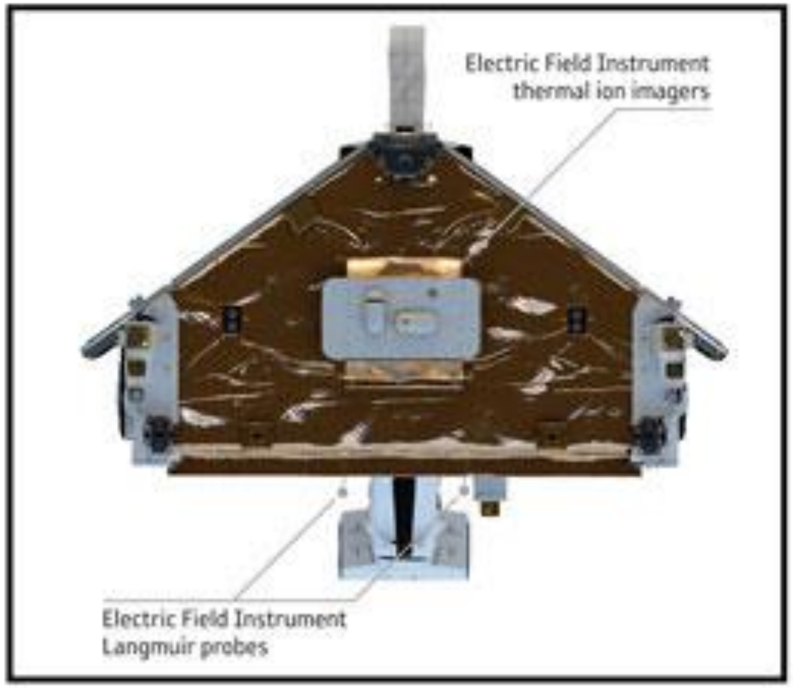




The ionospheric electron density and the height can be derived from radio probing (ground and space-based) exploiting the ionosphere property of influencing the radio wave propagation (from working frequancies spanning from kHz to GHz range).

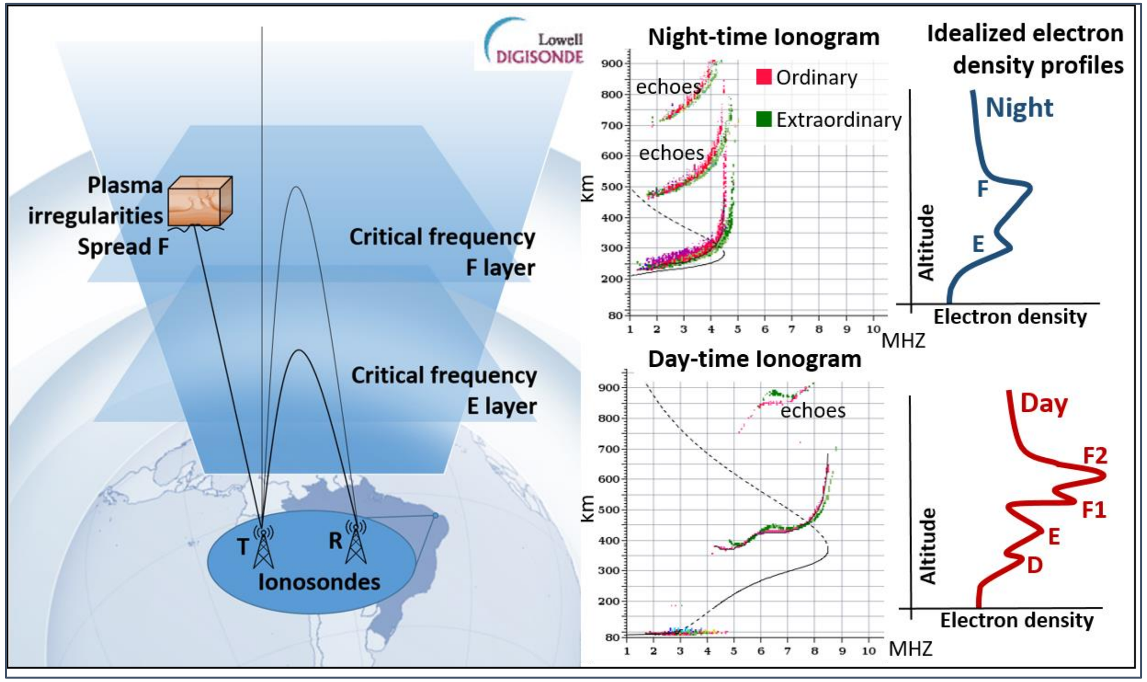
In-situ satellite measurements exploit the plasma property of the ionosphere deriving its electron density, electron temperature, ion drift and velocity.

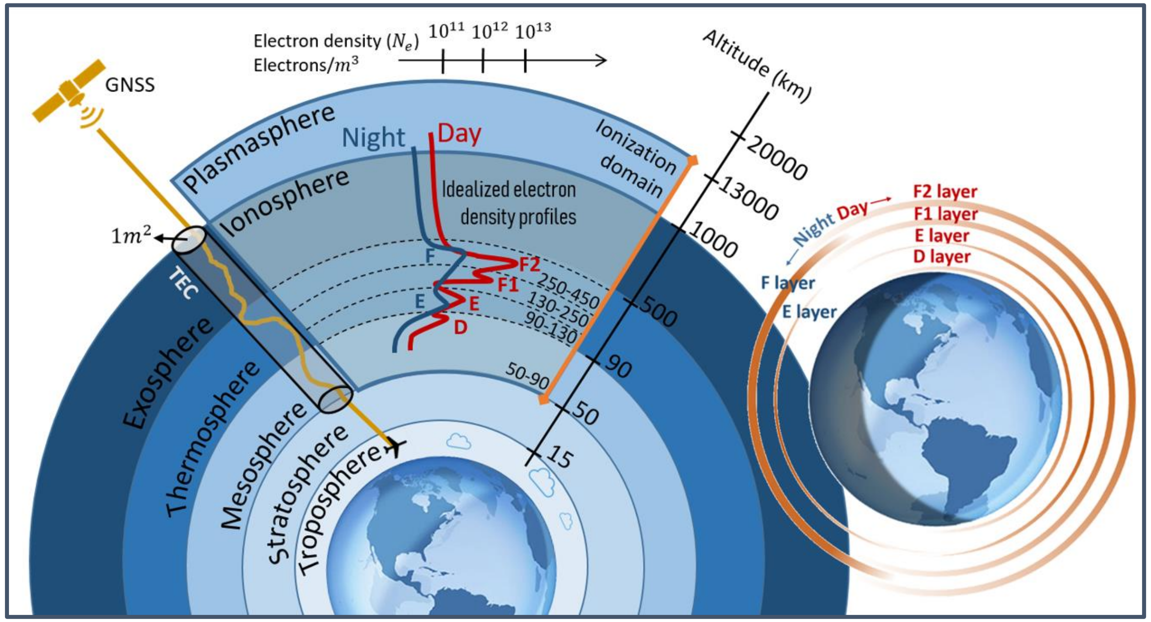


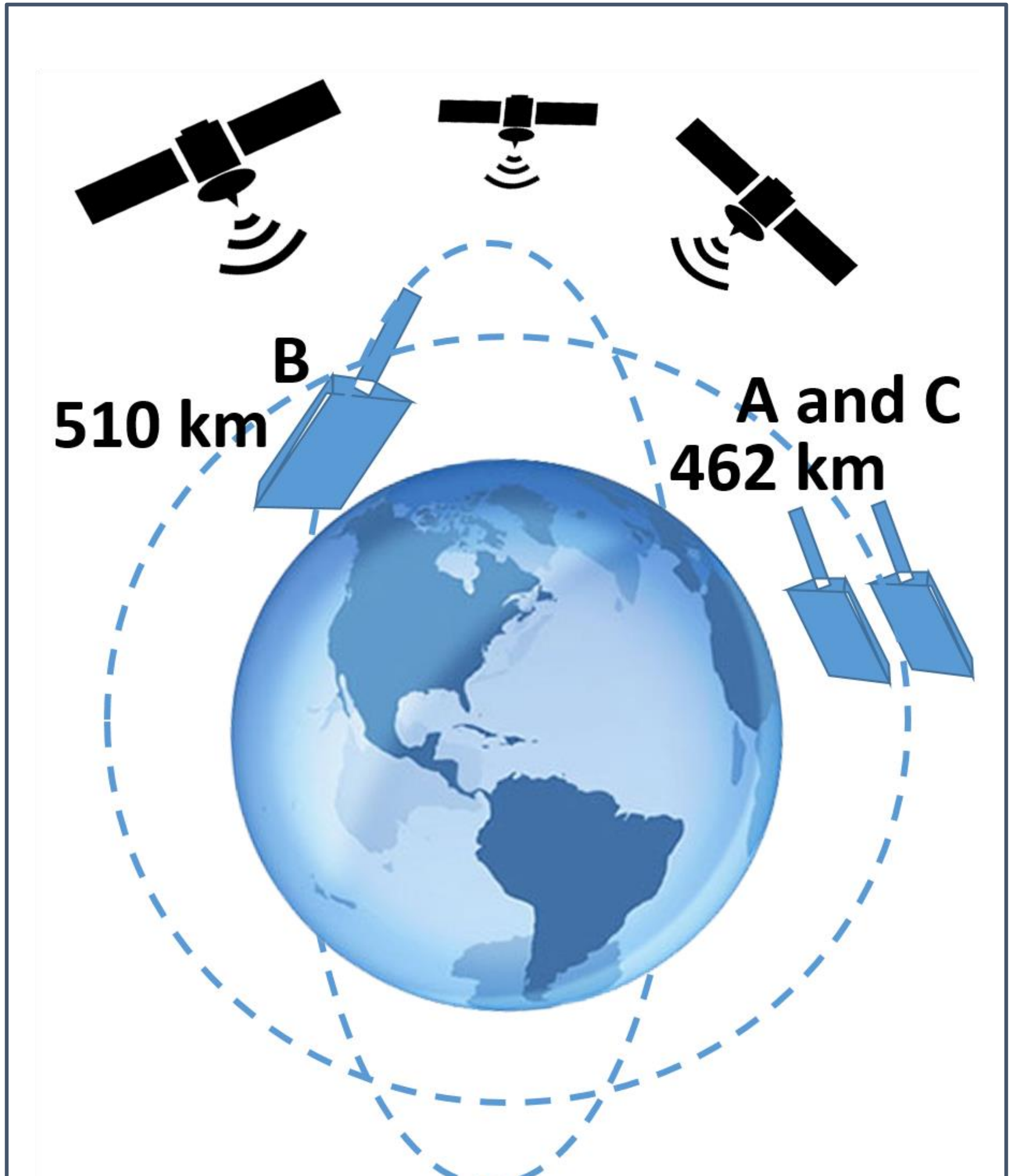


Credits: ESA Swarm

The combination of different kind of measurements is very informative to study the plasma irregularities, but…

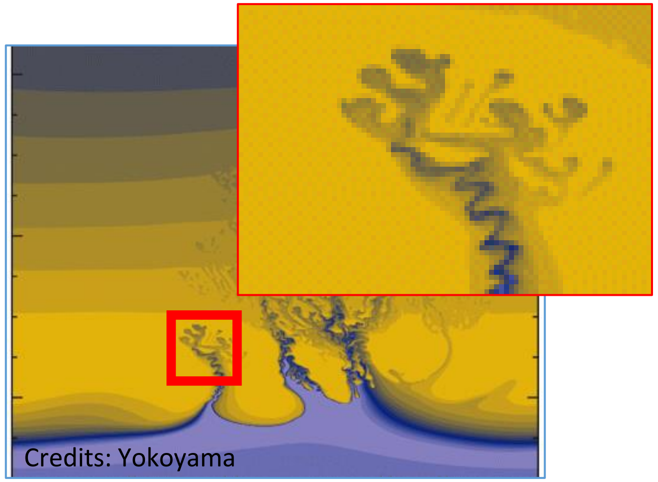


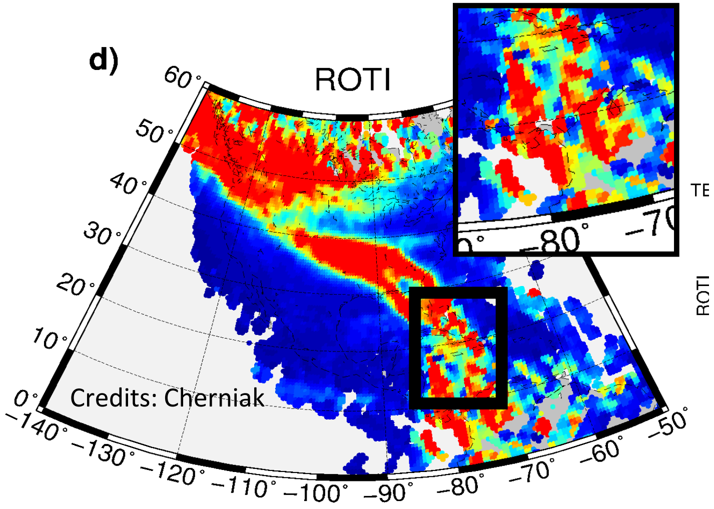


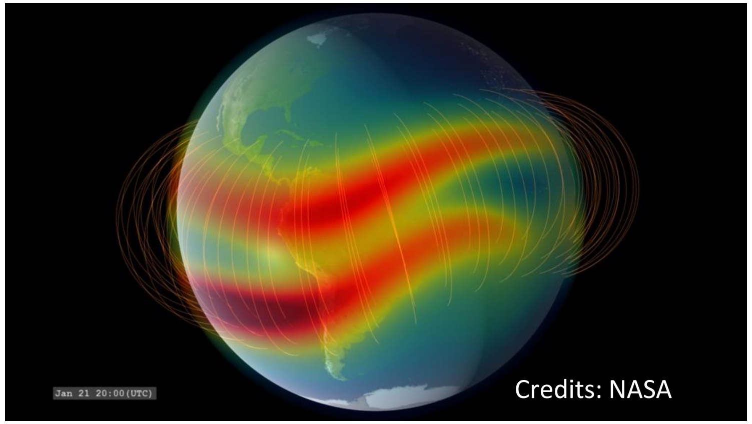


Courtesy J. Damaceno

Irregularities* in a nutshell







100 m | 1 km | 10 km | 100 km | 1000 km

Small scale
(Fresnel's scale)

Medium scale

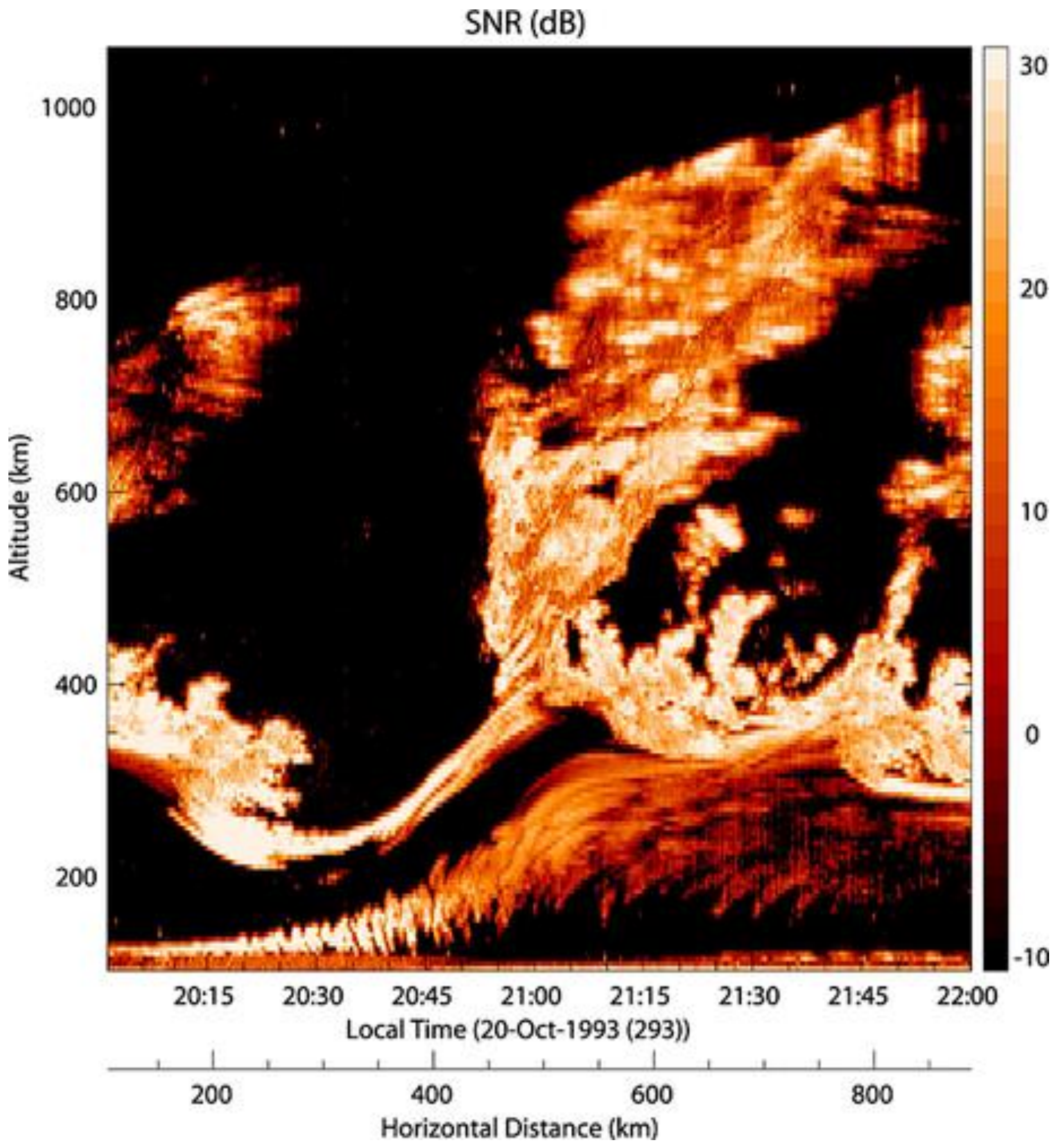
Large scale

*from a GNSS perspective

The combination of different kind of measurements is very informative to study the plasma irregularities, but…

- Different observation geometry
- Different sampling
- Different working frequency
- Different spatial coverage
- Different temporal coverage
- Differente metrics and standard

…

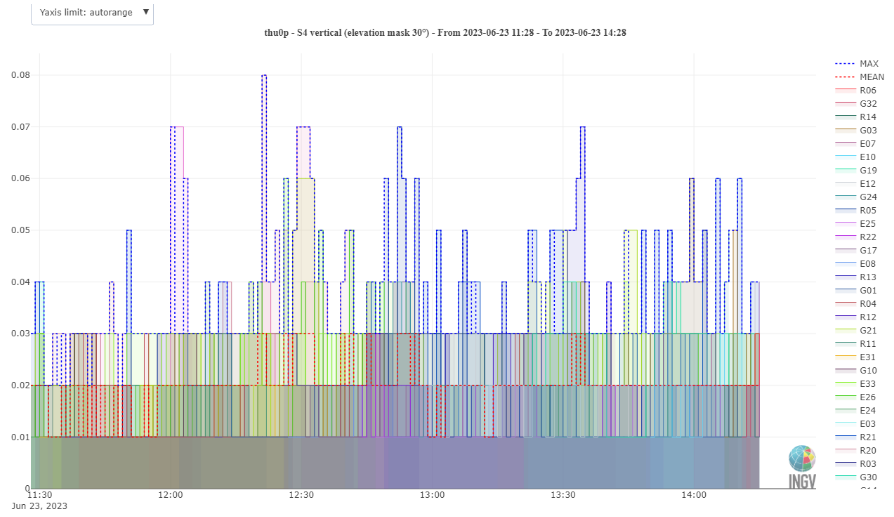


reproduced from Woodman and Chau, 2001

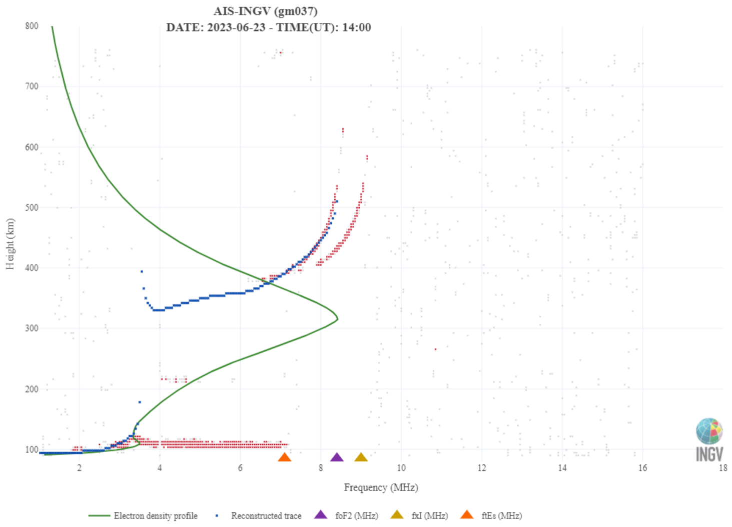
METRICS and STANDARD

a common language still missing in the ionospheric community **but crucial for space weather**

Instrument	Data metrics	Data standard
Ionosondes and Digisondes	✔	✔
Inchoerent Scatter radars	✔	✔
HF-backscattering radars	✔	✔
Ground-based GNSS receivers	X	✔
Space-based GNSS receivers	X	✔
In situ LP/TI	X	✔



AUTOSCALA PARAMETERS	
foF2 (MHz)	8.4
foF1 (MHz)	
fxI (MHz)	9
ftEs (MHz)	7.1
MUF3000F2 (MHz)	23.5
M(3000)f2	2.8
h'Es (km)	99
AIP PARAMETERS	
hmF2 (km)	314
fof2 (MHz)	8.4
fof1 (MHz)	0
hmF1 (km)	
D1	0
foE (MHz)	3.5
hmE (km)	110
ymE (km)	20
h_ve (km)	119
Ewidth (km)	36
DelN_ve (m^-3)	0.1
B0 (km)	114
B1	1.2
TEC bottom (TECu)	7.831
TEC top (TECu)	11.15



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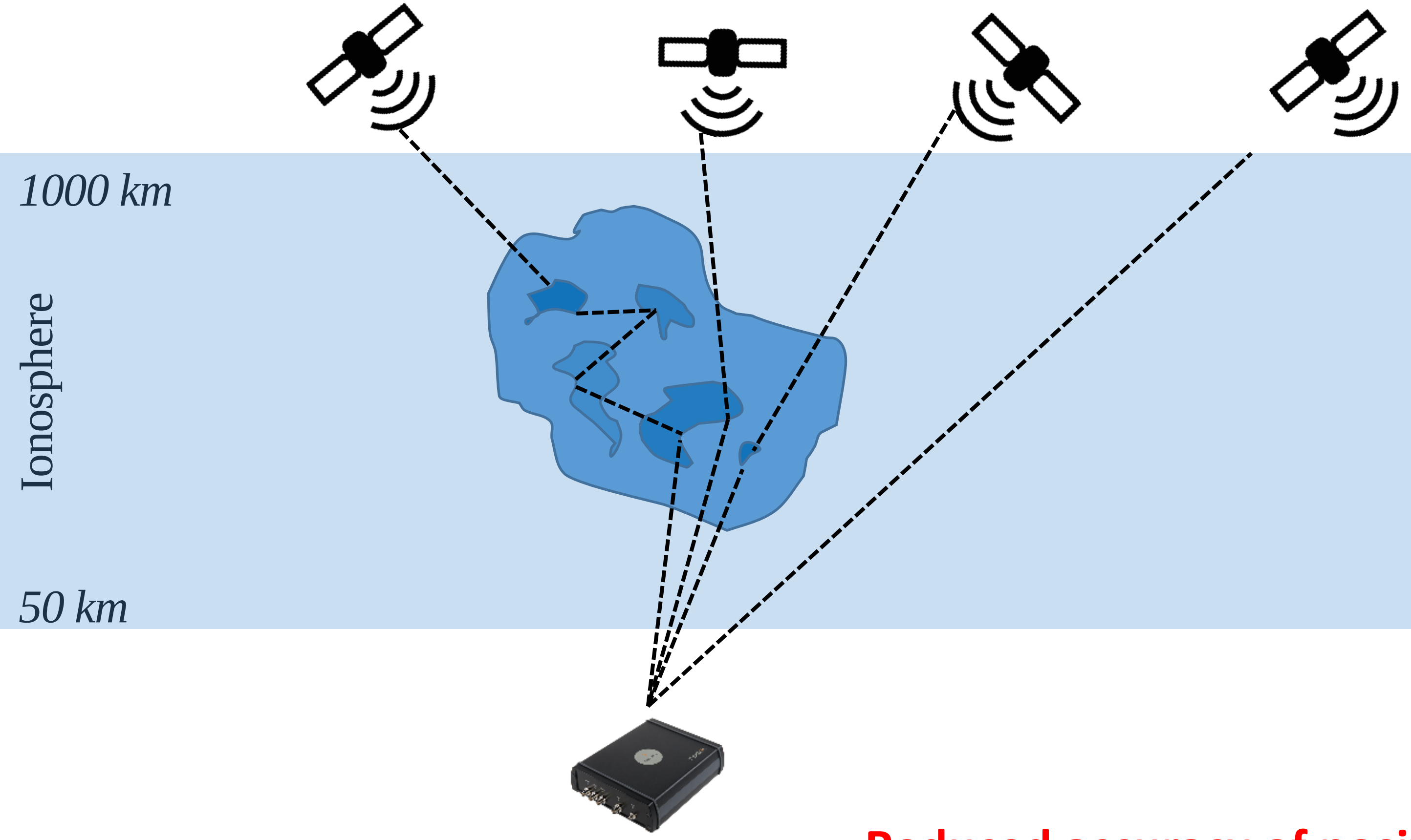
A simplified picture



Reduced accuracy of positioning

Loss of lock

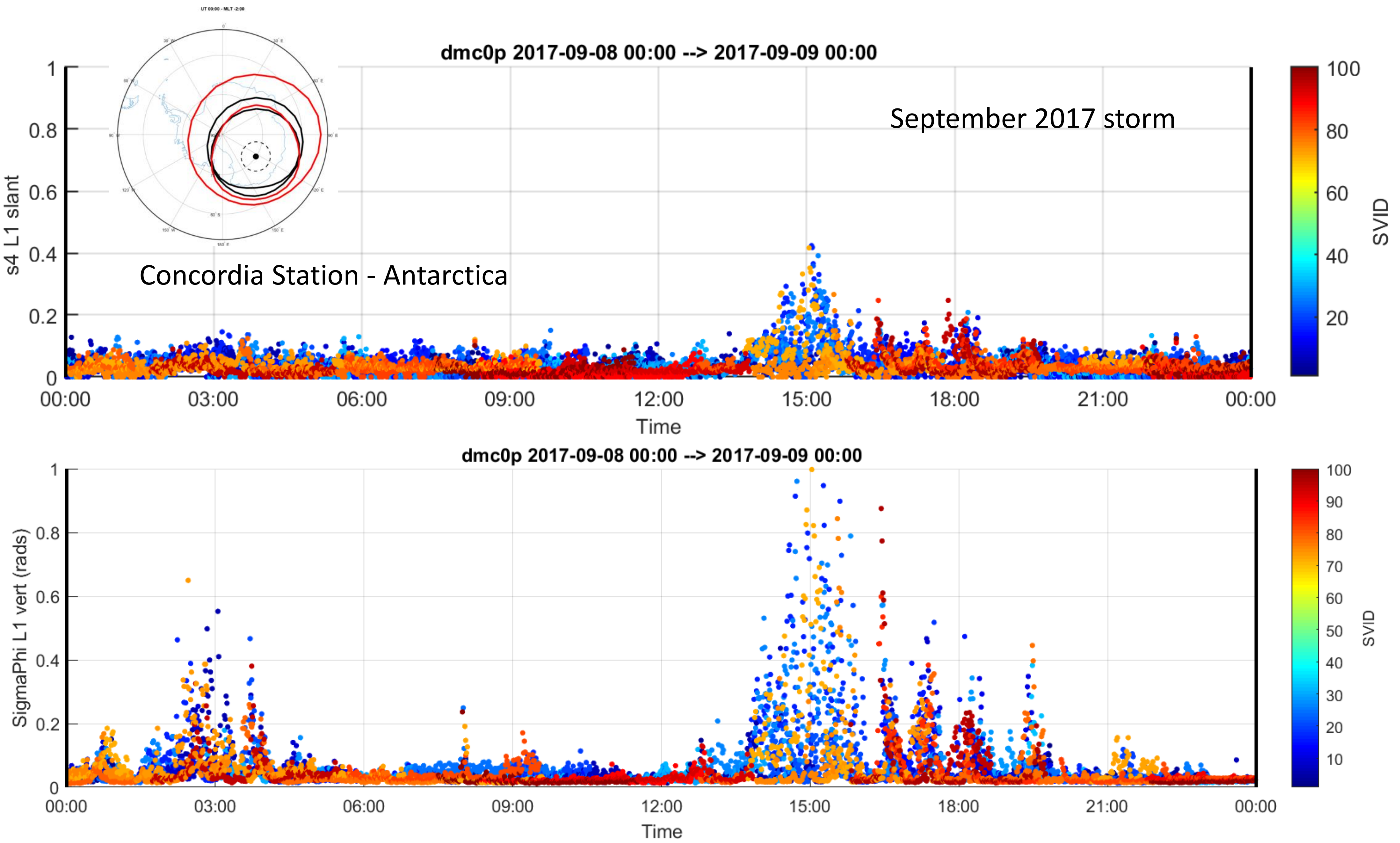
Scintillation indices

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

Ampl.

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

Phase

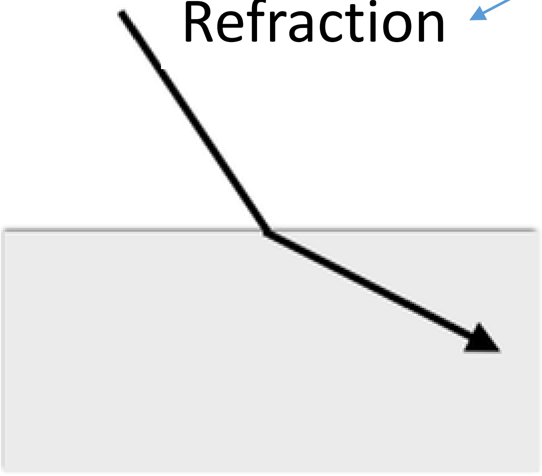


September 2017 storm
Concordia Station - Antarctica
UT 00:00 - MLT -2:00
dmc0p 2017-09-08 00:00 --> 2017-09-09 00:00
s4 L1 slant
SVID
Time
00:00
03:00
06:00
09:00
12:00
15:00
18:00
21:00
00:00
dmc0p 2017-09-08 00:00 --> 2017-09-09 00:00
SigmaPhi L1 vert (rads)
SVID
Time

What causes phase and amplitude fluctuations in the GNSS signals?

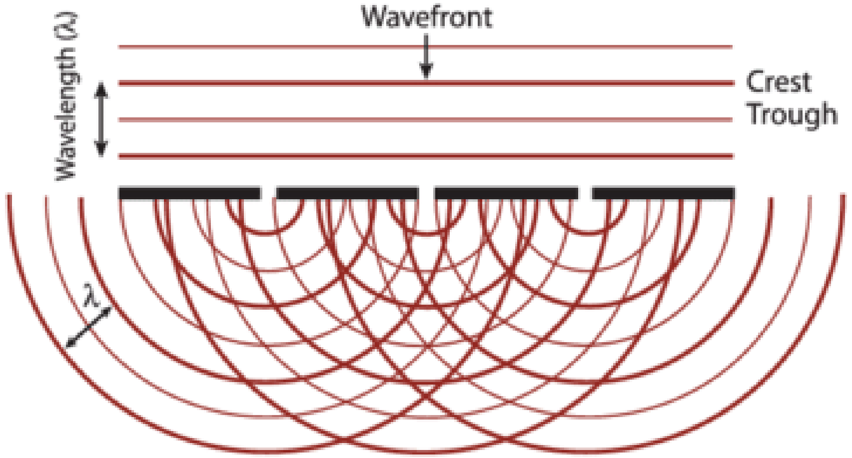
Ionospheric irregularities

Refraction



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

Diffraction



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?

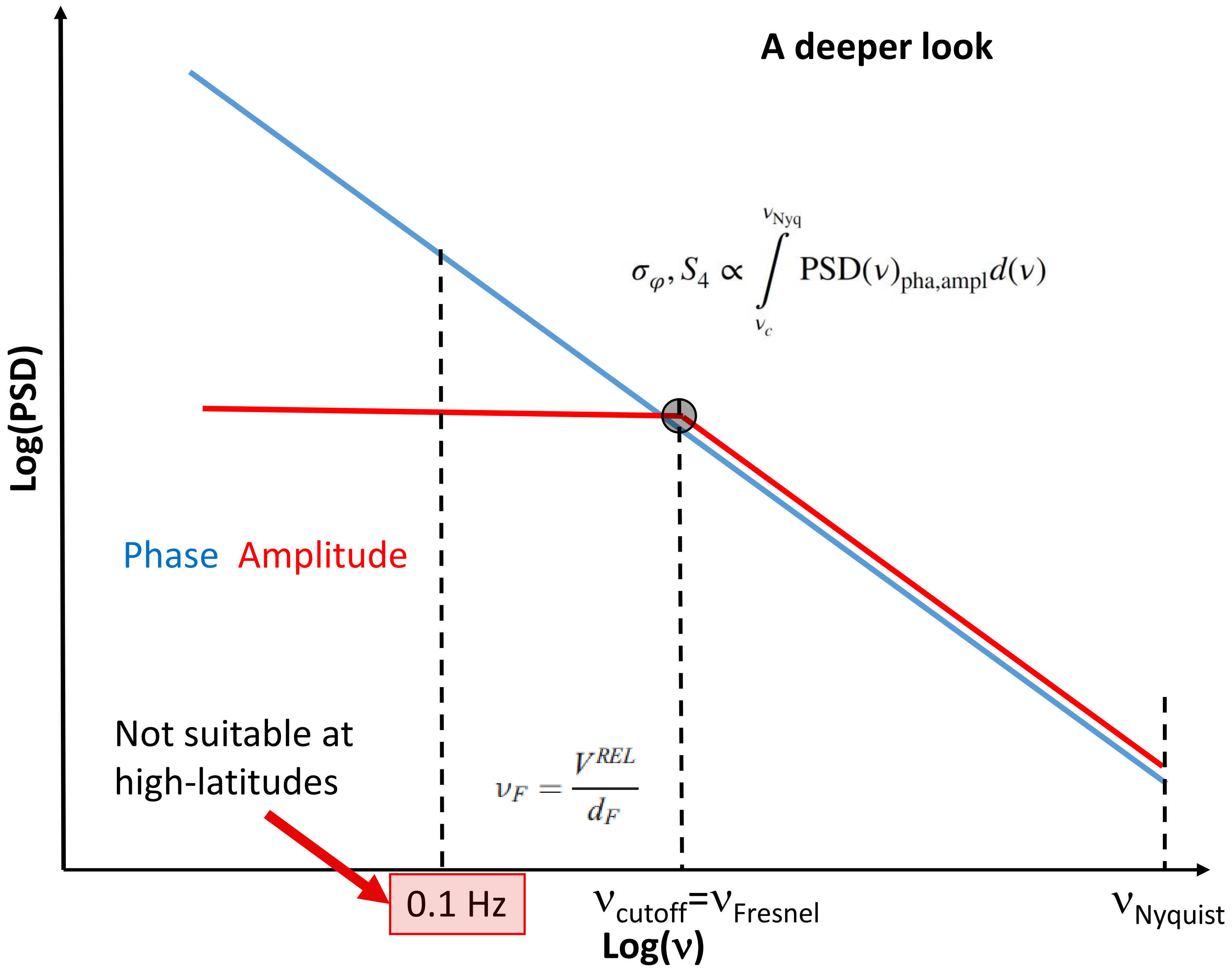
Phase "fluctuations":

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

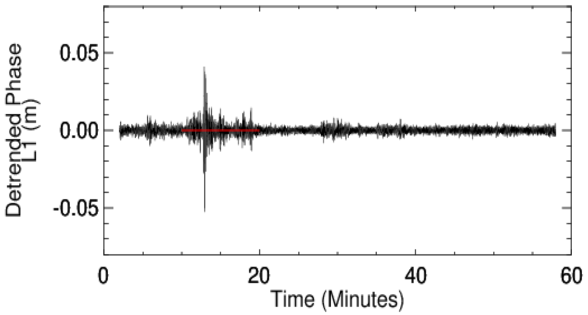
Stochastic and deterministic effects

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

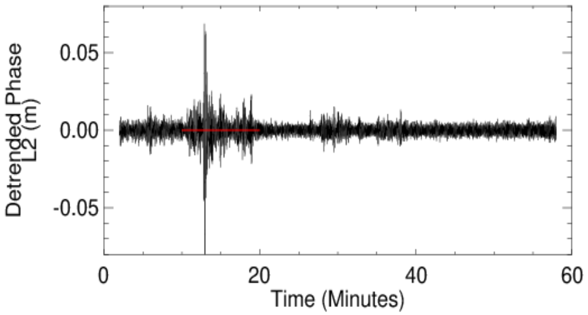
A deeper look



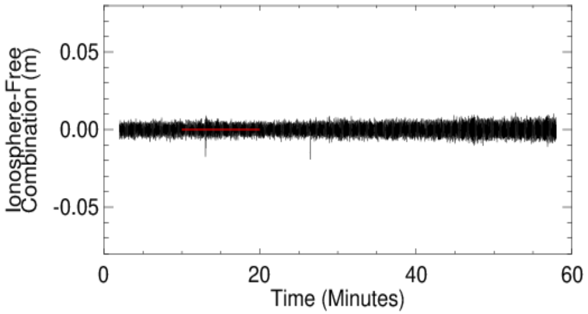
What is scintillation?



Scintillation on L1?



Scintillation on L2?

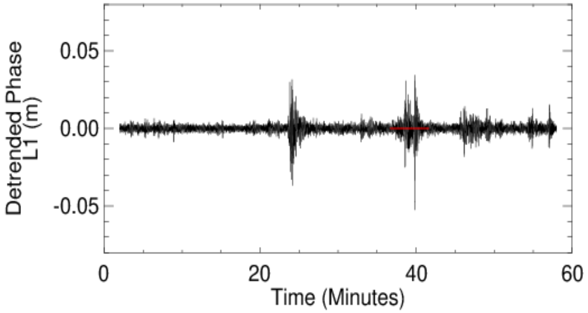


NO! Ionosphere-Free Linear Combination says NO!

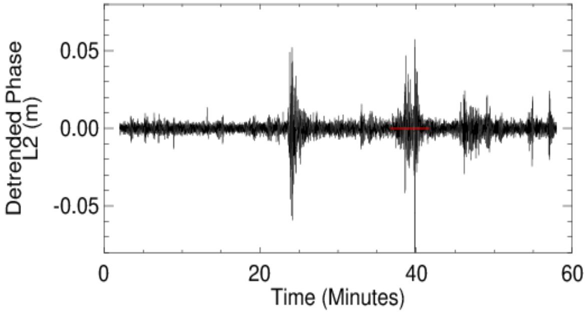
$$IFLC = \frac{\Phi_1 f_1^2 - \Phi_2 f_2^2}{f_1^2 - f_2^2}$$

*adapted from a slide by Jayachandran (UNB)

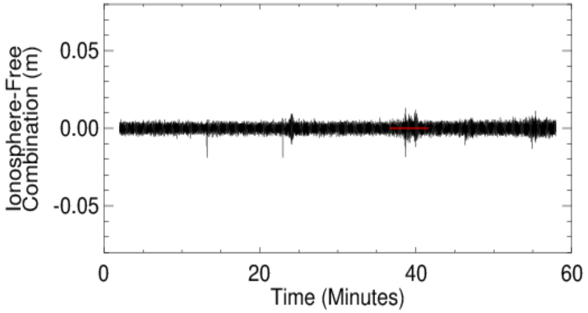
What is scintillation?



Scintillation on L1?



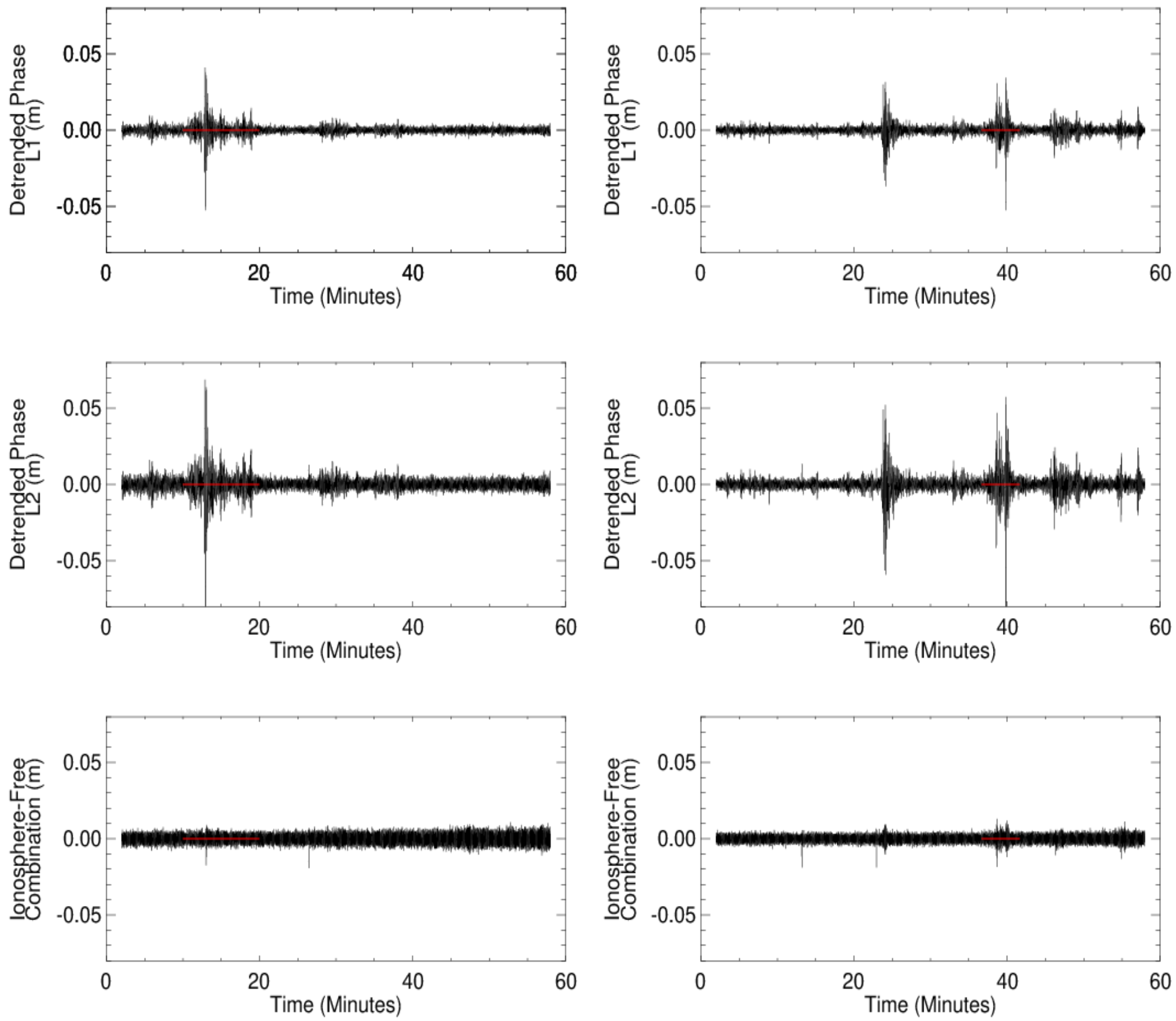
Scintillation on L2?



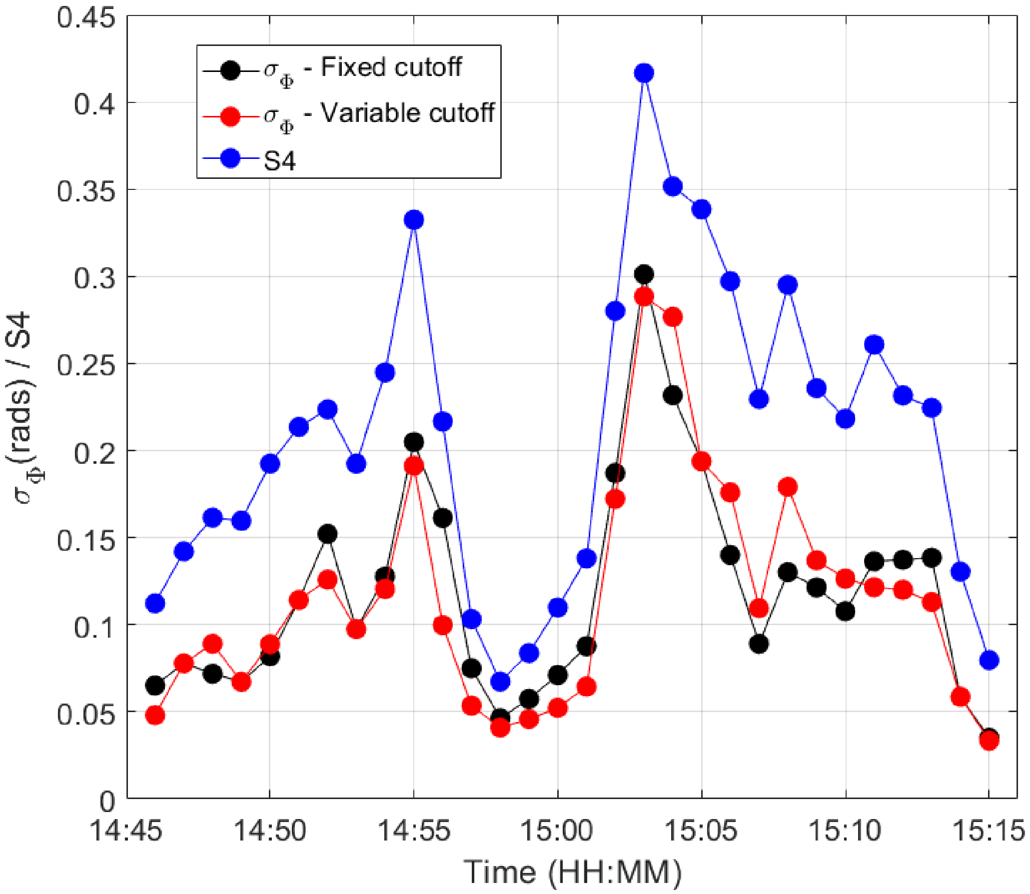
YES! Ionosphere-Free Linear Combination doesn't account for all fluctuations

*adapted from a slide by Jayachandran (UNB)

What is scintillation?



Courtesy of Jayachandran (UNB)

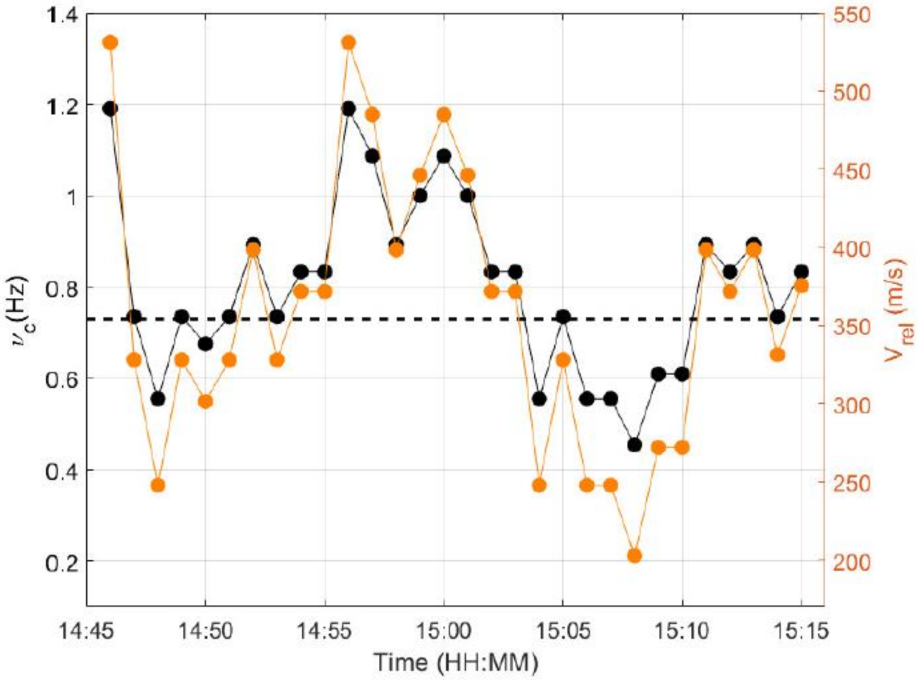


If properly detrended, SigmaPhi has almost the same information content of S4

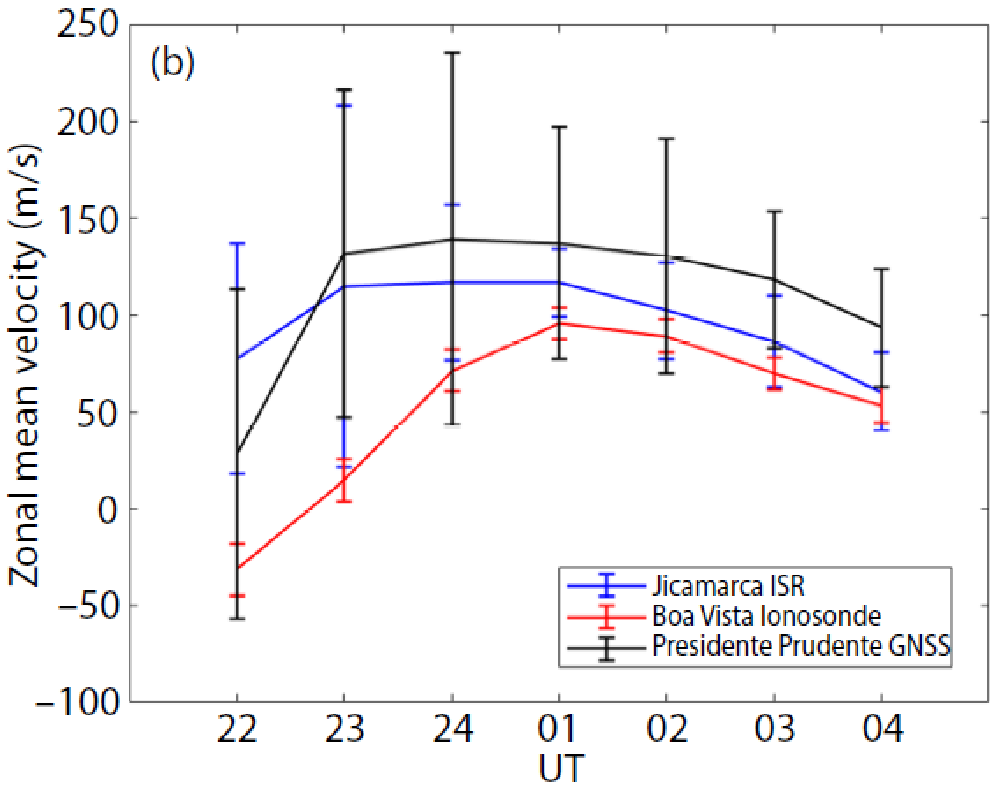
Ghobadi et al. (2020). *GPS Solutions*

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…