

A Long-Term LOFAR Survey of Ionospheric Morphology and Dynamics

Rebecca Ghidoni⁽¹⁾, Luca Spogli^(1,2), Maaijke Mevius^(3,4)
and Claudio Cesaroni⁽¹⁾

(1) Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy

e-mail: rebecca.ghidoni@ingv.it

(2) SpacEarth Technology, Rome, Italy

(3) ASTRON - The Netherlands Institute for Radio Astronomy, Dwingeloo, The Netherlands

(4) Kapteyn Astronomical Institute, University of Groningen, P.O. Box 800, 9700 AV Groningen, The Netherlands

11 June 2026

What is the ionosphere?

What is the ionosphere?

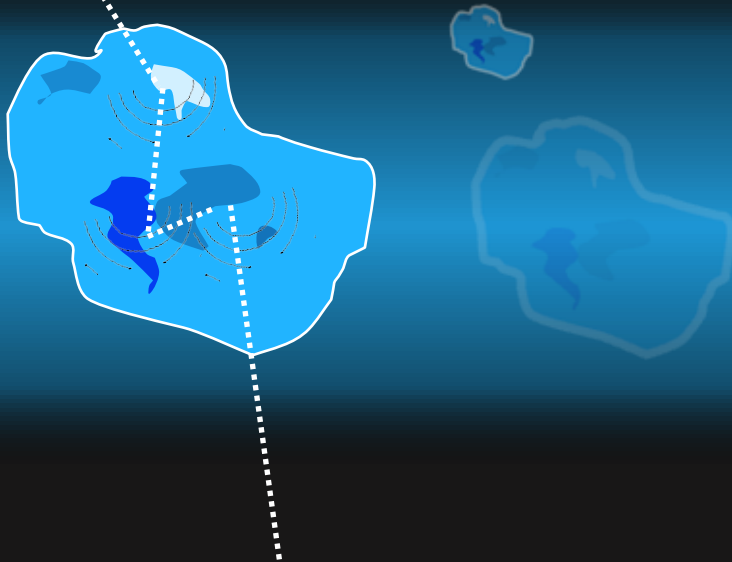
Astronomer's Nightmare



1000 km

350 km

50 km



What is the ionosphere?



1000 km

350 km

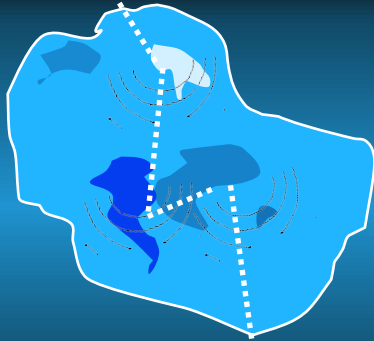
50 km



Astronomer's
Nightmare

Space Weather
Scientist's True
Love

The approach



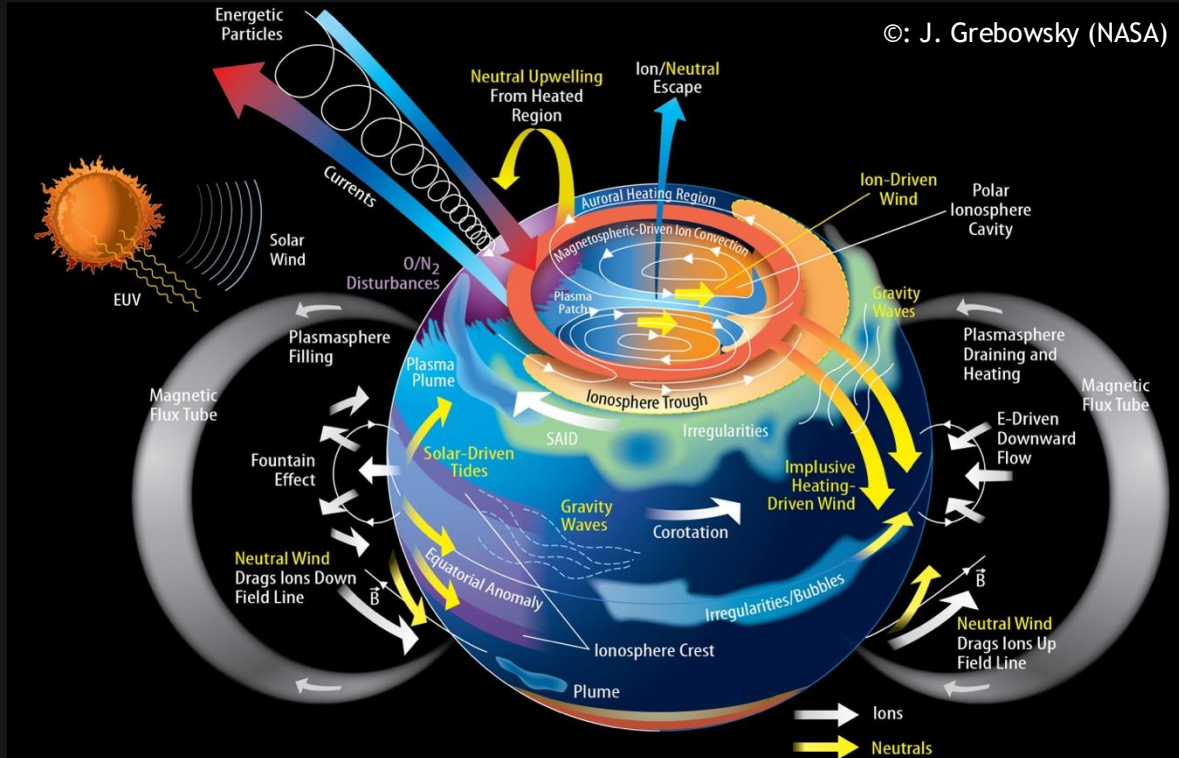
Exploit the LOFAR radiotelescope
as an ionospheric probe



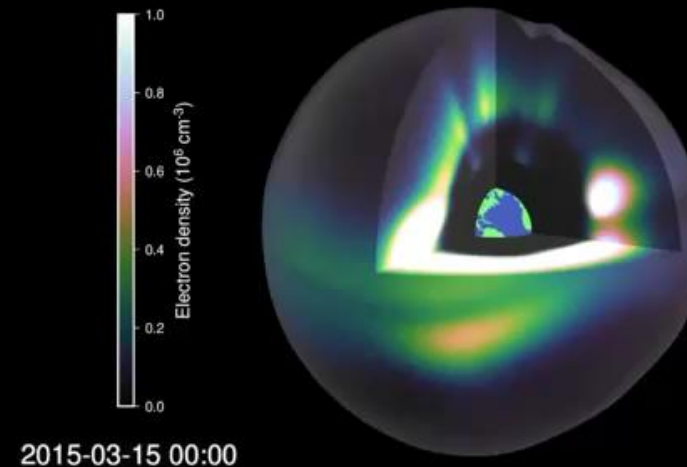
Analise features of the ionosphere
irregular behaviour that can be
investigated solely thanks to the
LOFAR characteristics
(Dense Core Stations + Low
Frequency)

The ionosphere

It is a turbulent, dispersive plasma and it is influenced by numerous external forces from above and below

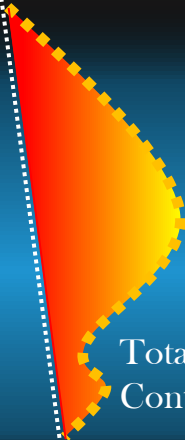
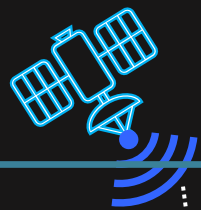


2015 St. Patrick's day geomagnetic storm



©: Eelco Doornbos (KNMI)

Probe the ionosphere



Total Electron
Content (TEC)

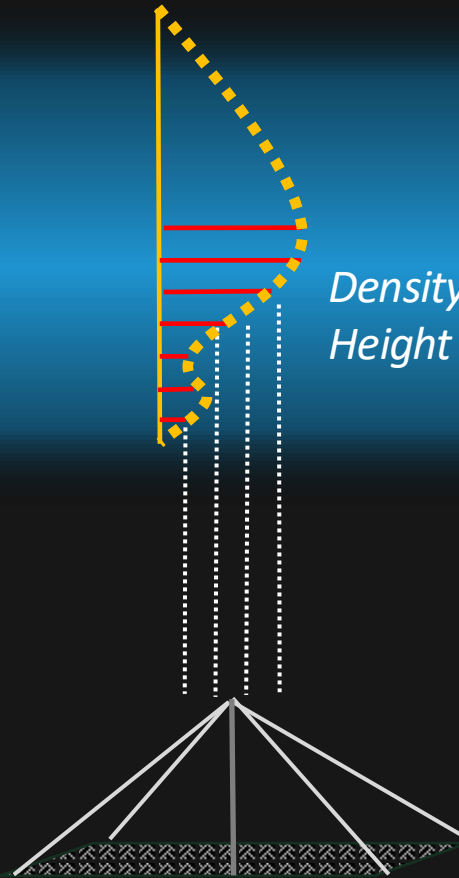


GNSS receivers

Probe the ionosphere

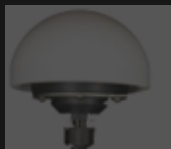


GNSS receivers

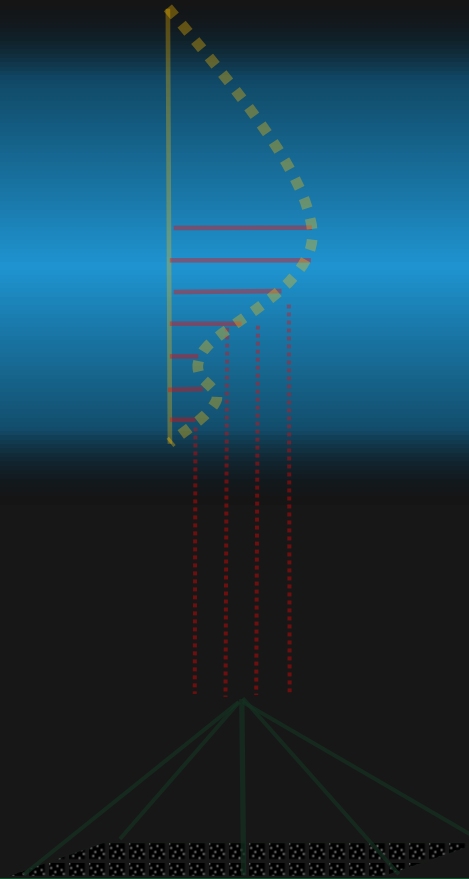


Ionosonde

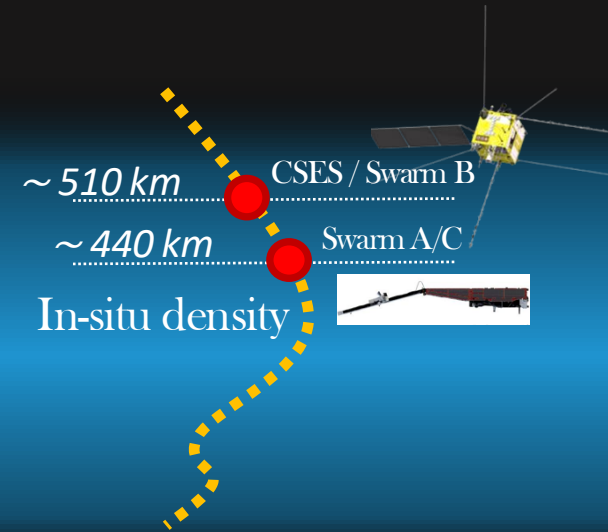
Probe the ionosphere



GNSS receivers



Ionosonde

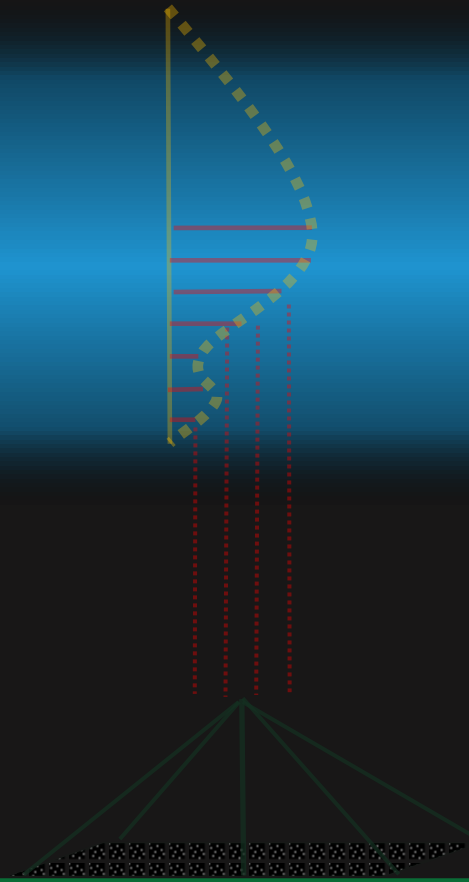


In-situ satellites

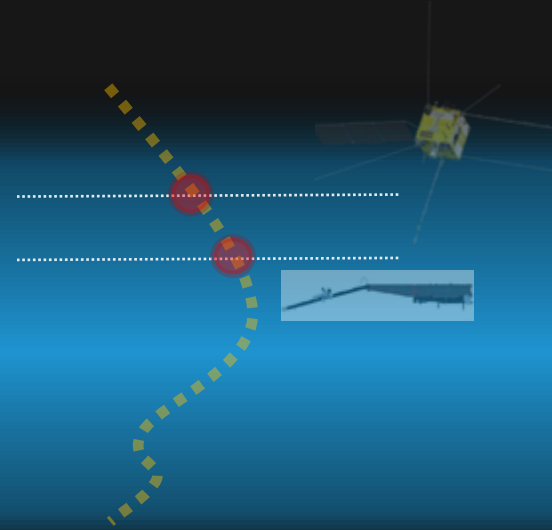
Probe the ionosphere



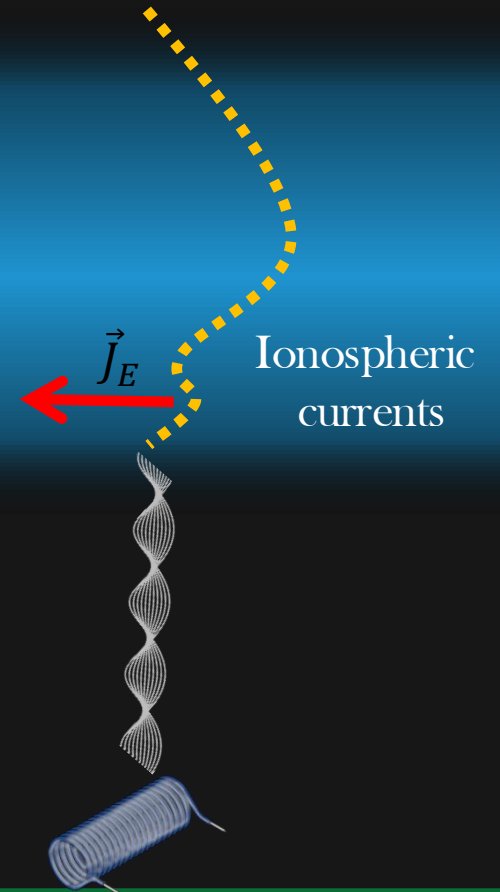
GNSS receivers



Ionosonde



In-situ satellites



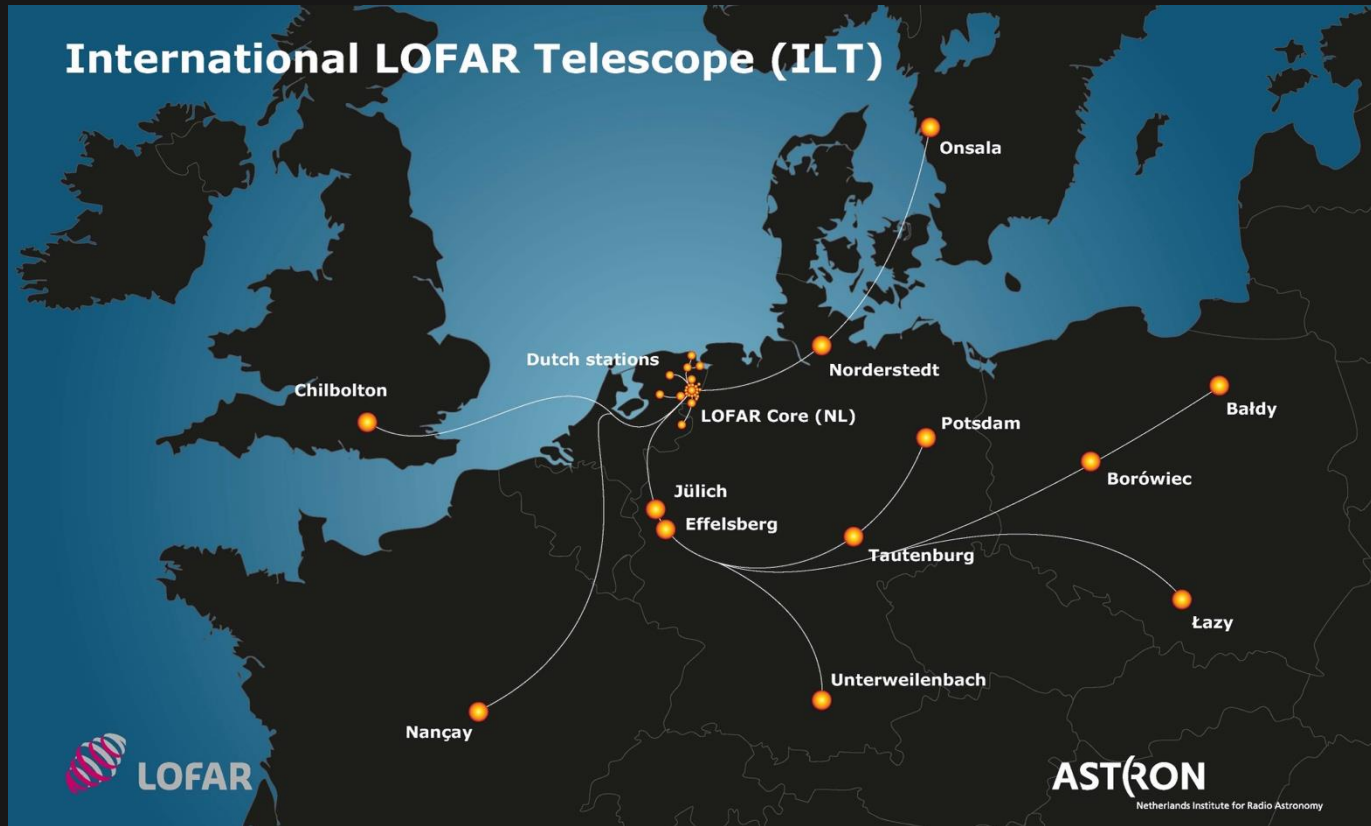
Magnetometer

A new prospective:

NO PRESENTATION NEEDED...

A new perspective: LOFAR

NO PRESENTATION NEEDED...



Radio telescope network

High Band Antenna (HBA)



110-240 MHz

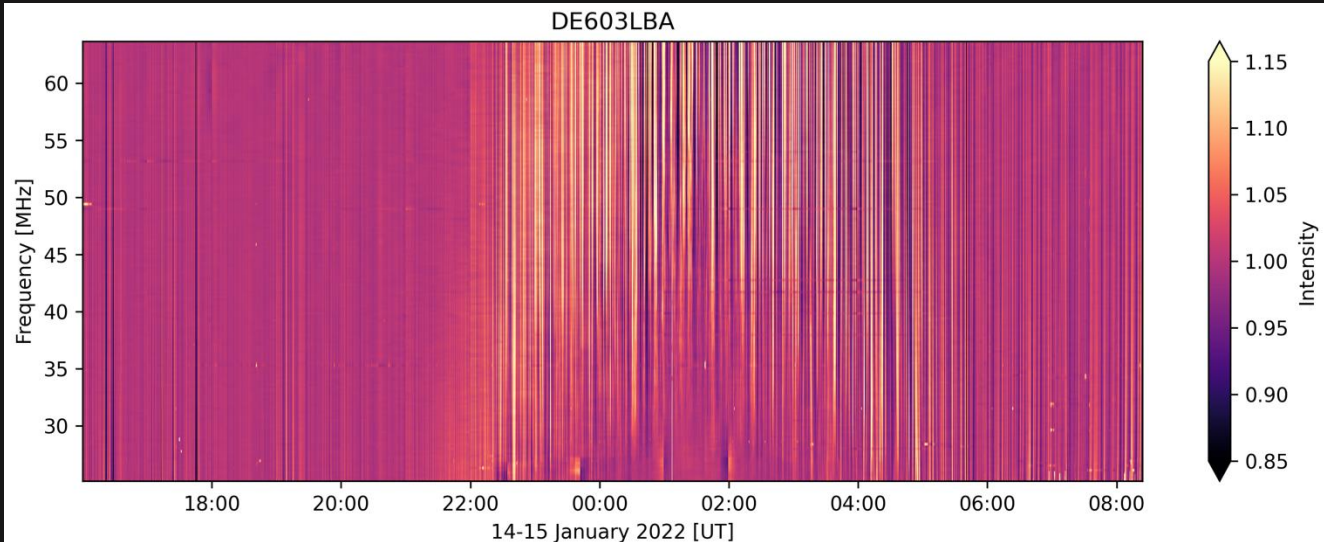
Low Band Antenna (LBA)



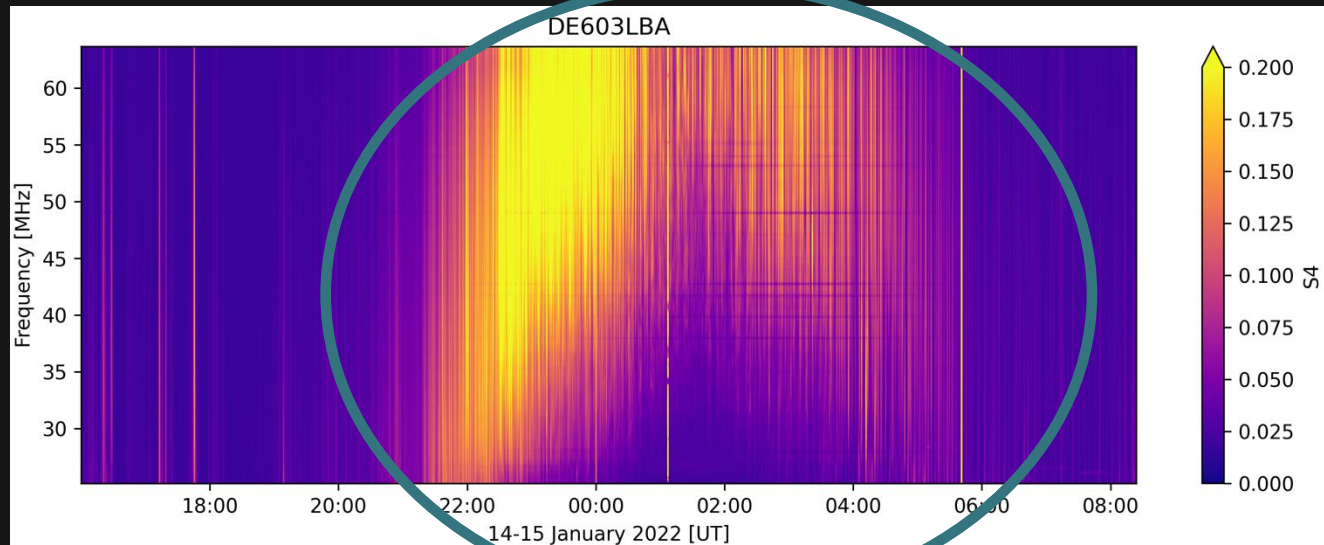
10-90 MHz

LOFAR: A new prospective

1s and 0.195 MHz



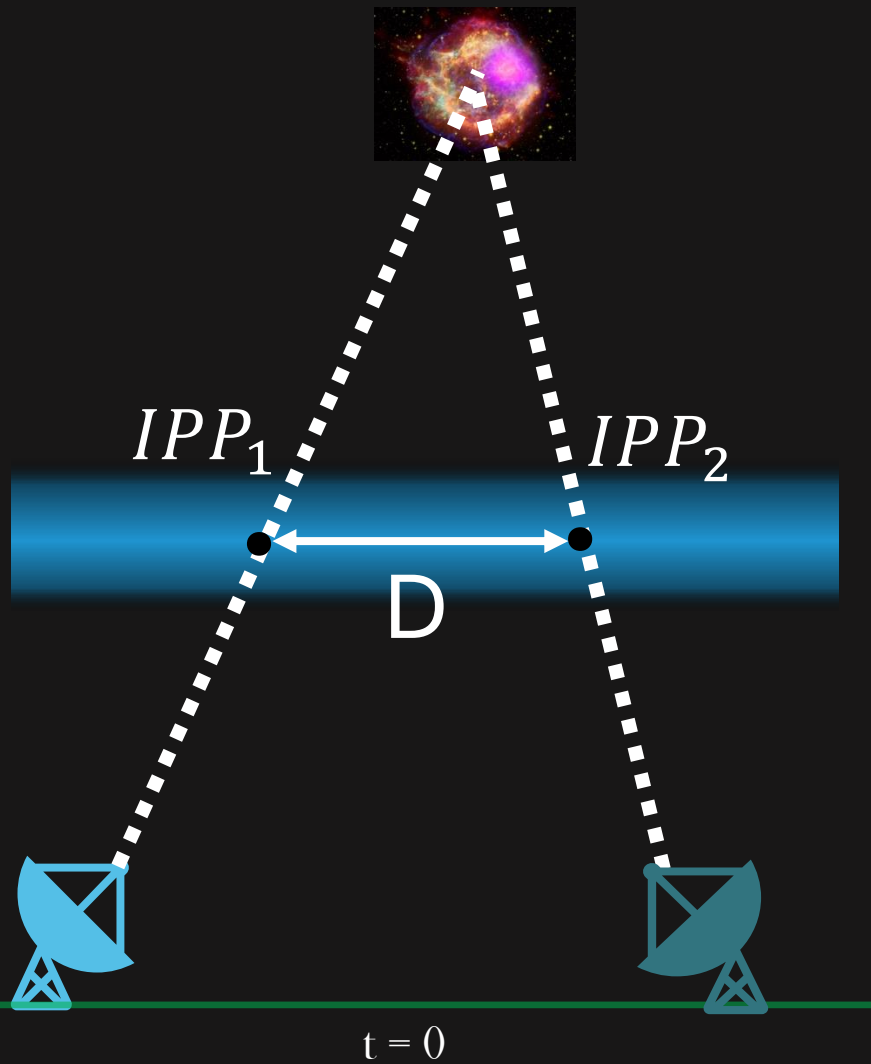
The ionosphere introduces a
DIFFRACTION EFFECT



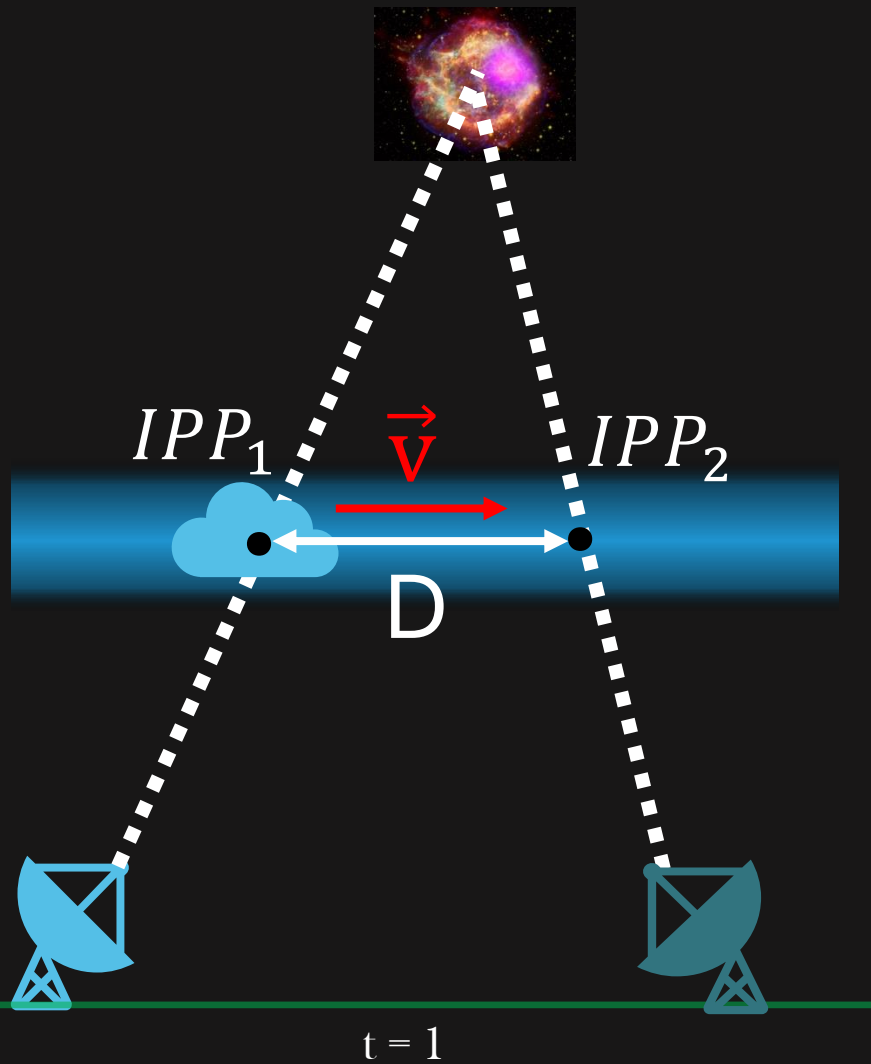
Signal amplitude scintillation index S_4

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

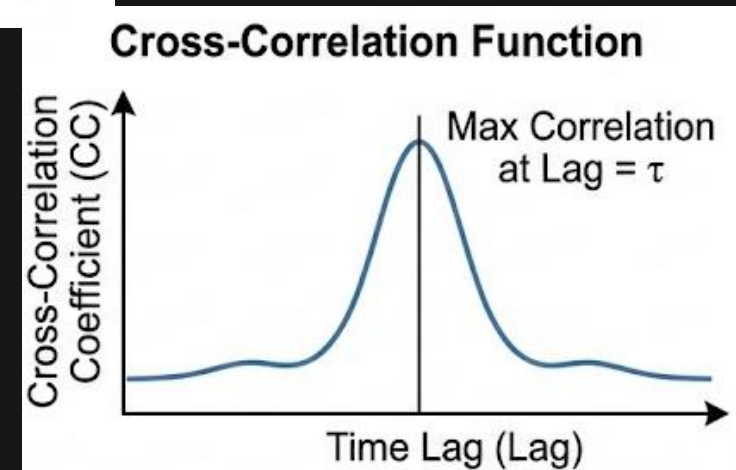
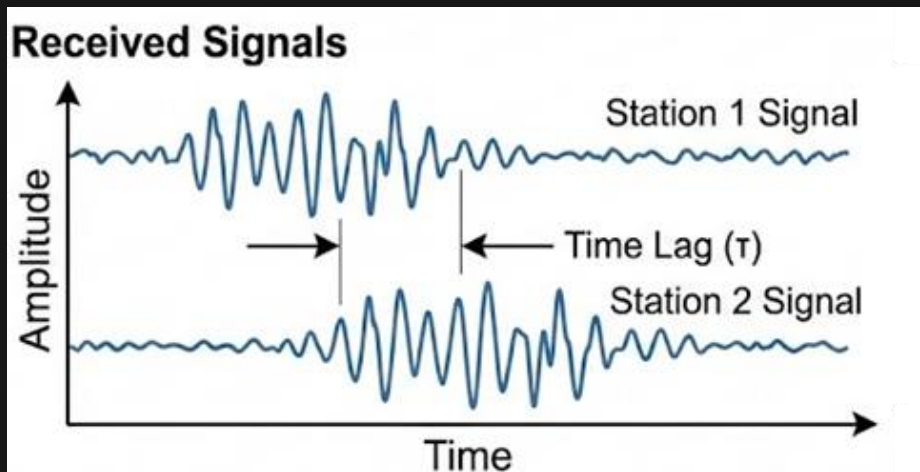
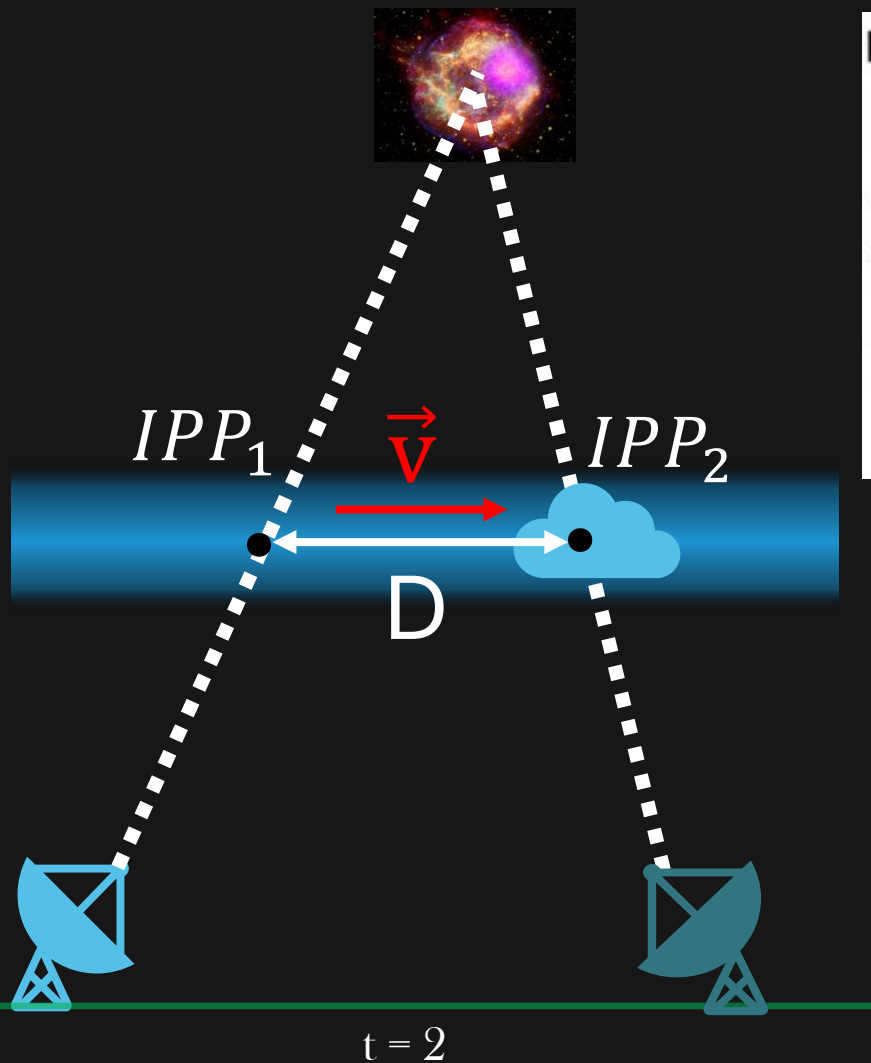
Cross-correlation Algorithm



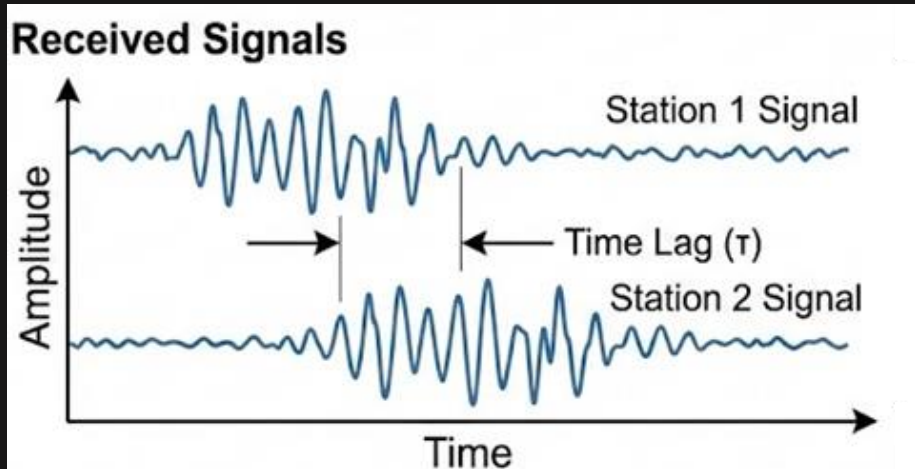
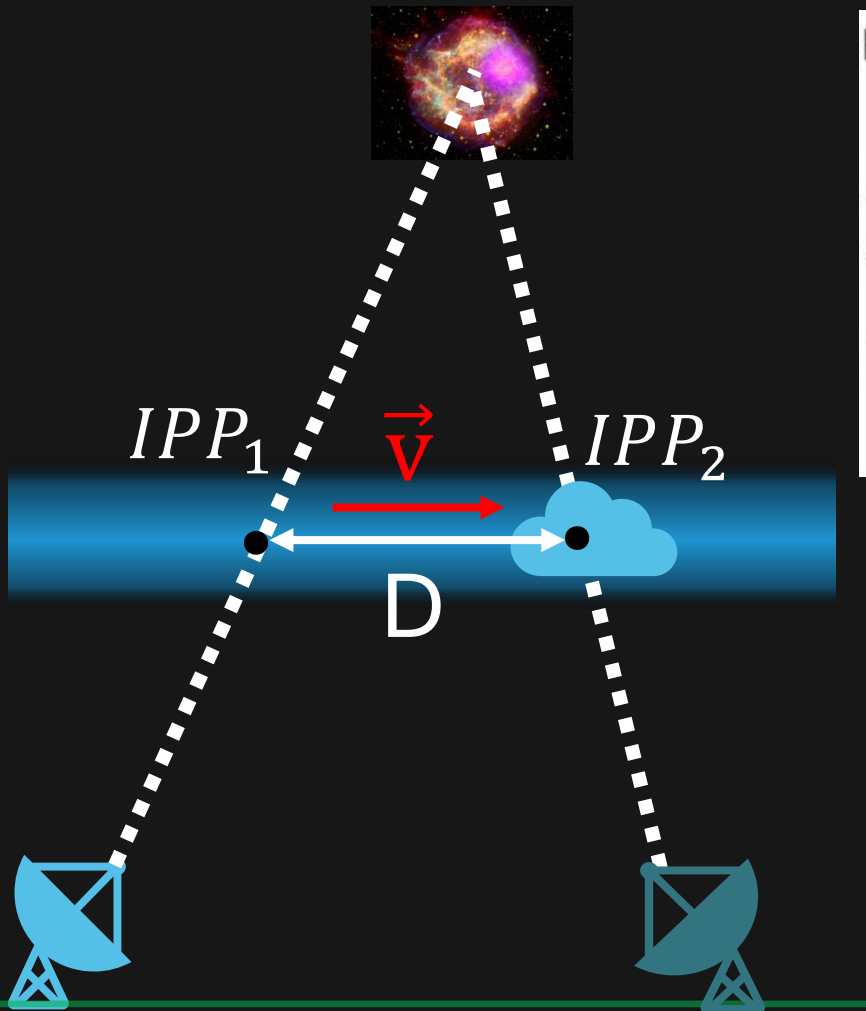
Cross-correlation Algorithm



Cross-correlation Algorithm

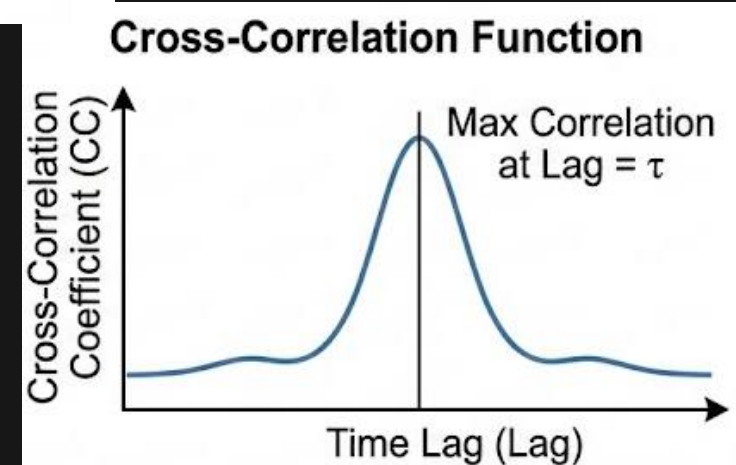


Cross-correlation Algorithm



$$\mathbf{V} = \frac{\mathbf{B}^\dagger \mathbf{T}}{||\mathbf{B}^\dagger \mathbf{T}||^2}$$

$\mathbf{B}$: Matrix of LOFAR baselines
 $\mathbf{T}$: Vector of time lags between signals at each antenna pair



The results

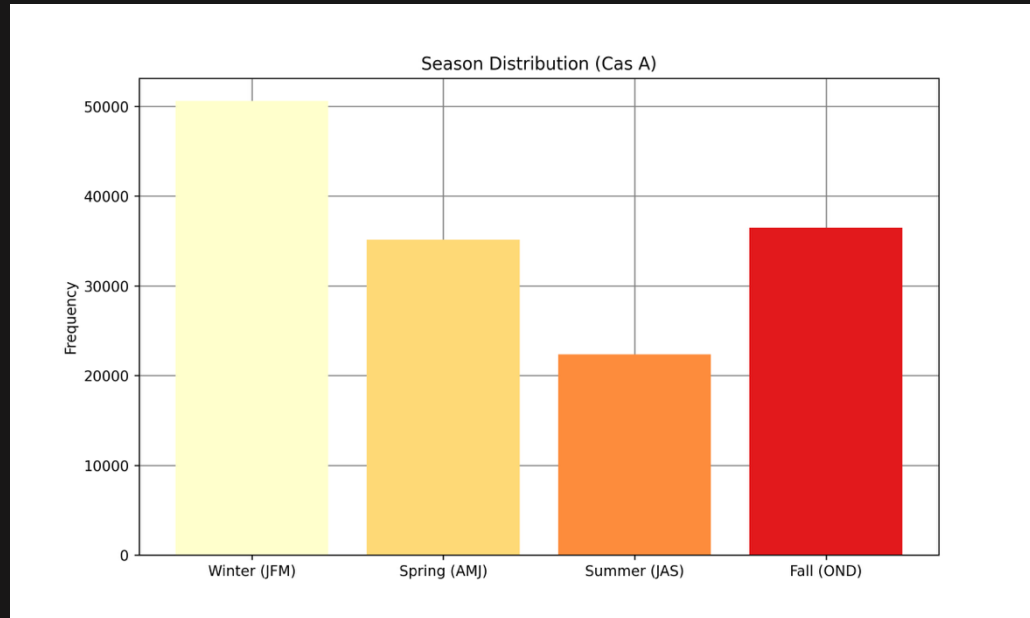
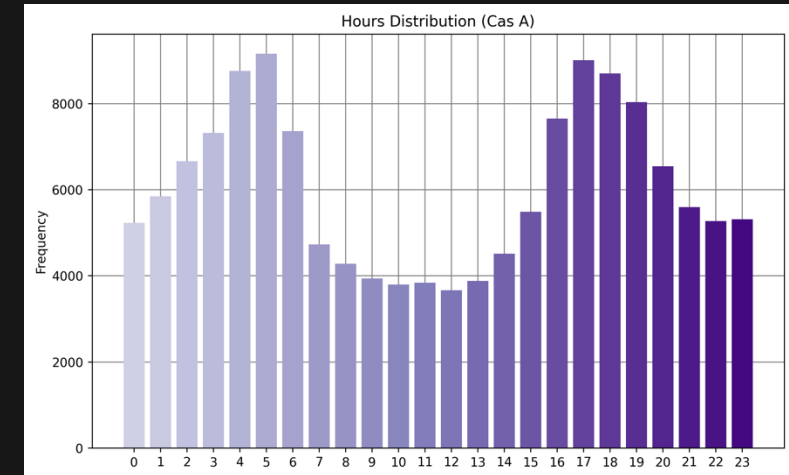
Statistical Analysis

Type of data: Velocity measurements

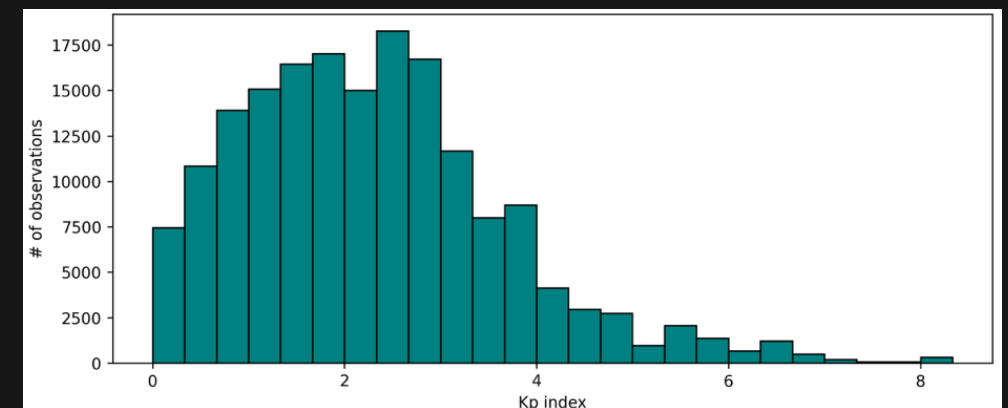
Period: Between 28/6/2014 and 24/7/2016

Data availability: ≈ 2410 hours of Cas A

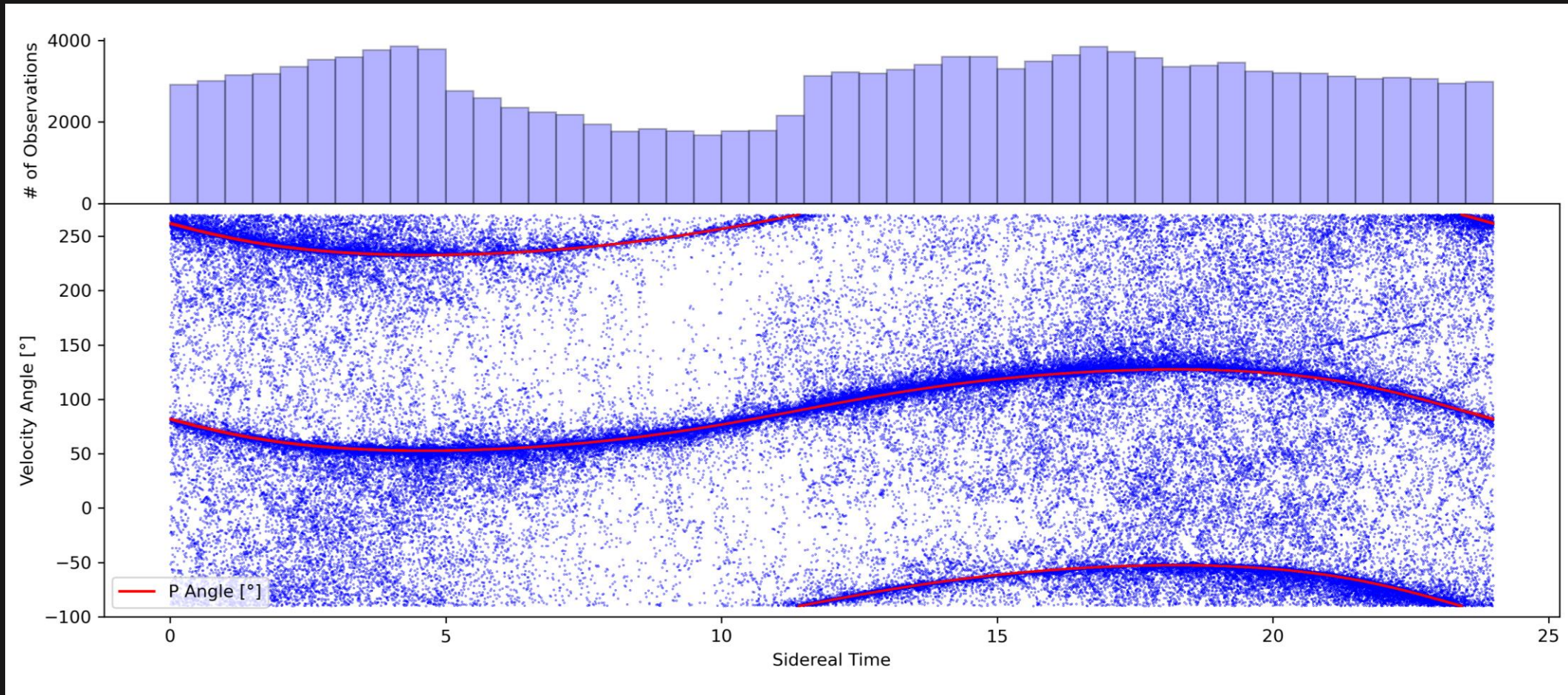
Resolution: 1 minute



We have analysed the angular distribution of the velocities reconstructed by the LOFAR core stations

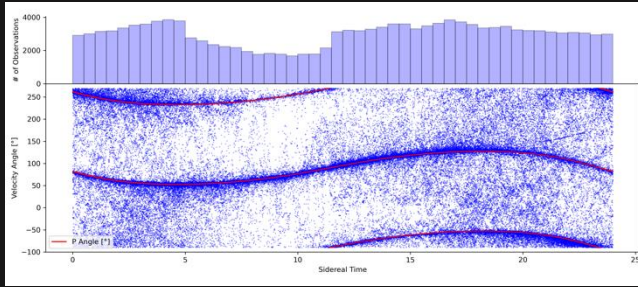


Statistical Analysis



Distribution of the direction of the velocities reconstructed by the intensity data of the LOFAR core stations

Statistical Analysis

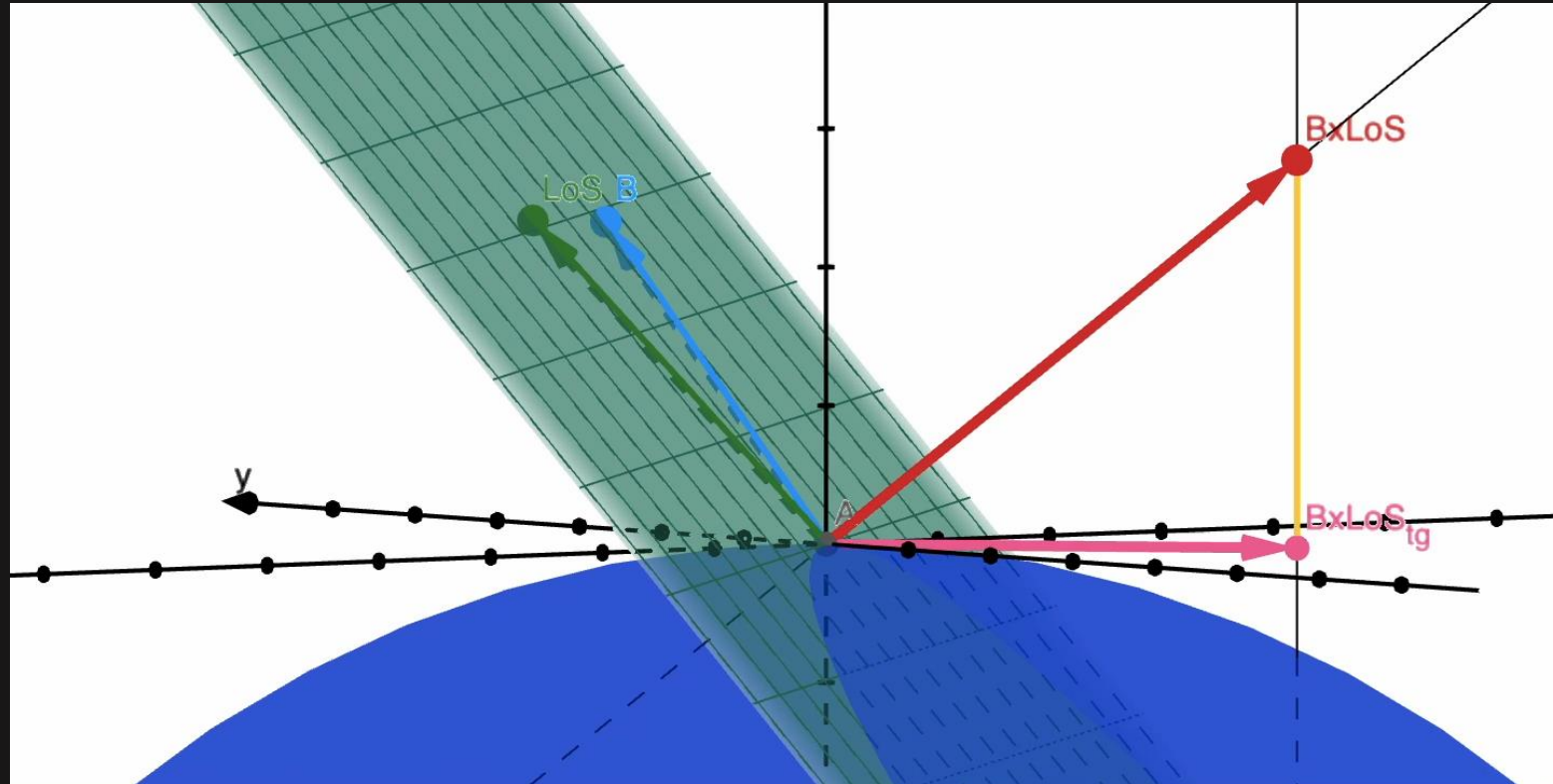


Most of the velocities are aligned with the vector perpendicular to both the LOFAR line of sight and to the magnetic field line:

$$\overrightarrow{B \times LOS} = \overrightarrow{B} \times \overrightarrow{LOS}$$

$\overrightarrow{B}$ = Magnetic field

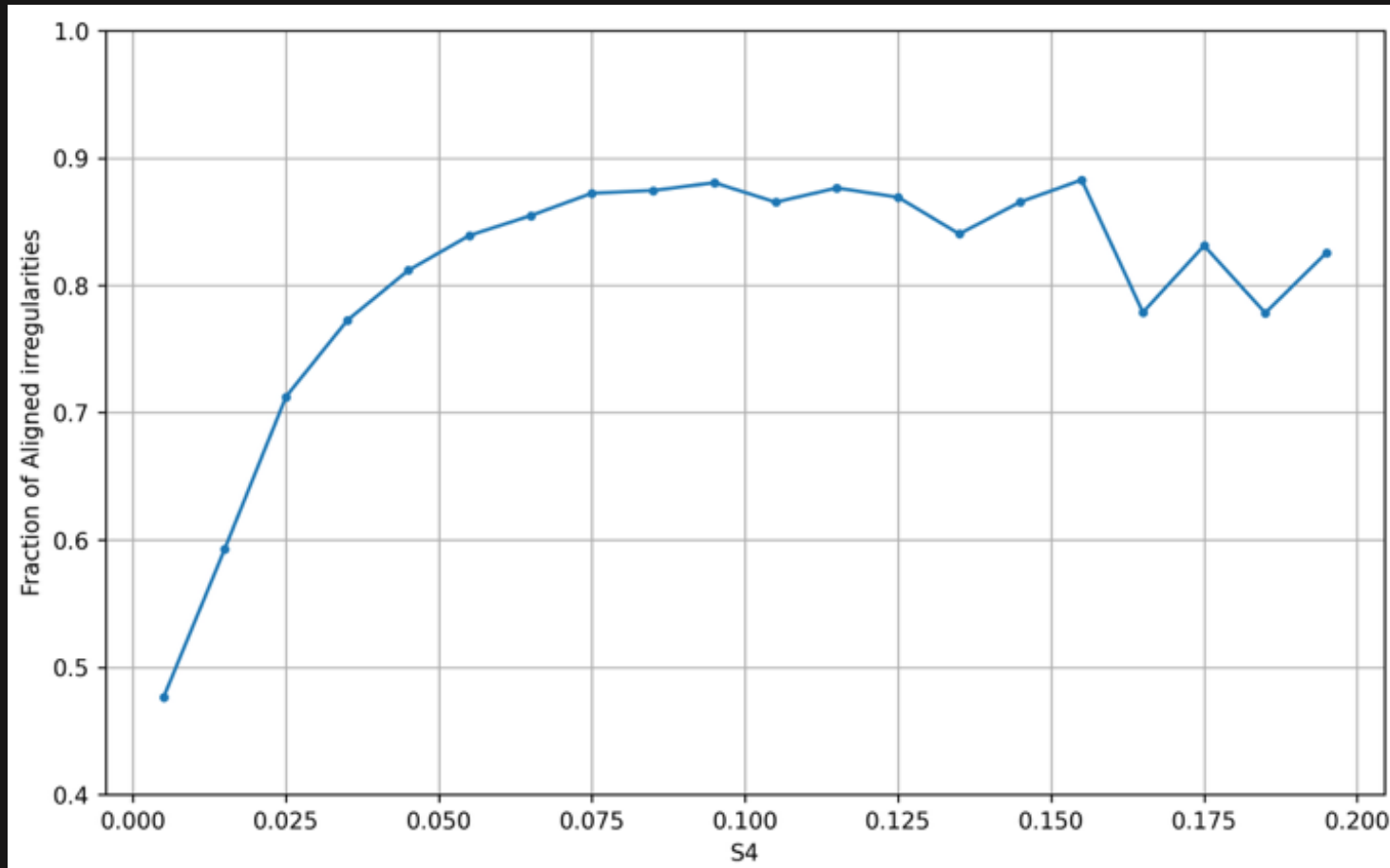
$\overrightarrow{LOS}$ = Line of Sight



Due to geometrical reasons the algorithm however reconstruct only the component of the velocity in the plane tangent to the ionospheric thin layer defined by $B \times LoS_{tg}$

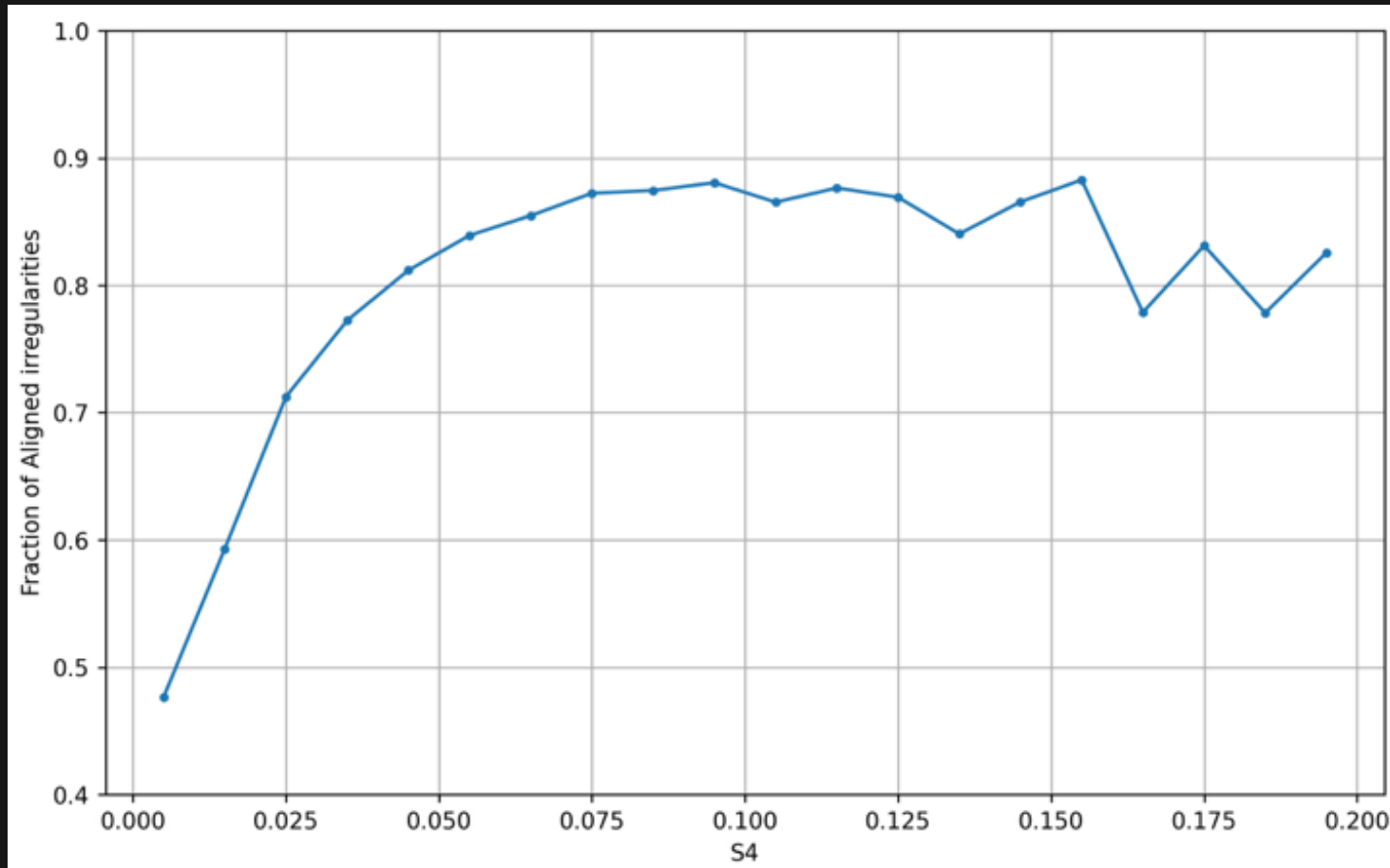
The expected result

The larger the S4, the better the alignment



The expected result

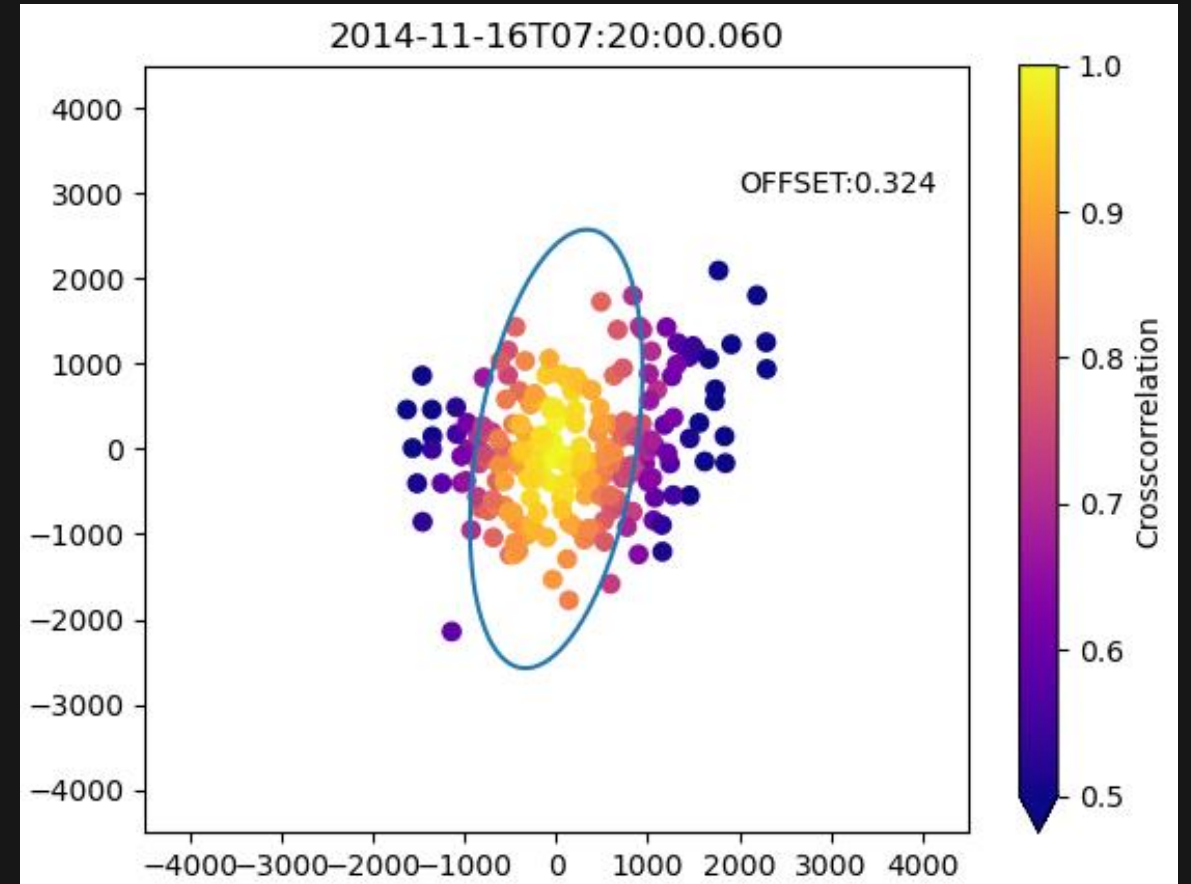
The larger the S4, the better the alignment



Due to the properties of the cross-correlations algorithm that needs higher variations in the signals to perform better

The unexpected result

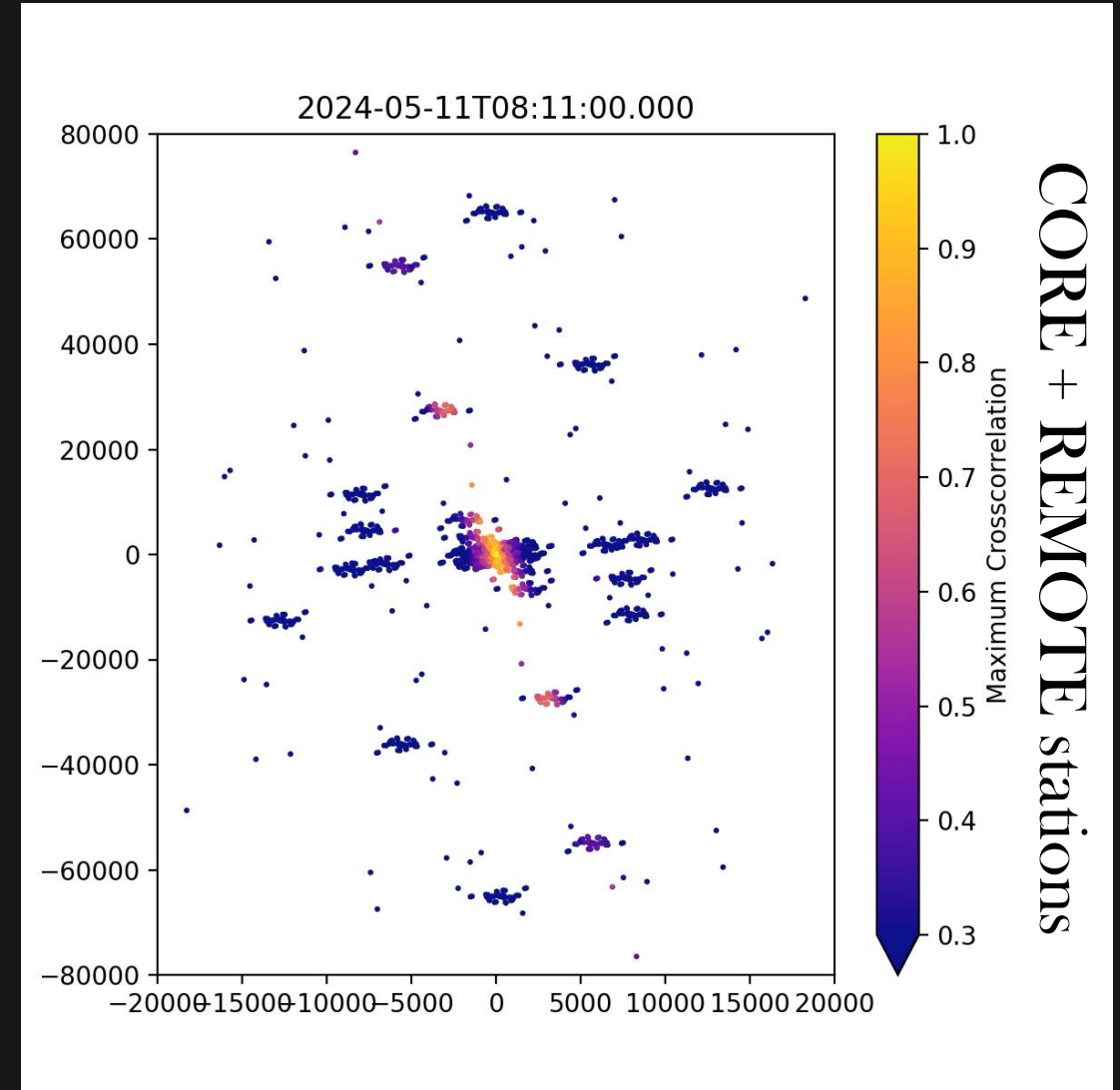
From crosscorrelation is also possible to get the shape of the irregularities and not only the velocity.



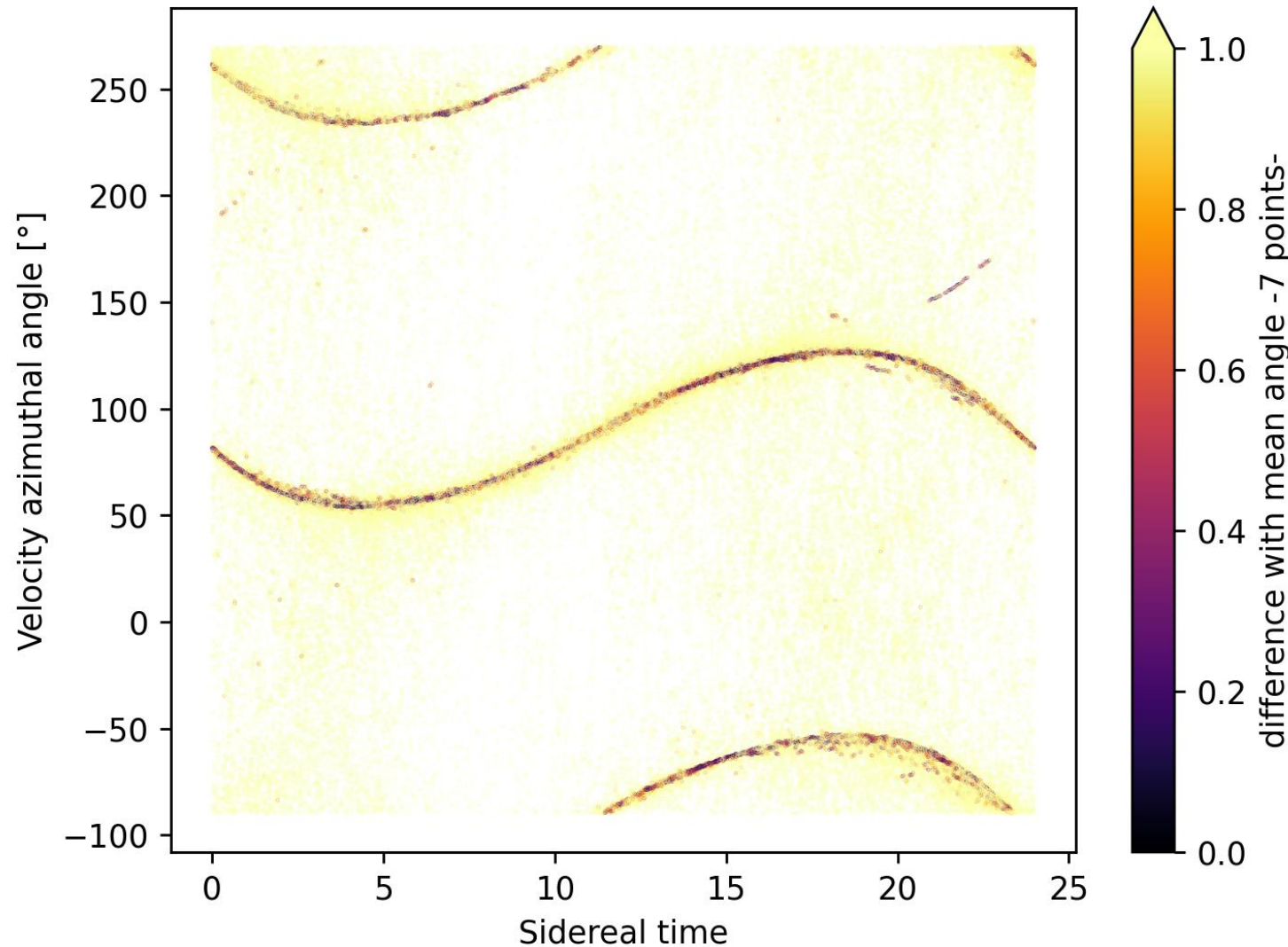
The unexpected result

From crosscorrelation is also possible to get the shape of the irregularities and not only the velocity.

With LOFAR we can observe extremely elongated structures (captured by Remote and Core stations)



The new main result



The velocity angle shift is coherent ($<1^\circ$ in 7 min) in time only for irregularities aligned with the magnetic field.

This means that the other velocities are due to limitations of the algorithm or to structures with a short life span.

It is now possible to better categorise the irregularities seen by LOFAR

Take home message

Main results:

Geometric Bounds

Due to tracking constraints, the correlation algorithm selectively resolves motion in the plane tangent to the ionosphere

S4 Correlation

This directional alignment becomes increasingly pronounced during high S4 scintillation events, confirming a physical wave-front connection

$\mathbf{B} \times \mathbf{LoS}$ Alignment

The reconstructed velocities are strongly aligned perpendicular to both the local magnetic field and the line-of-sight

Future developments:

- Incorporate data from geomagnetic storms
- Leveraging LOFAR 2.0 increased capabilities (i.e. LBA+ HBA observations)
- Combining LOFAR's measurements with dual-frequency GNSS receivers

A Long-Term LOFAR Survey of Ionospheric Morphology and Dynamics

Rebecca Ghidoni, Luca Spogli, Maaijke Mevius and Claudio Cesaroni

Email: rebecca.ghidoni@ingv.it

Any Question?

Additional Material

Cross-correlation Algorithm

Input: Normalized power measurements from each LOFAR Core Station antenna at a specific frequency

Methodology:

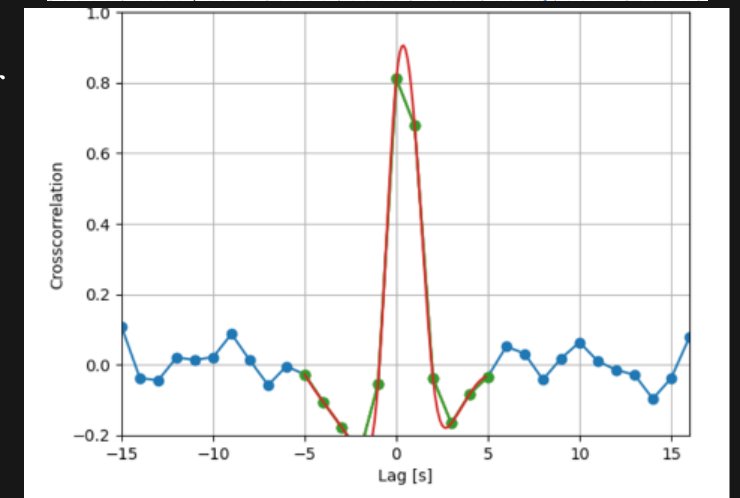
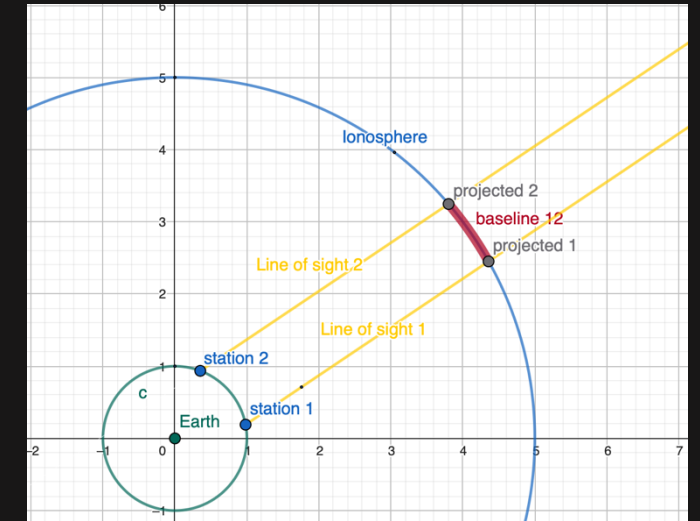
1. Analyzes signals from each baseline B (pair of core stations) projected at a specific altitude.
2. Uses Fast Fourier Transform (FFT) convolutions on six-minute windows for the first station and a one-minute window for the second, performed every 30 seconds.
3. Cubic spline interpolation is applied to the peak cross-correlation values for more precise lag estimates T .

$$v_{SC} = \frac{B^{\dagger}T}{||B^{\dagger}T||^2}$$

B : Matrix of LOFAR baselines
 T : Vector of time lags between signals at each antenna pair

From Fallows et al., 2020

Scheme of baseline construction algorithm



Example of time Lag estimation

Output: Provides a velocity vector in the plane connecting the Ionospheric Pierce Points (IPPs).

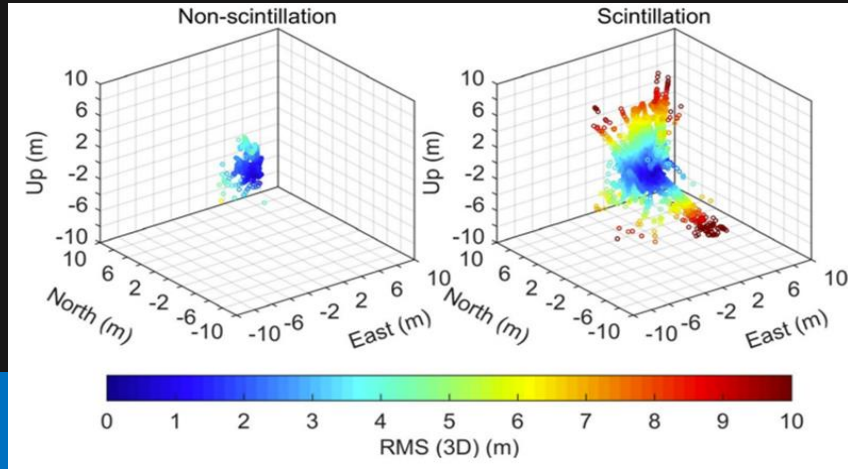
The effects of ionospheric irregularities on systems

(A simplified picture)

The effects of ionospheric irregularities still poses a challenge for modelling and mitigations for various application

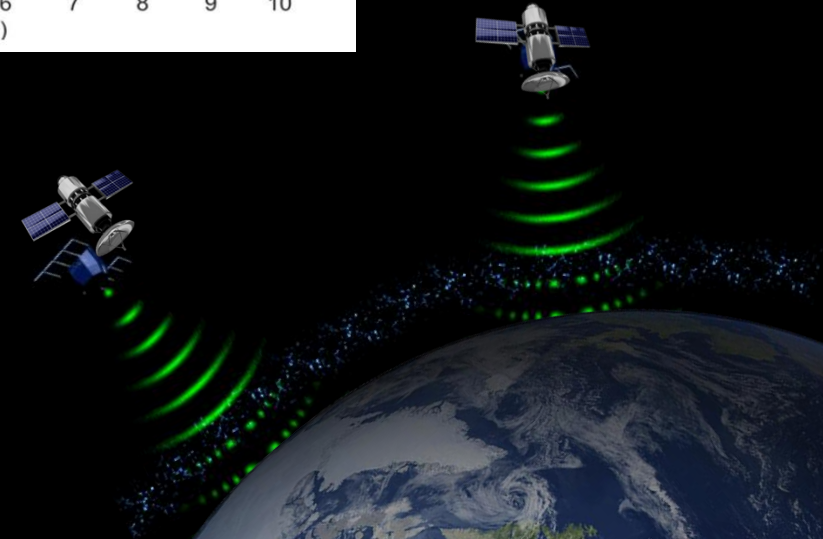
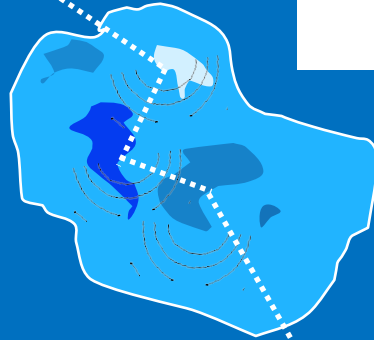
Luo et al. (2018). GPS solutions, 22(3)

The GNSS case as a societal challenge:

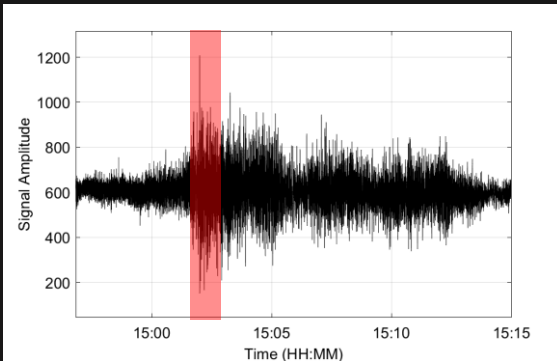


1000 km

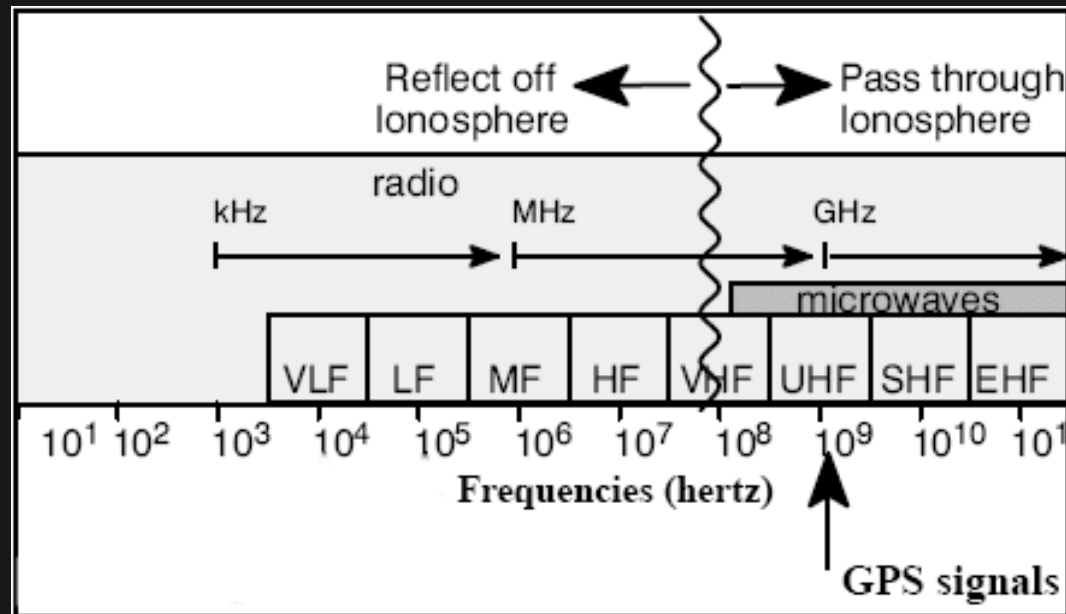
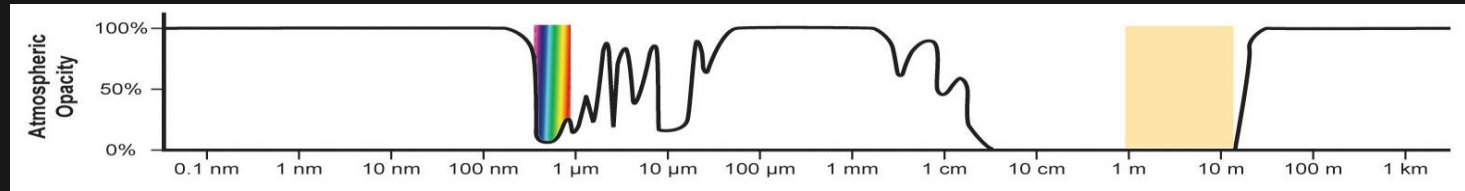
Ionosphere



50 km



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 (by working frequencies spanning from kHz to GHz range).

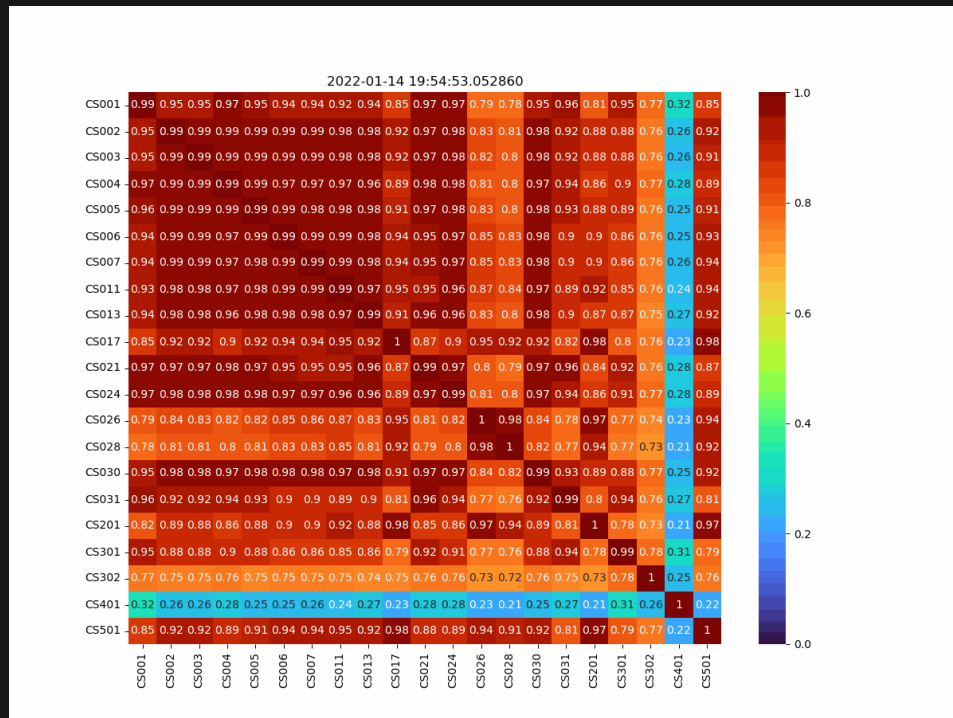


VHF, HF radars and receivers (ground- or space-based) provide several information on plasma structuring and variability but the devices are sparse and offer poor coverage (in time and space)

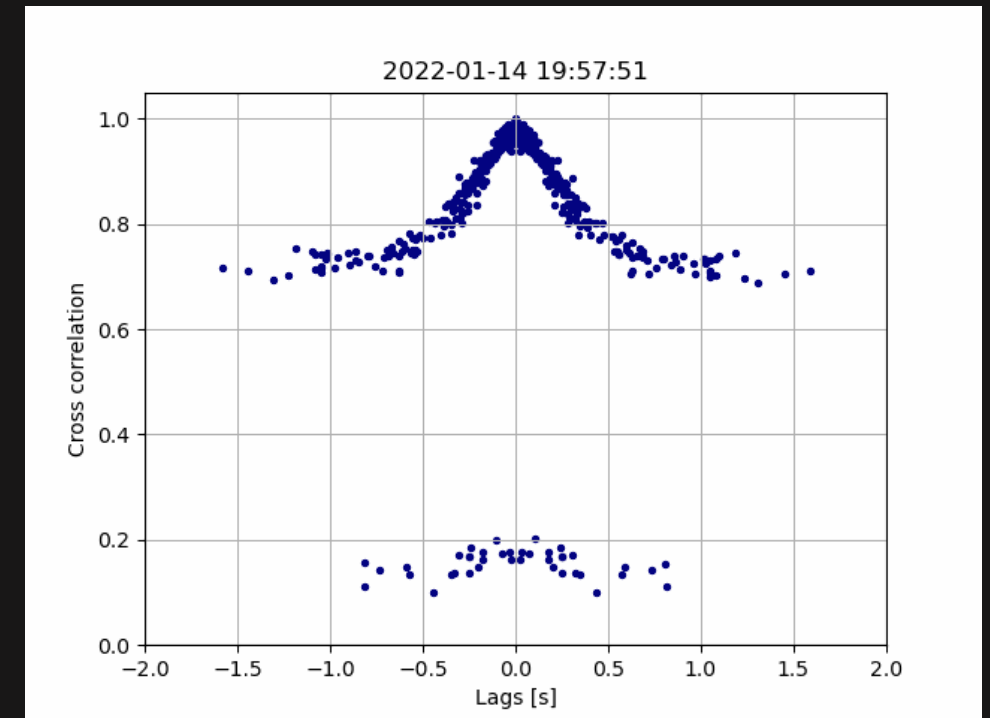
L-band (eg. GNSS) is a very powerful diagnostic tool but often does not provide a complete picture in time and space

ERROR ON THE VELOCITY: Mean crosscorrelation between all stations

Every minute, for every couple of stations, we get a time lag and a crosscorrelation coefficient



Crosscorrelation heat map.
Nearest stations have better correlation



Relation between Cross correlation and lags.
We can observe the nodes ad full seconds