Recent advances in ionospheric scintillation on Global Navigation Satellite System signals

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SEZIONE 4 - Geofisica e fisica dell’ambiente

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Scientific background

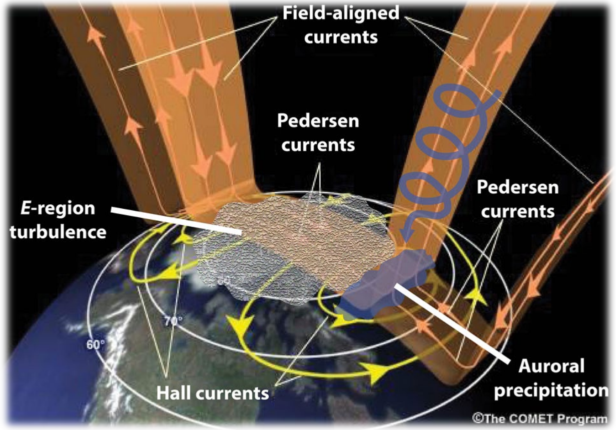
High-latitude ionosphere is directly connected with the Solar Wind through the coupling with the magnetosphere.

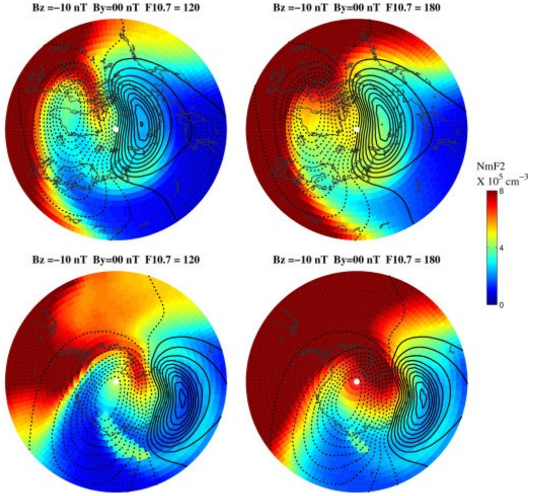
Solar events typically disturb the complex system of currents circulating in M-I system

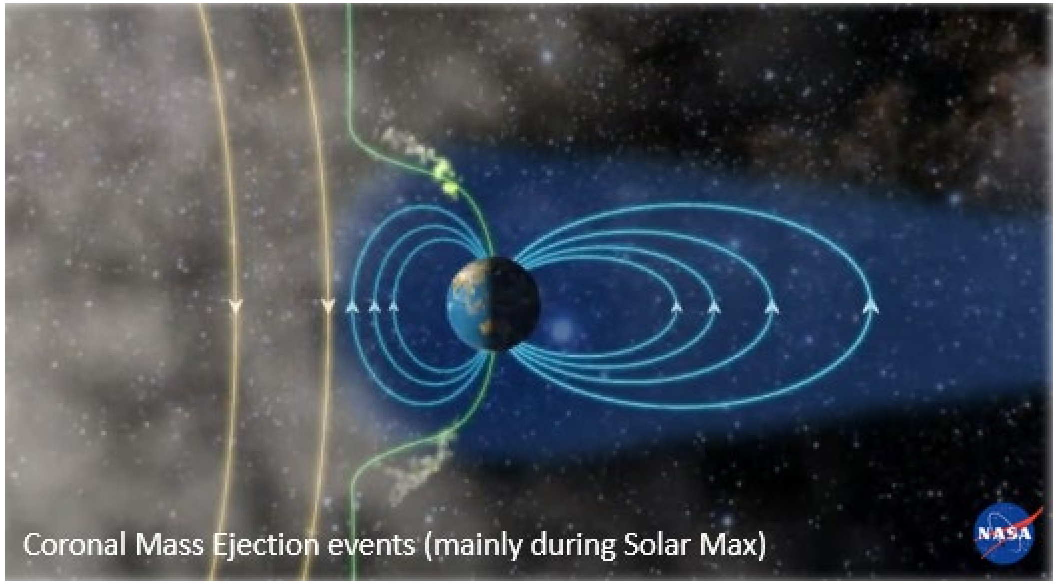
Electron concentration in the ionosphere encounters the formation of spatio-temporal gradients, i.e. **ionospheric irregularities**

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

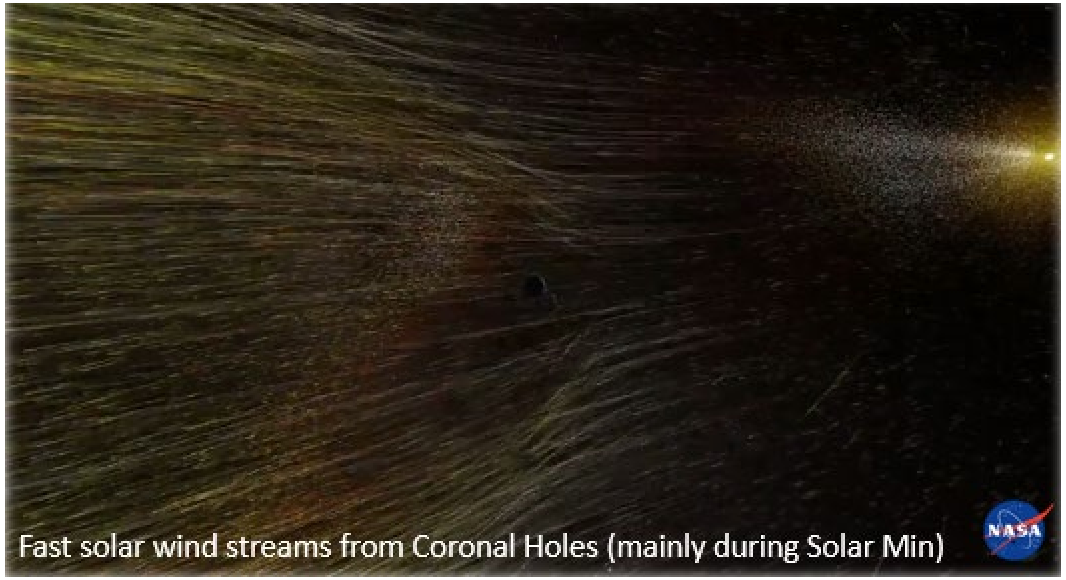
Ionospheric irregularities varies on large number of spatial scales (from few cm's to about 1000 km)





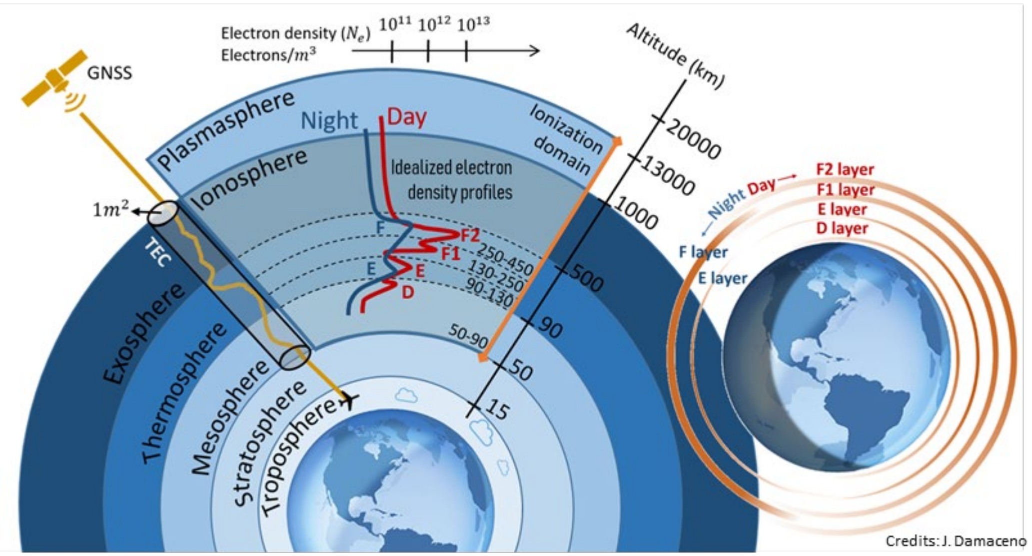


Coronal Mass Ejection events (mainly during Solar Max)

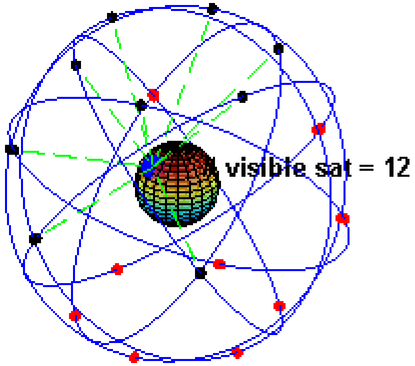


Fast solar wind streams from Coronal Holes (mainly during Solar Min)

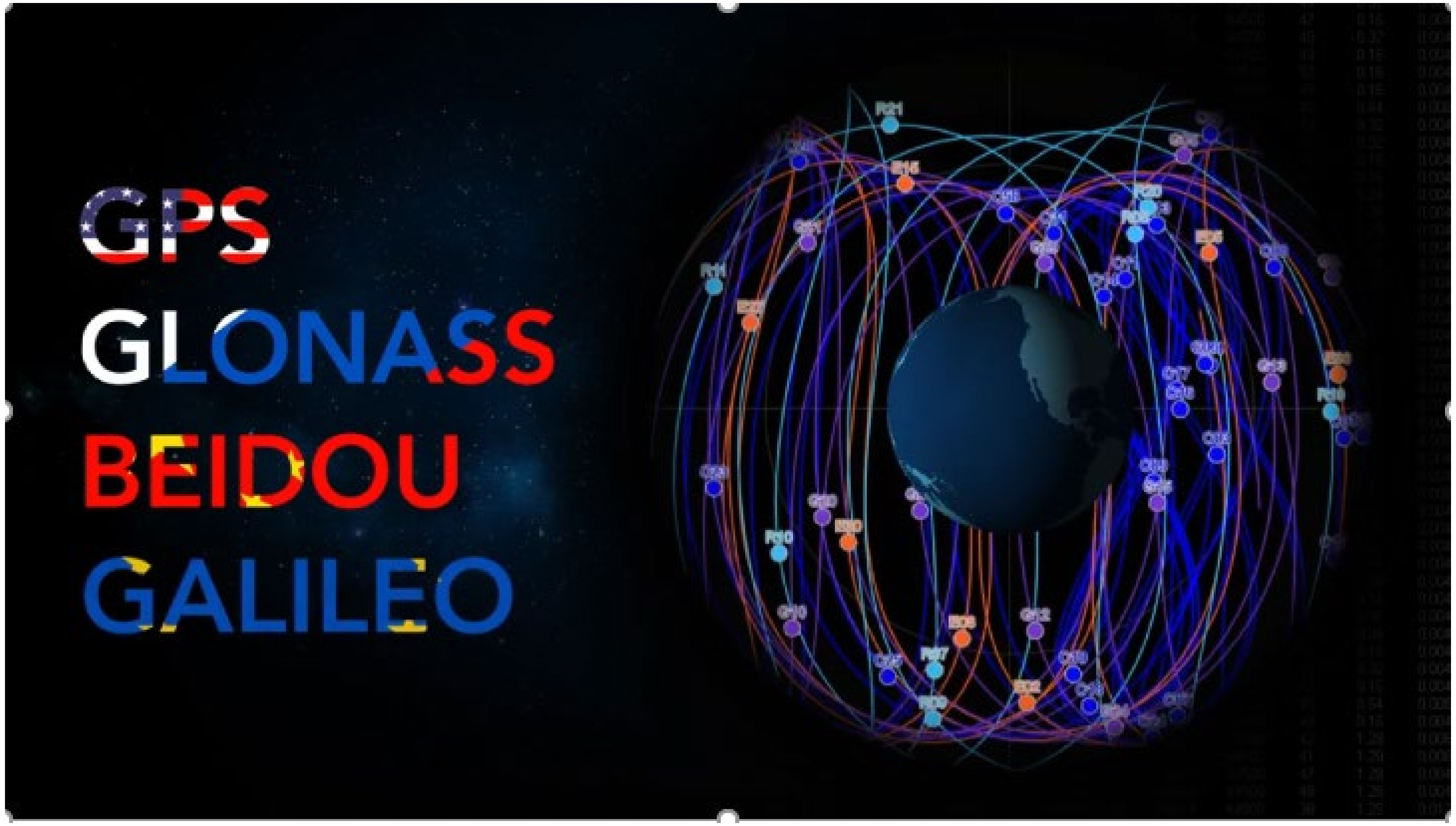
Probing the ionosphere with GNSS*



Credits: J. Damaceno



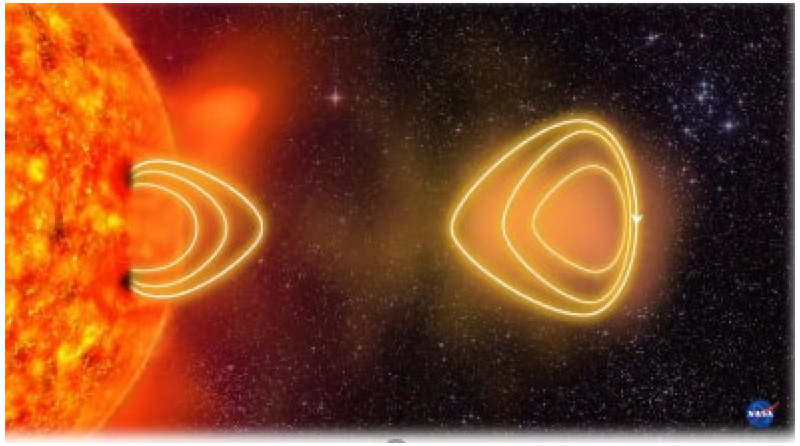
Source	Effect
Ionospheric effects	± 5 m
Ephemeris errors	± 2.5 m
Satellite clock errors	± 2 m
Multipath distortion	± 1 m
Tropospheric effects	± 0.5 m
Numerical errors	± 1 m



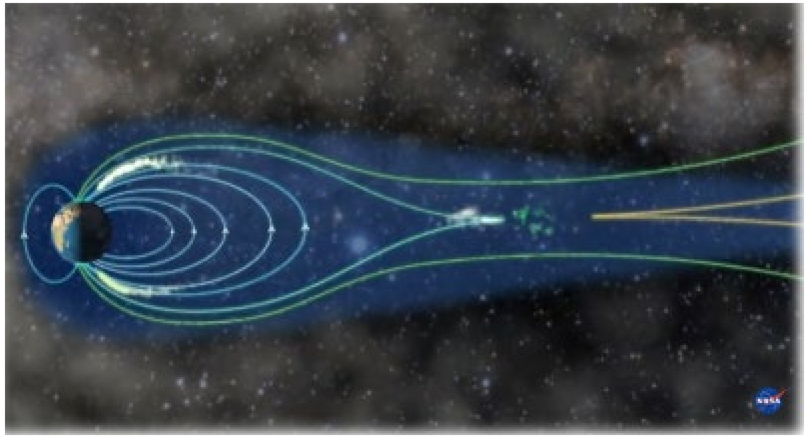
GNSS Signals are in L-band (1-2 GHz)

*Global Navigation Satellite System

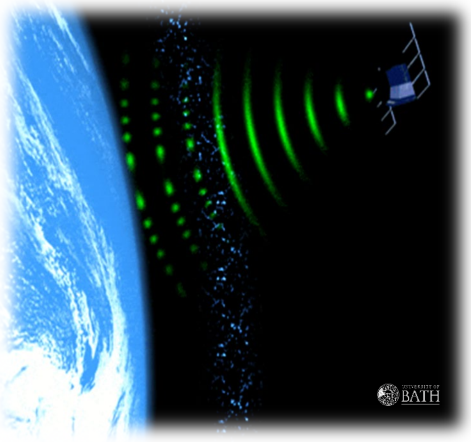
Scientific background: studying ionospheric irregularities with GNSS



Ionospheric irregularities,
i.e.
Fluctuations of ambient electron density Dn_e



Diffraction and refraction of trans-ionospheric e.m. waves



Scintillation: phase and amplitude sudden fluctuations of the trans-ionospheric e.m. wave

Reduced accuracy of positioning

GNSS

Loss of satellite lock

HOW TO STUDY IONOSPHERIC IRREGULARITIES:
Radio signals **carry memory** of the ionosphere portion they cross.

Scintillation indices

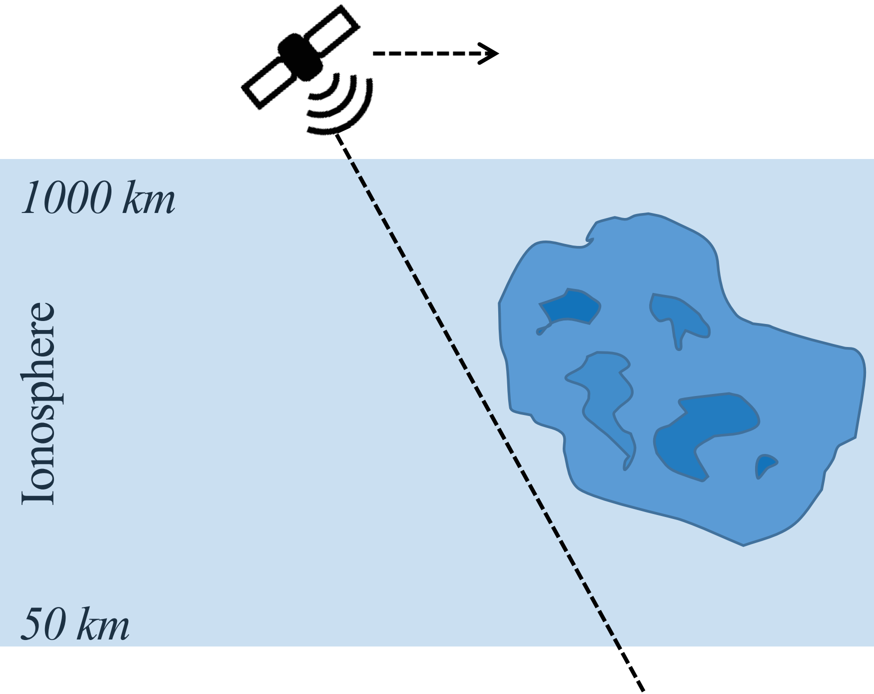
$$S_4^2 = \left(\langle I^2 \rangle - \langle I \rangle^2\right) / \langle I \rangle^2. \qquad \sigma_\phi^2 = \langle \phi^2 \rangle - \langle \phi \rangle^2$$

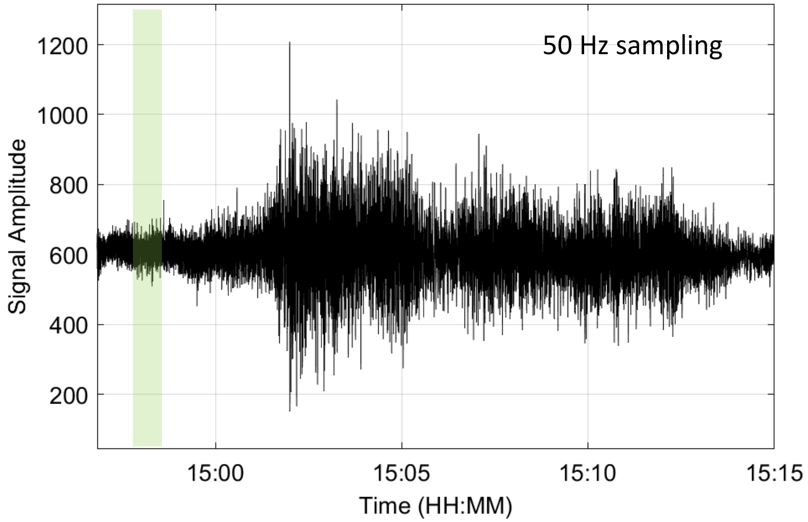
Ampl. Phase

50 Hz sampling
1-min values

INGV contributed to the PolaRxS development in the frame of CIGALA project (funded by FP7, ended Jan 2012)

A simplified picture





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Ampl.

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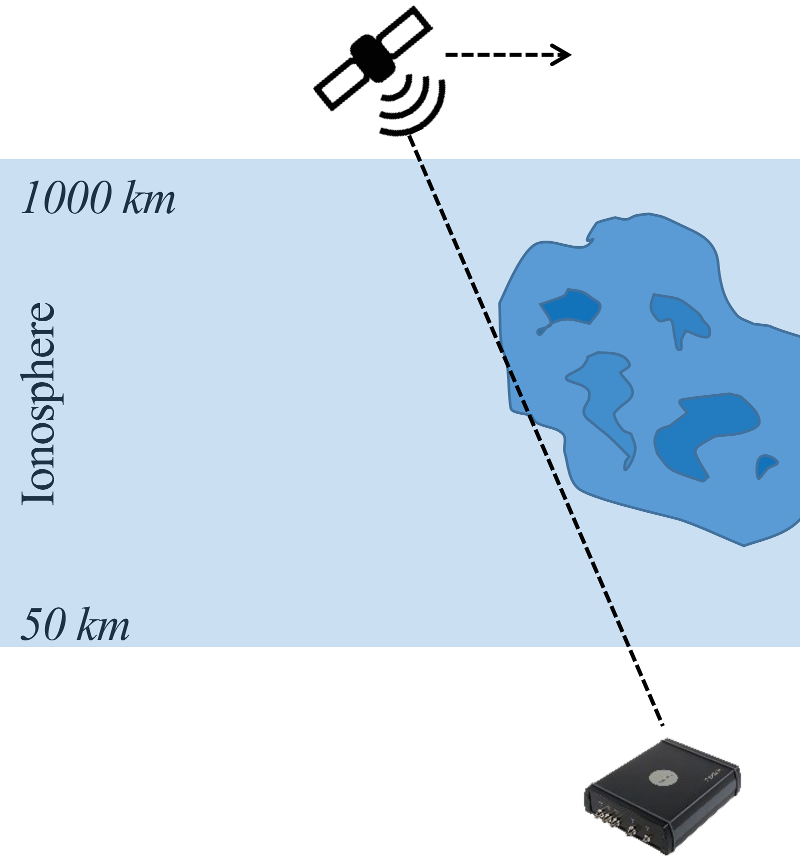
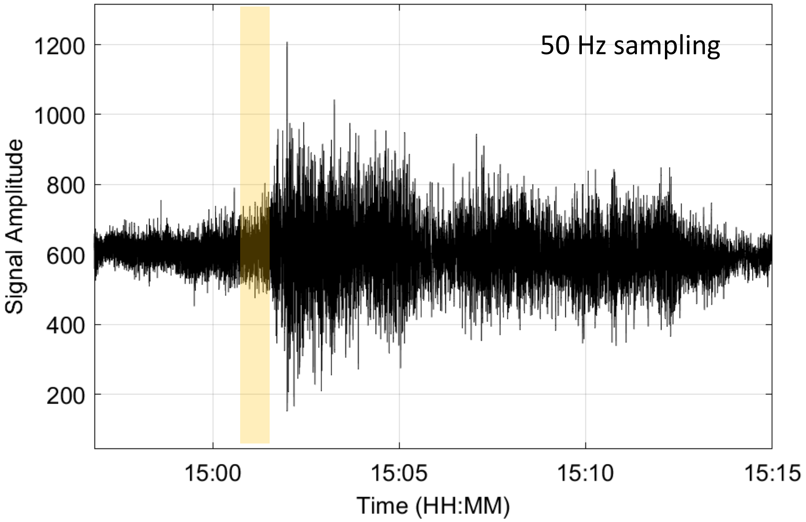
Phase

A simplified picture





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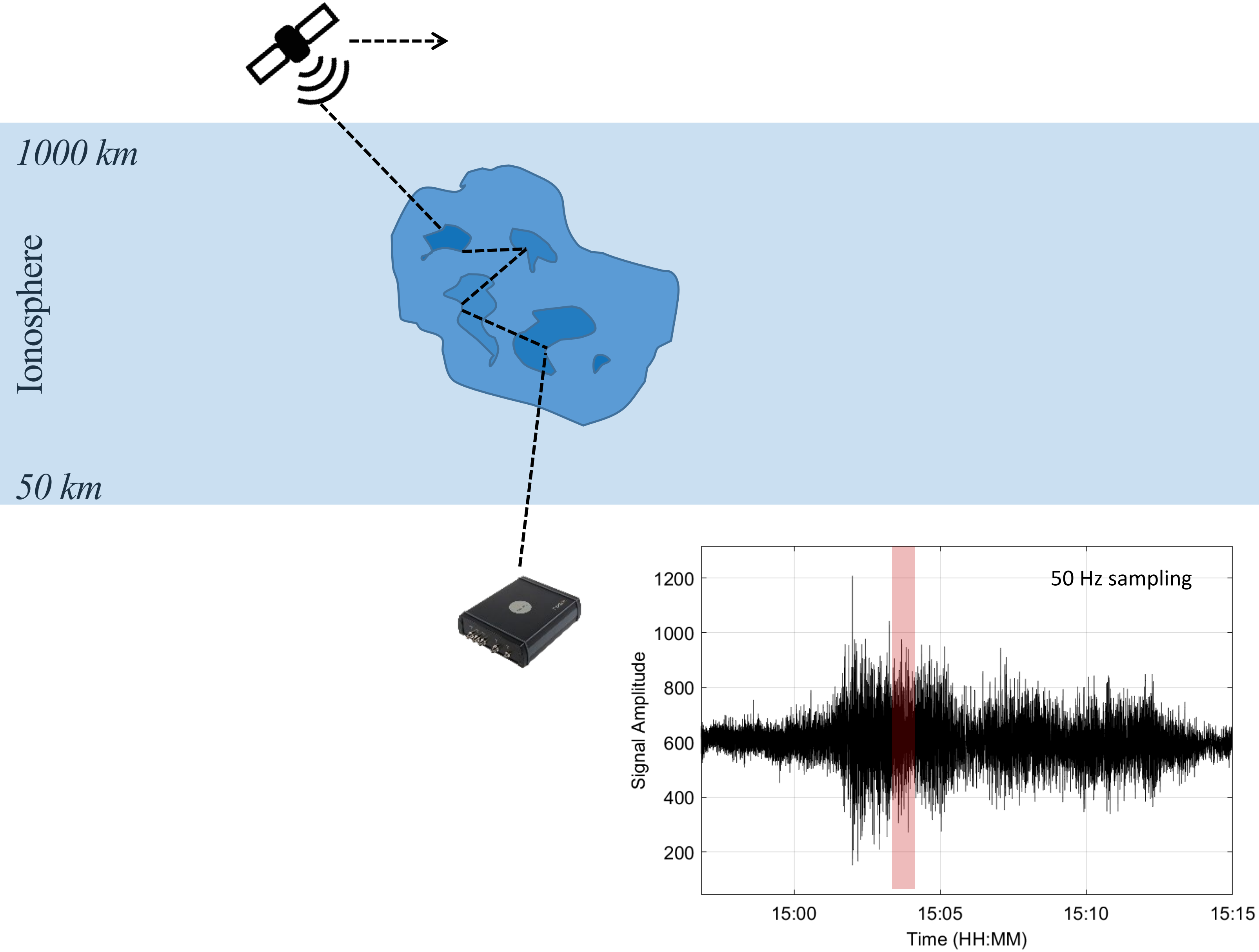
A simplified picture



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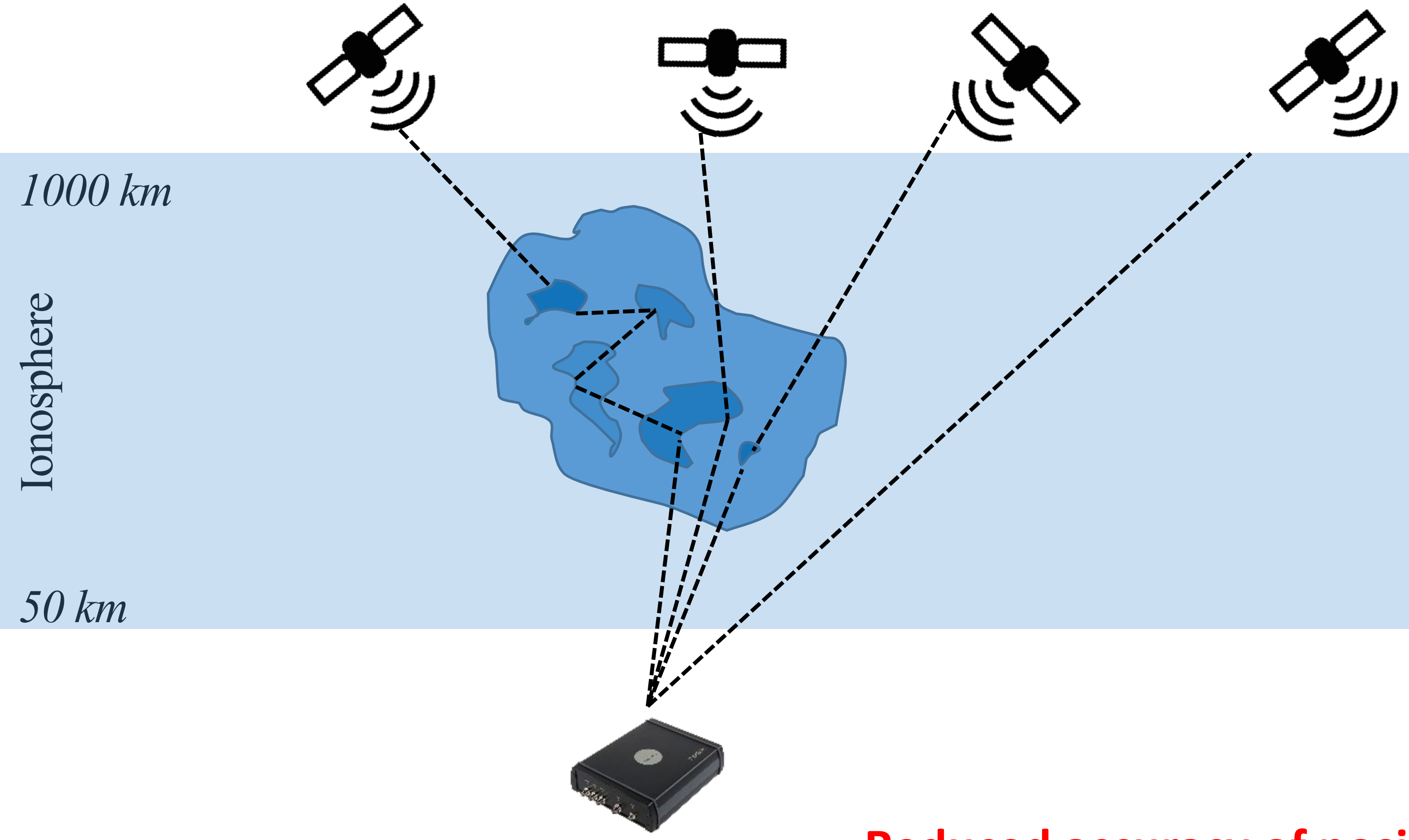
Phase

A simplified picture



Reduced accuracy of positioning

Loss of lock

Scintillation indices

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Phase

What is scintillation?

A deeper look

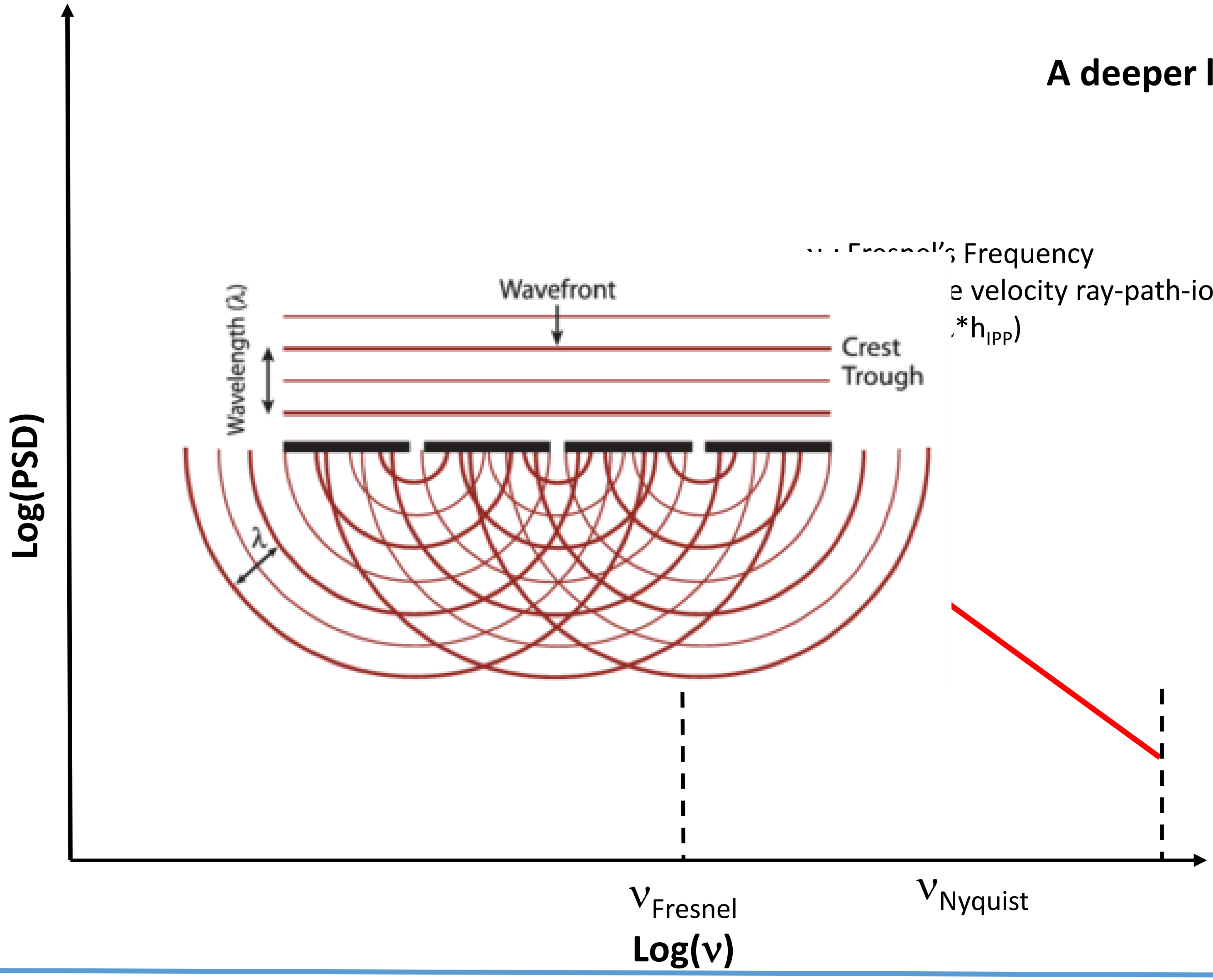
Amplitude scintillation:

1 mechanism:
diffraction triggered by
small-scale irregularities

Stochastic effect

↓

Stochastic effects are
the actual problem 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 effect

Phase Scintillation

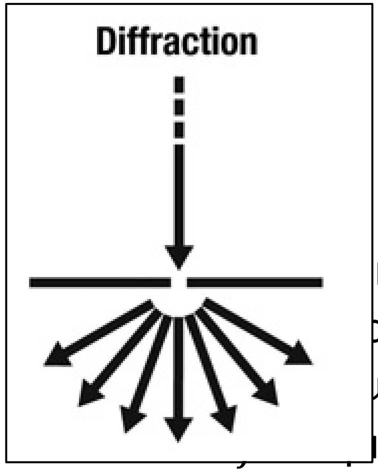
Phase Fluctuation

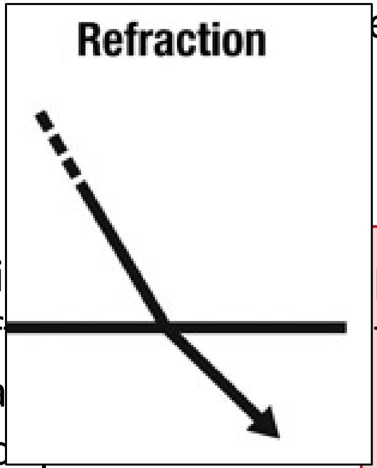
Eliminated through

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

Ionosphere-Free Linear Combination

f: frequency of 1st and 2nd signal
Φ: corresponding phase





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Best estimator is based on IFLC fluctuations and/or stochastic TEC characterization

A deeper look

e Scintillation

phase scintillation is based on the frequency content

$$\sigma_\phi = \sqrt{\langle \phi_{\mathrm{detr}}^2 \rangle - < \phi_{\mathrm{detr}} >^2}$$

What is scintillation?

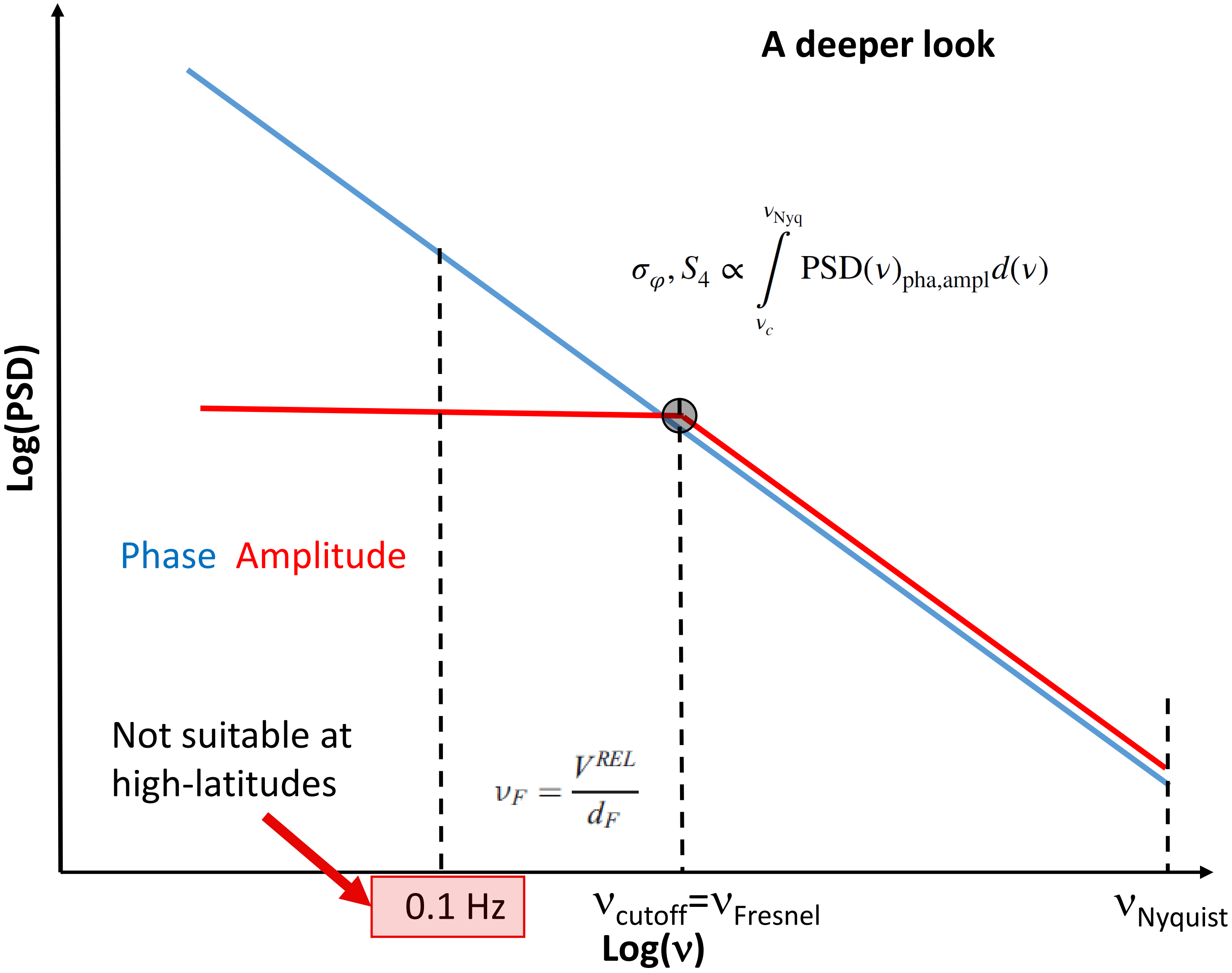
Phase “fluctuations”:

2 mechanisms:
-**<u>diffraction</u>** (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.
<u>Overestimated σ_Φ</u>

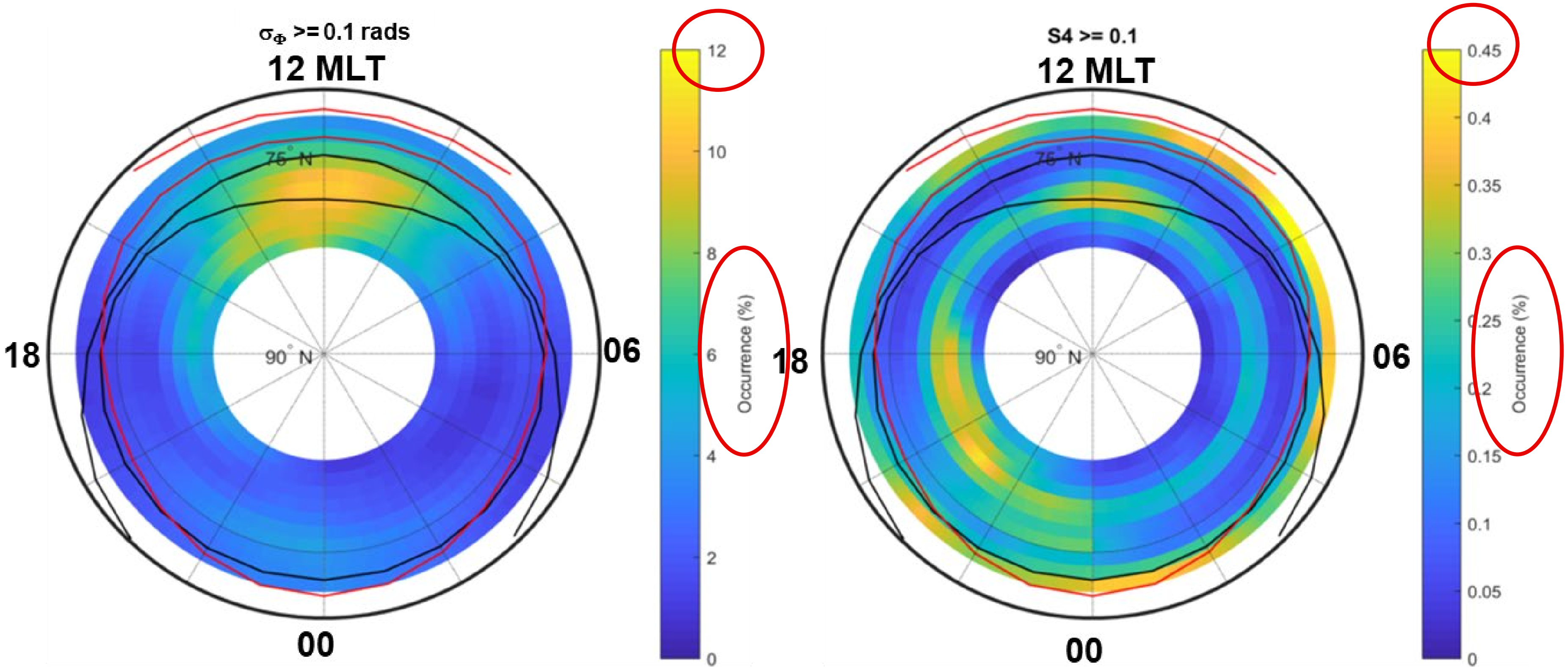
A deeper look



$$\sigma_\varphi, S_4 \propto \int_{\nu_c}^{\nu_{\mathrm{Nyq}}} \mathrm{PSD}(\nu)_{\mathrm{pha,ampl}}\, d(\nu)$$

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

“Phase-without-amplitude scintillation at high latitude”



De Franceschi et al. (2019) Sci. Rep.

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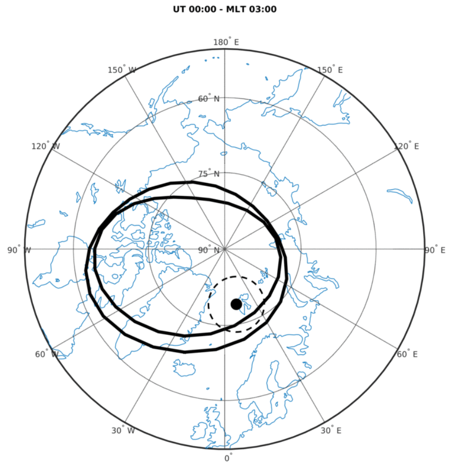
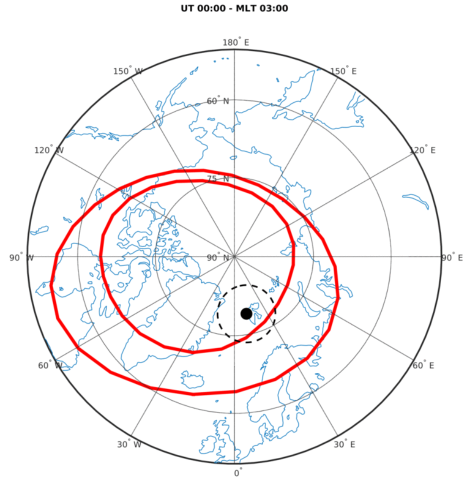
Overestimated σ_Φ

Ny-Ålesund



Quiet conditions IQ = 0



Disturbed conditions IQ = 6

Where:

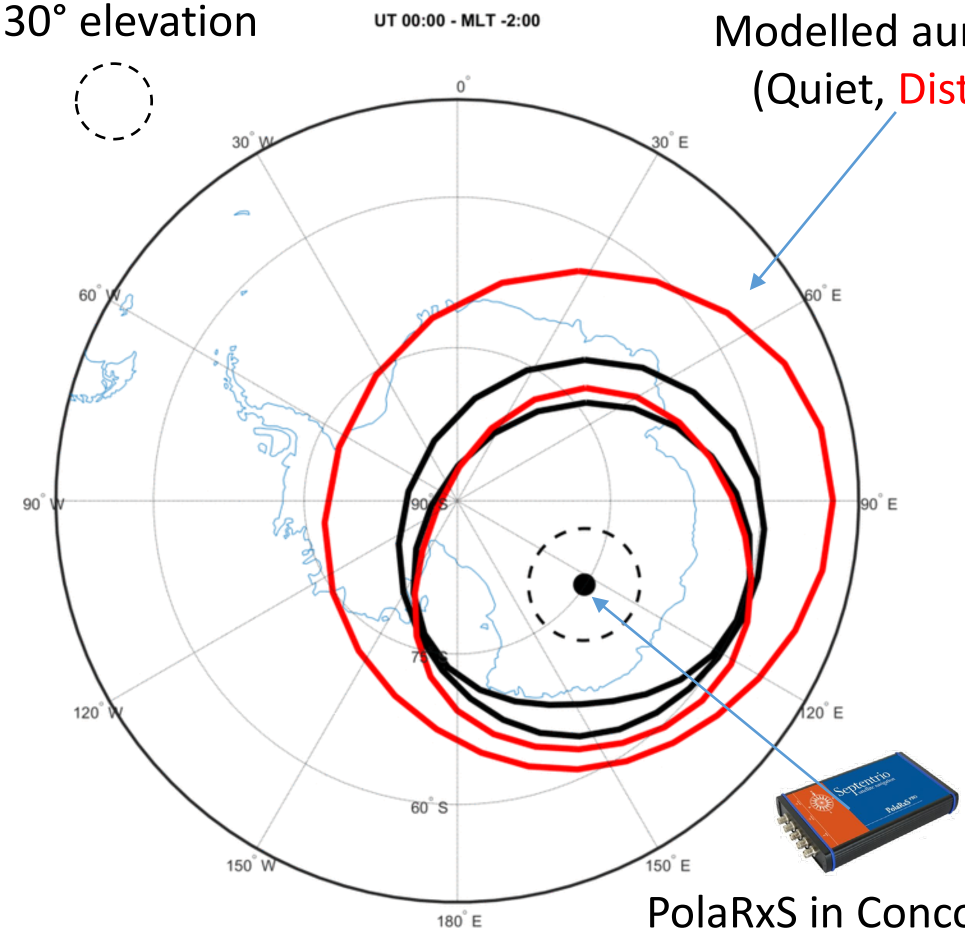
In Antarctica, where ionospheric threats are more probable.

When:

During the geomagnetic storm occurred in September 2017.

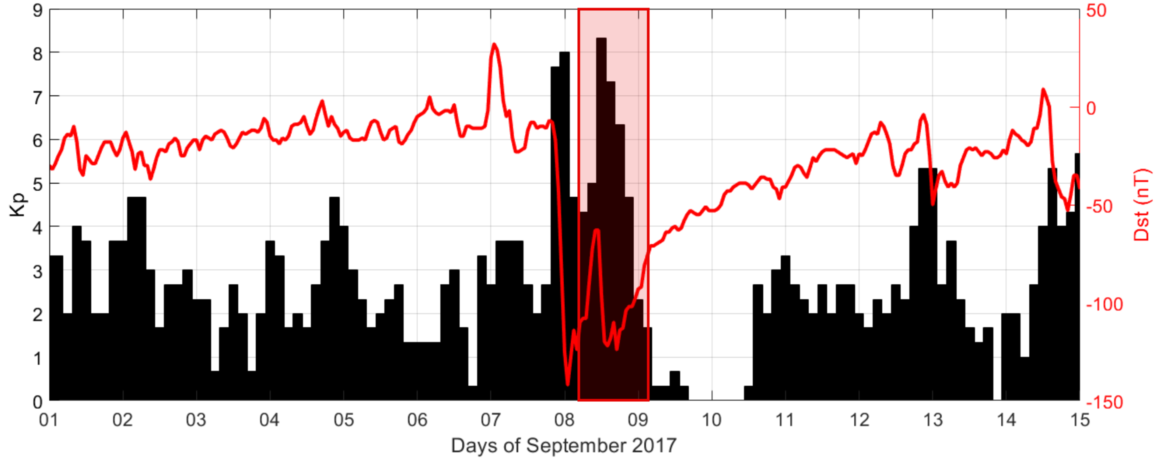
30° elevation

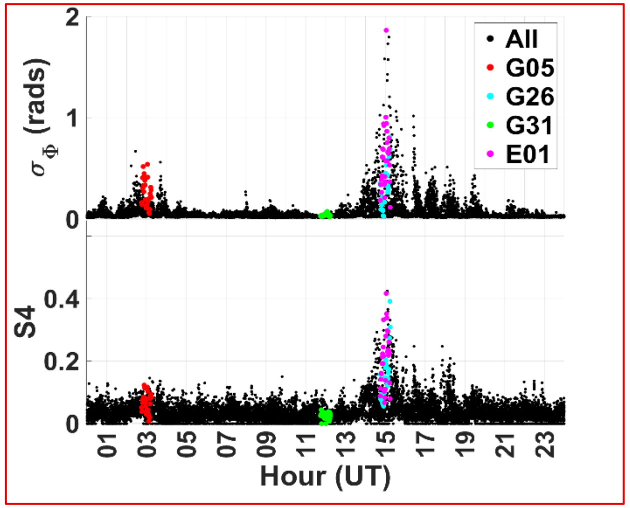
Modelled auroral oval (Quiet, Distrubed)



PolaRxS in Concordia Station

Data doi: 10.13127/ESWUA/GNSS





Case event	Satellite	Time	Parsed Indices S_4	Parsed Indices σ_φ
1	G05	02:45 – 03:15	low	high
2	G31	11:45 – 12:15	low	low
3	G26	15:00 – 15:30	high	high
4	E01	14:45 – 15:15	high	high

Fast Iterative Filtering (FIF) algorithm

is a decomposition method that split a nonstationary signal s into simple oscillatory components, a.k.a. IMCs

Thm – Fast Iterative Filtering (FIF) convergence – C., Zhou - '21

Given $s \in \mathbb{R}^n$, a filter w and periodical extension at the boundaries, Then

$$\mathrm{IMC}_1 = U(I-D)^{N_0} U^T s = \mathrm{IDFT}\left(\left(I - \mathrm{diag}\left(\mathrm{DFT}(w)\right)\right)^{N_0} \mathrm{DFT}(s)\right)$$

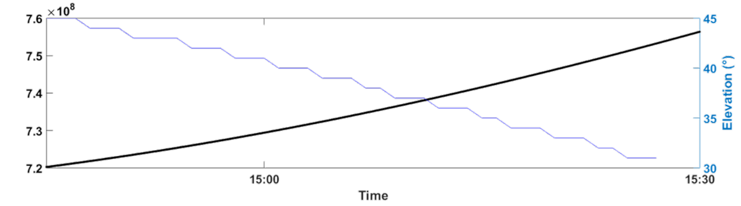
Fast calculations

The **FIF algorithm** is convergent and stable, and, on average, roughly **100 times faster than IF and EMD-based methods**.

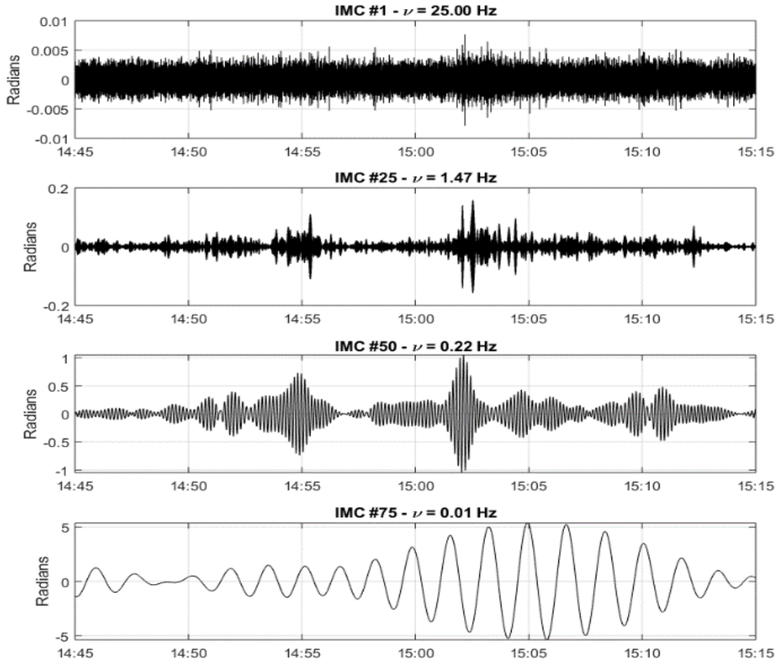
FIF code for MATLAB is available at www.cicone.com

Cicone A (2020) Iterative filtering as a direct method for the decomposition of nonstationary signals. Numer Algorith 2020:1–17

Raw Phase (50 Hz)

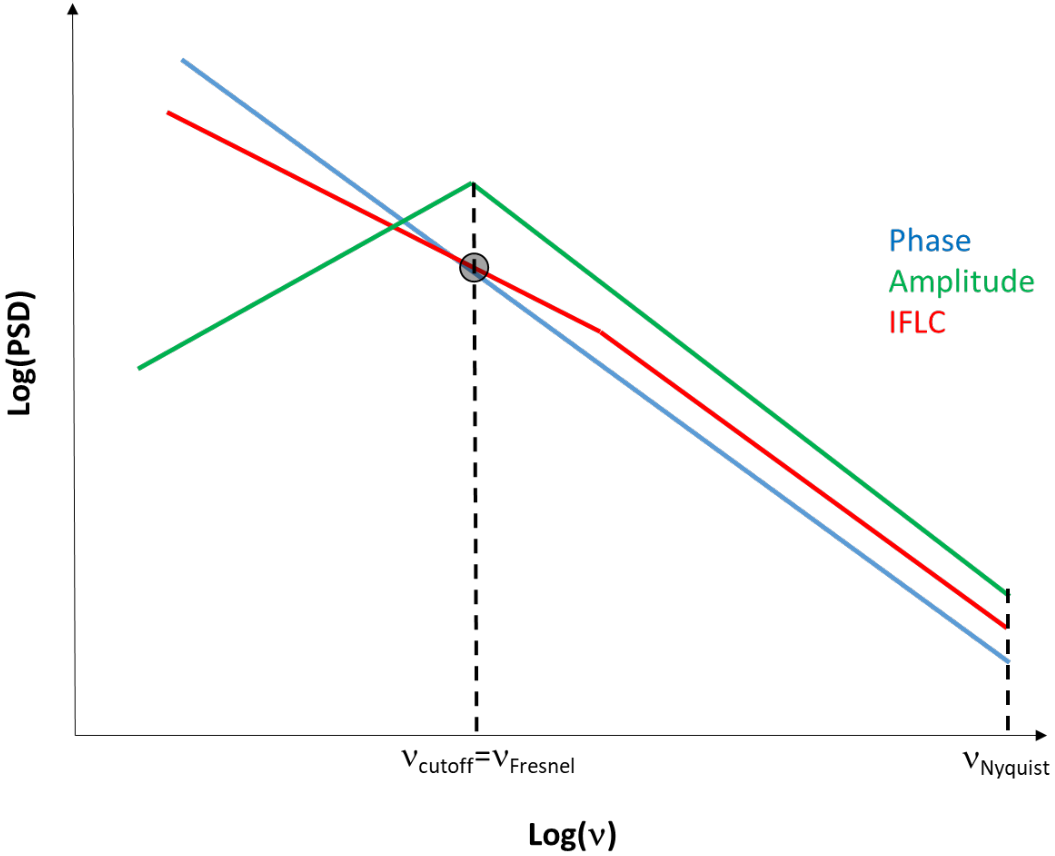


$$s = \sum_{i=1}^{N_{IMC}} IMC_i(\nu) + res$$

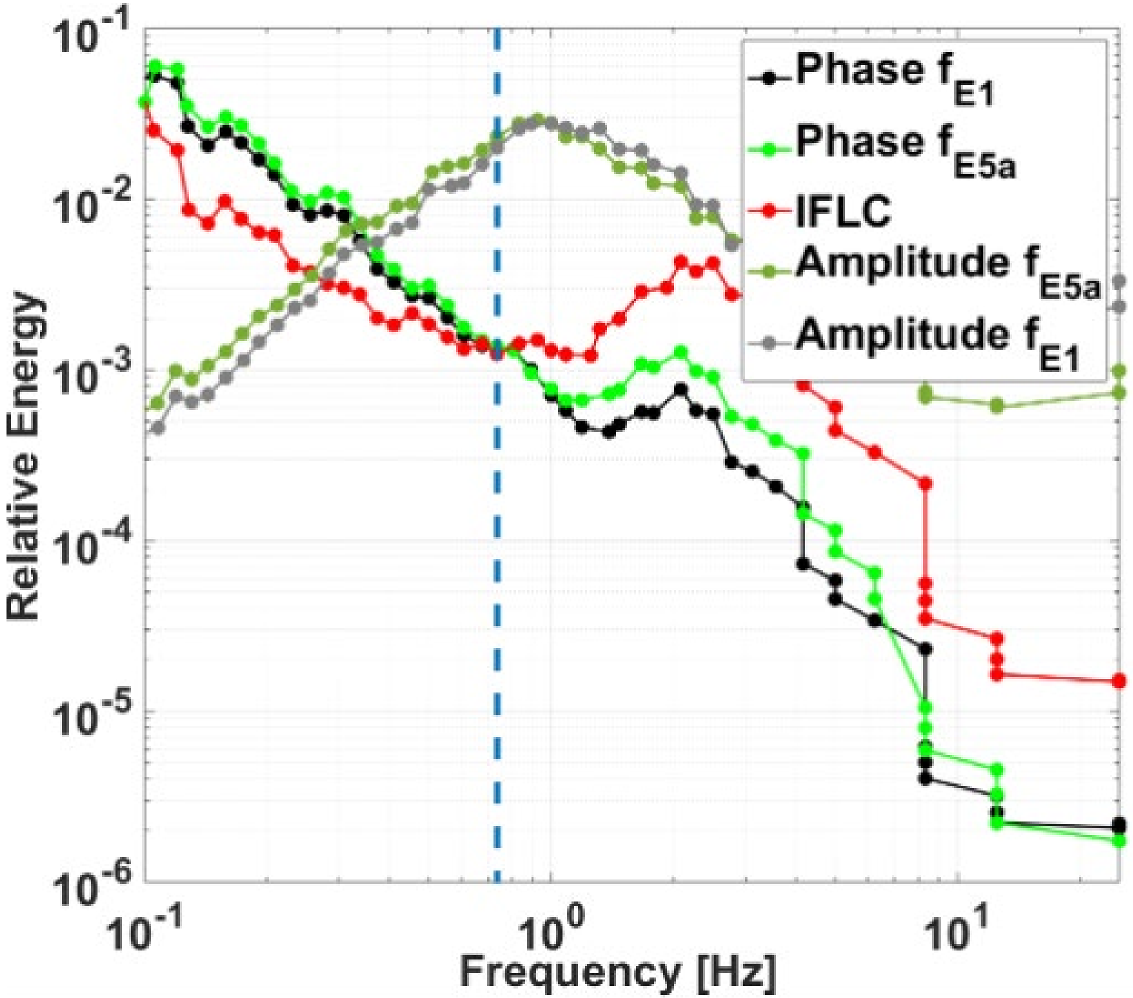


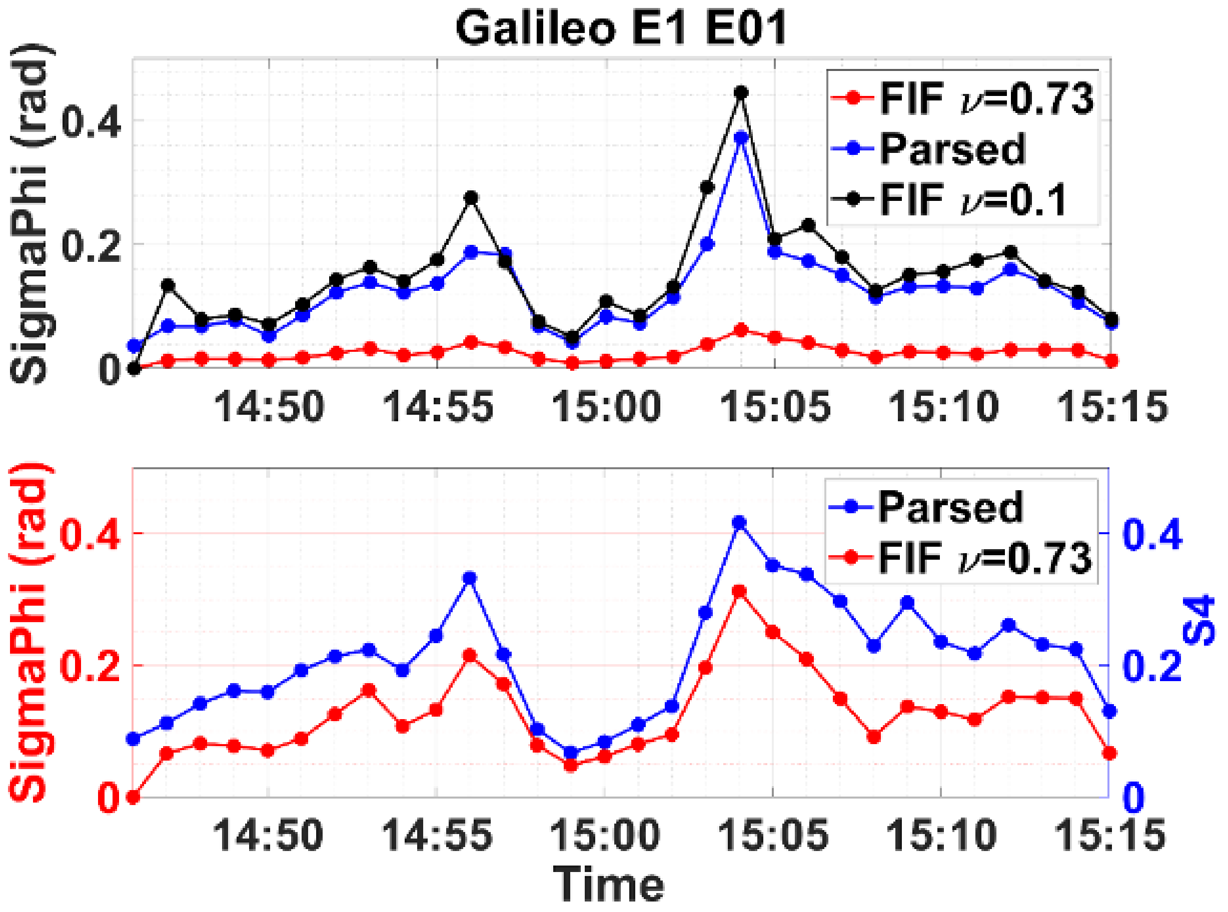
Measuring the cutoff frequency

IFLC takes into account the bulk of the refractive effects
The crossing points between f1/f2 phase PSD and IFLC PSD indicate the refined cutoff frequency
Amplitude spectrum decreases in corspondence with the Fresnel's frequency

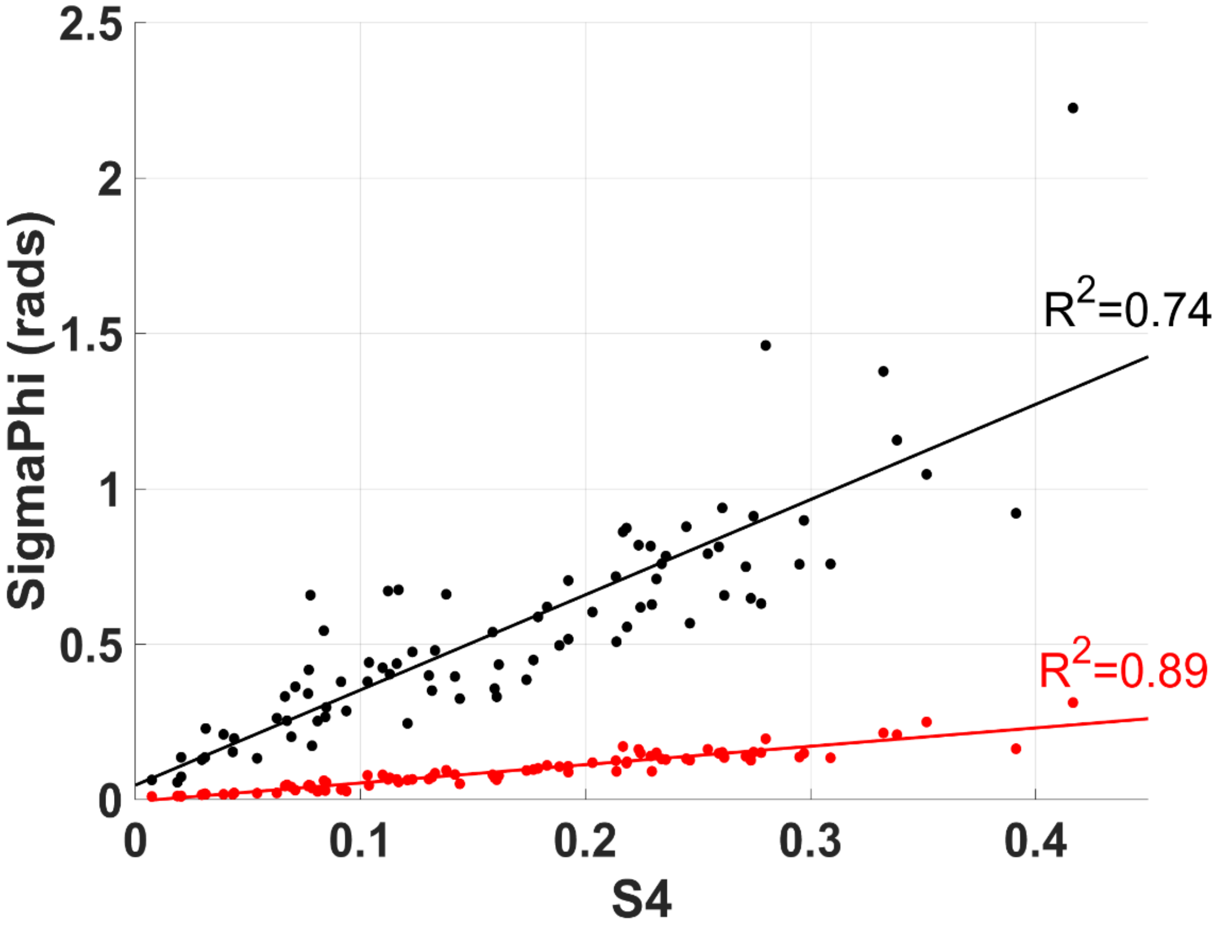


$$E^{k}_{\mathrm{rel}}(\nu^{*}) = \frac{< \mathrm{IMC}_k^2(\nu^{*}) >}{< \sum_{i=1}^{N_{\mathrm{IMC}}} \mathrm{IMC}_i^2(\nu) >}$$





H. Ghobadi et al., "Disentangling ionospheric refraction and diffraction effects in GNSS raw phase through Fast Iterative Filtering technique", GPS Solut., 24 (85), 2020, DOI: 10.1007/s10291-020-01001-1



A refined value of the cutoff frequency has been determined for 4 GPS (G) and Galileo (E) signals.

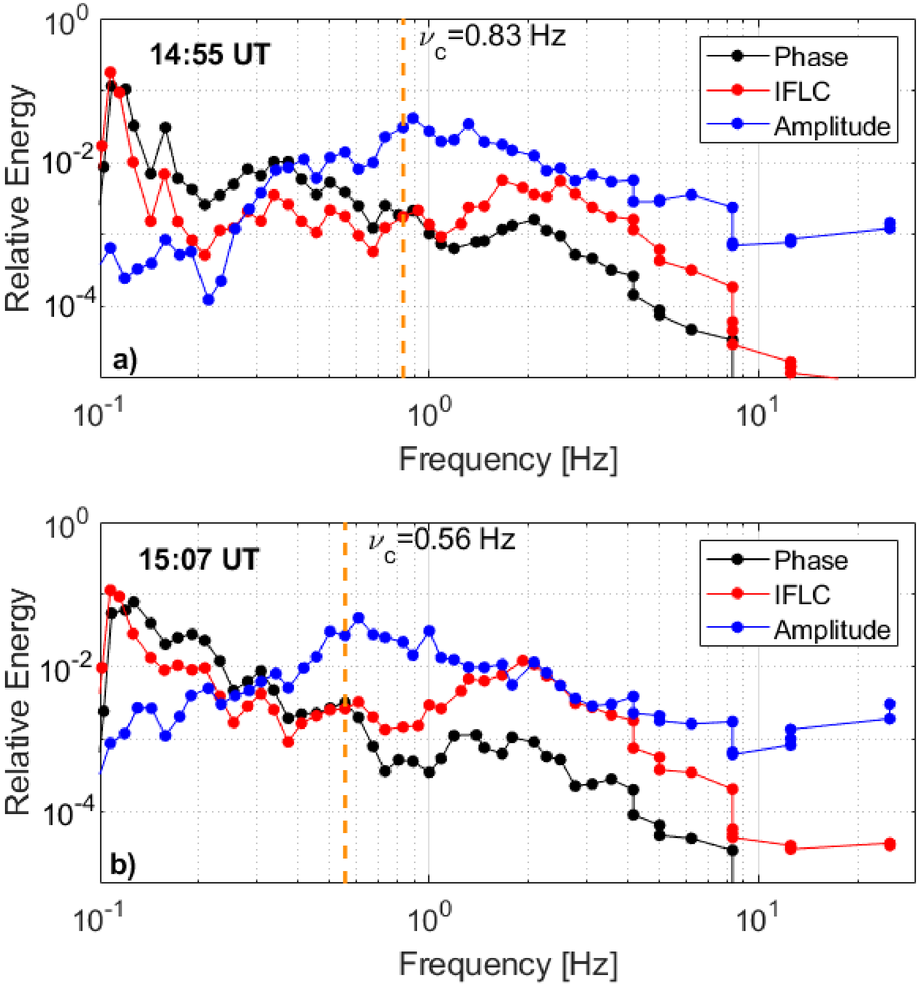
Case #	Satellite	Scale range	ν_c (Hz)
1	G05	Large	0.83
2	G31	N/A	N/A
3	G26	Large and small	0.73
4	E01	Large and small	0.73

Summary of the correlation between S_4 and σ_Φ as computed with 0.1 Hz cutoff frequency and with the refined cutoff

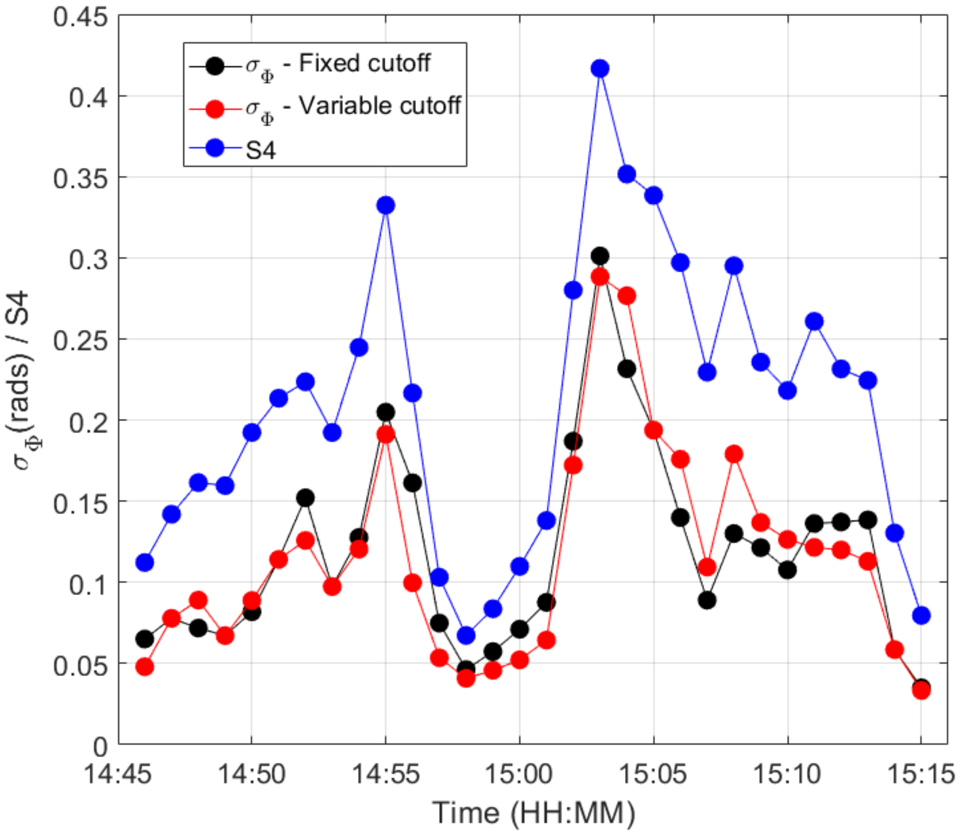
Case #	R^2	
	$\nu_c = 0.1$ Hz	Refined ν_c
1	0.65	0.79
3	0.71	0.77
4	0.71	0.85
Overall	0.74	0.89

H. Ghobadi et al., "Disentangling ionospheric refraction and diffraction effects in GNSS raw phase through Fast Iterative Filtering technique", GPS Solut., 24 (85), 2020, DOI: 10.1007/s10291-020-01001-1

E01 8 September 2017



The detrending can be further improved by making it adaptive not only per each satellite, but also per epoch to investigate the temporal variability of the cutoff frequency.



Spogli et al., "Adaptive phase detrending for GNSS scintillation detection: a case study over Antarctica Submitted" , IEEE-GRSL, 2021

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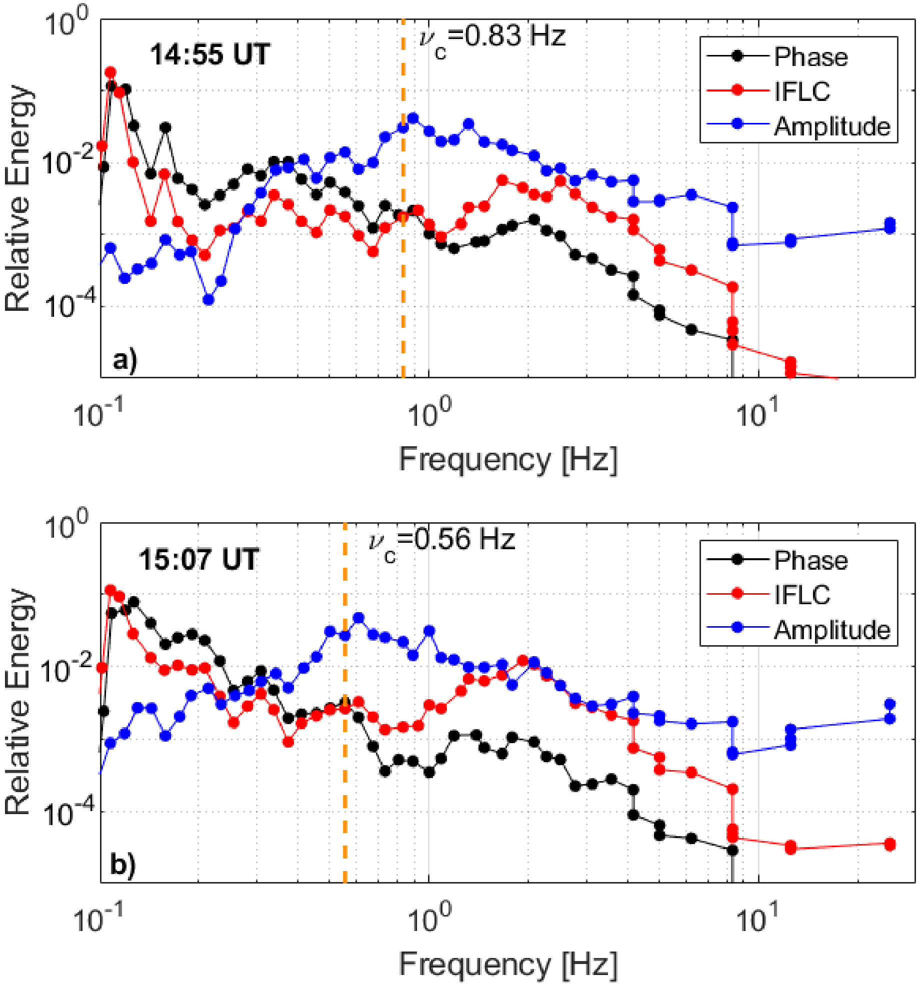
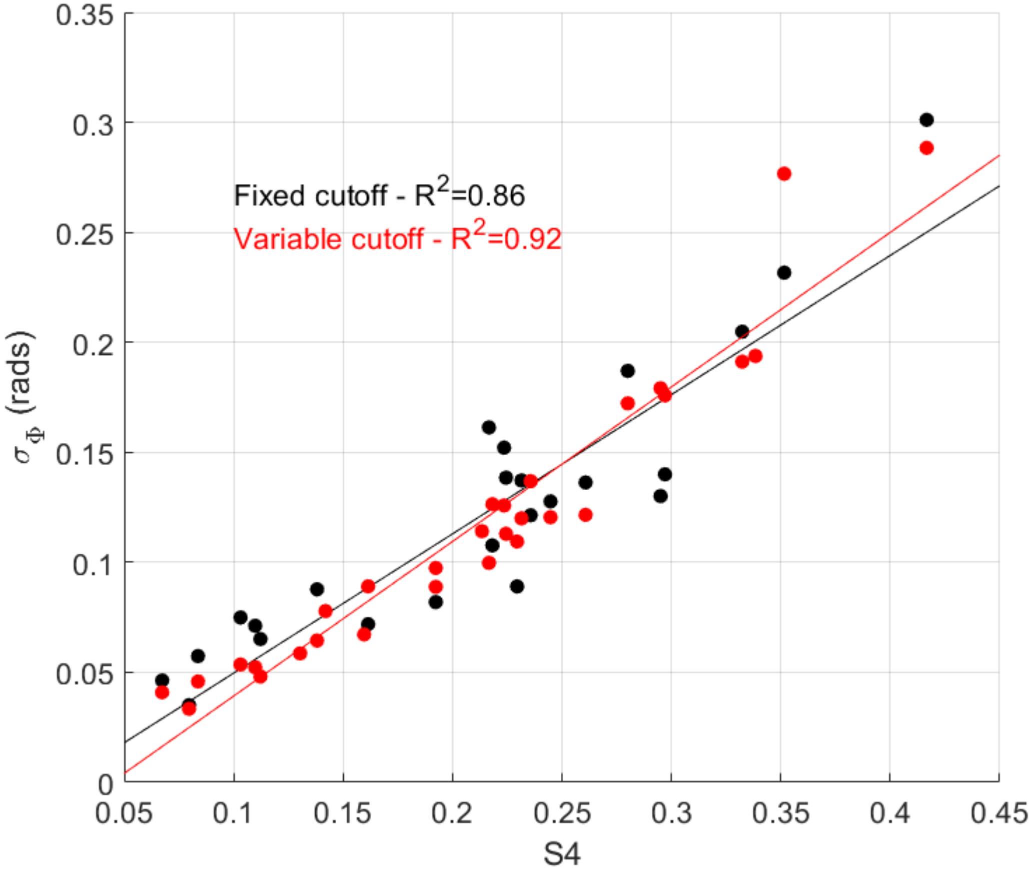
E01 8 September 2017





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Conclusions

In view of providing an index that accounts only for the most disruptive effects on the phase of GNSS signals we have proved the following:

- The **inappropriateness of the adoption of a detrending with a fixed cutoff frequency at 0.1 Hz** value to determine the σ_Φ at high latitude
- The need for a **proper identification of the cutoff frequency** for phase detrending through an original detrending scheme
- The effectiveness of the adopted detrending scheme in **accounting for phase fluctuations due to diffraction** in the σ_Φ computation
- The further improvement of the determination of σ_Φ by means of an **adaptive (per epoch) evaluation of the cutoff frequency** for phase detrending

GPS Solutions (2020) 24:85
https://doi.org/10.1007/s10291-020-01001-1

ORIGINAL ARTICLE

Disentangling ionospheric refraction and diffraction effects in GNSS raw phase through fast iterative filtering technique

Hossein Ghobadi[1,2] · Luca Spogli[1,3] · Lucilla Alfonsi[1] · Claudio Cesaroni[1] · Antonio Cicone[4] · Nicola Linty[5] · Vincenzo Romano[1,3] · Massimo Cafaro[2]

Received: 31 January 2020 / Accepted: 19 June 2020 / Published online: 29 June 2020

Abstract

We contribute to the debate on the identification of phase scintillation induced by the ionosphere on the global navigation satellite system (GNSS) by introducing a phase detrending method able to provide realistic values of the phase scintillation index at high latitude. It is based on the fast iterative filtering signal decomposition technique, which is a recently developed fast implementation of the well-established adaptive local iterative filtering algorithm. FIF has been conceived to decompose nonstationary signals efficiently and provide a discrete set of oscillating functions, each of them having its frequency. It overcomes most of the problems that arise when using traditional time–frequency analysis techniques and relies on a consolidated mathematical basis since its a priori convergence and stability have been proved. By relying on the capability of FIF to efficiently identify the frequencies embedded in the GNSS raw phase, we define a method based on the FIF-derived spectral features to identify the proper cutoff frequency for phase detrending. To test such a method, we analyze the data acquired from GPS and Galileo signals over Antarctica during the September 2017 storm by the ionospheric scintillation monitor receiver (ISMR) located in Concordia Station (75.10° S, 123.33° E). Different cases of diffraction and refraction effects are provided, showing the capability of the method in deriving a more accurate determination of the σ_ϕ index. We found values of cutoff frequency in the range of 0.73–0.83 Hz, providing further evidence of the inadequacy of the choice of 0.1 Hz, which is often used when dealing with ionospheric scintillation monitoring at high latitudes.

Keywords Ionospheric scintillation · Plasma drift velocity · Scintillation indices · Refractive and diffractive effects · Galileo and GPS signals · Data detrending

Introduction

Irregularities in ionospheric plasma density give rise to perturbations on Global Navigation Satellite System (GNSS) signals in space. Such irregularities are variations of the plasma density with respect to the ambient ionosphere that may vary on a large range of scale sizes: from centimeters up to a few hundreds of kilometers. The nature of the perturbation depends on the typical scale of the irregularities and on their dynamics. The threshold separating small from large-scale irregularities is given by the Fresnel scale that is of the order of a few hundreds of meters for L-band signals. Irregularities having scale sizes above the Fresnel scale cause a refractive effect of the trans-ionospheric signals, because of the variation of the refractive index of the ionosphere. Below the Fresnel scale, refractive and diffractive effects concur. The latter is because, when crossed by the plane-wave, small-scale irregularities act as a new wave source, resulting in an interference pattern when received at the ground (Wernik et al. 2003). Neglecting the effect of the ionospheric turbulence, the refractive effects can be considered deterministic in nature (Rino 2011, chapter 3). On the other hand, diffractive effects are stochastic (McCaffrey and Jayachandran 2019 and references therein). The following represents the ionospheric refractive contribution to the carrier phase equation:

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Ghobadi, H., Spogli, L., Alfonsi, L., Cesaroni, C., Cicone, A., Linty, N., ... & Cafaro, M. (2020). Disentangling ionospheric refraction and diffraction effects in GNSS raw phase through fast iterative filtering technique. *GPS Solutions*, *24*(3), 1-13.

Spogli, L., Ghobadi, H., Cicone, A., Alfonsi, L., Cesaroni, C., Linty, N., ... & Cafaro, M. (2021). Adaptive Phase Detrending for GNSS Scintillation Detection: A Case Study Over Antarctica. *IEEE Geoscience and Remote Sensing Letters*.

Adaptive Phase Detrending for GNSS Scintillation Detection: A Case Study Over Antarctica

Luca Spogli, Hossein Ghobadi, Antonio Cicone, Lucilla Alfonsi, Claudio Cesaroni, Nicola Linty, Vincenzo Romano, and Massimo Cafaro, *Senior Member, IEEE*

***Abstract*—We aim at contributing to the reliability of the phase scintillation index on Global Navigation Satellite System (GNSS) signals at high-latitude. To the scope, we leverage on a recently introduced detrending scheme based on the signal decomposition provided by the fast iterative filtering (FIF) technique. This detrending scheme has been demonstrated to enable a fine-tuning of the cutoff frequency for phase detrending used in the phase scintillation index definition. In a single case study based on Galileo data taken by a GNSS ionospheric scintillation monitor receiver (ISMR) in Concordia Station (Antarctica), we investigate how to step ahead of the cutoff frequency optimization. We show how the FIF-based detrending allows deriving adaptive cutoff frequencies, whose value changes minute-by-minute. They are found to range between 0.4 and 1.2 Hz. This allows better accounting for diffractive effects in phase scintillation index calculation and provides a GNSS-based estimation of the relative velocity between satellite and ionospheric irregularities.**

***Index Terms*—Galileo, Global Navigation Satellite Systems (GNSSs), ionosphere, ionospheric irregularities, iterative filtering, modal analysis, signal processing algorithm, transform.**

I. INTRODUCTION

THE reliability and accuracy of Global Navigation Satellite System (GNSS) signals in space are threatened by the presence of ionospheric irregularities. They are gradients of electron density embedded in the ambient ionosphere, having typical scale sizes ranging from centimeters up to a few hundreds of kilometers. When a planar wave crosses such irregularities, fluctuations of both amplitude and phase of the received signal at the ground may occur. The Fresnel's filtering mechanism (see [1]–[3]) defines the nature of such fluctuations. Such mechanism makes the Fresnel's scale, being of the order of a few hundred meters for GNSS signals, the fine line between irregularities driving purely refractive fluctuations and those triggering mostly diffractive fluctuations. Specifically, above Fresnel's scale the variation of the refractive index of the ionosphere results in refraction. In this frequency range, the stochastic component of ionospheric effects driven by large-scale and medium-scale structures can be efficiently monitored by using the rate of total electron content (TEC) change index (ROTI), as recently demonstrated by Rino *et al.* [4]. Conversely, below the Fresnel's scale, both diffractive and refractive effects occur. Diffraction is due to the fact that small-scale irregularities behave like wave sources [5], resulting in stochastic fluctuations of the received signal at the ground [1].

Currently, an unambiguous definition of phase scintillation is still missing. In [4], phase scintillation is defined as the "residual after extraction of structure that followed the TEC $1/f_c$ frequency dependence." This definition does not make direct use of the standard deviation of the detrended phase of the received signal, as historically introduced by early works on scintillation and routinely monitored through σ_Φ index by ionospheric scintillation monitor receivers (ISMRs) (see [6], [8]). Because of the need of a phase detrending, the use of σ_Φ implicitly requires a definition of the phase scintillation based on the frequency content, while the definition by Rino *et al.* [4] leverages on the frequency dependence. It is out of the scope of this letter to revise and compare the two definitions, even if some considerations are provided in the conclusions section. Bearing this in mind, we adopt the definition based on the frequency content and we base this work on some recent literature (see [9]–[11]), which tends to call "ionospheric scintillation" only those phase and amplitude fluctuations due to small-scale irregularities. Those are the most challenging threats to GNSS-based positioning services (see [12], [13]). The scintillation is usually quantified through the amplitude and phase scintillation indices, termed S_4 and σ_Φ, respectively [14]. The former is the standard deviation of the normalized signal intensity, while the latter has been defined above.

This work is framed into the recent efforts made by the community to find a proper detrending scheme aimed at serving both science and application. In this context, we aim

Manuscript received September 15, 2020; revised December 14, 2020 and March 1, 2021; accepted March 17, 2021. This work was supported by the TREASURE, a project funded by the European Union's Horizon 2020 Research and Innovation Program through the Marie Skłodowska-Curie Actions under Grant 722023 (http://ww.treasure-gnss.eu). The work of Antonio Cicone was supported by the Italian Space Agency under Contract ASI "LIMADOU scienza" n 2016-16-H0. *(Corresponding author: Luca Spogli.)*

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Color versions of one or more figures in this letter are available at https://doi.org/10.1109/LGRS.2021.3067727.

Digital Object Identifier 10.1109/LGRS.2021.3067727

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Recent advances in ionospheric scintillation on Global Navigation Satellite System signals

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Acknowledgments: Lucilla Alfonsi, Giorgiana De Franceschi, Claudio Cesaroni, Vincenzo Romano, Antonio Cicone, Hossein Ghobadi, Nicola Linty, Massimo Cafaro, Charles Rino, P.T. Jayachandran

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