Ionospheric irregularities in LOFAR and GNSS observations

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Context

The radio wave scintillation mechanism

LOFAR scintillation observations

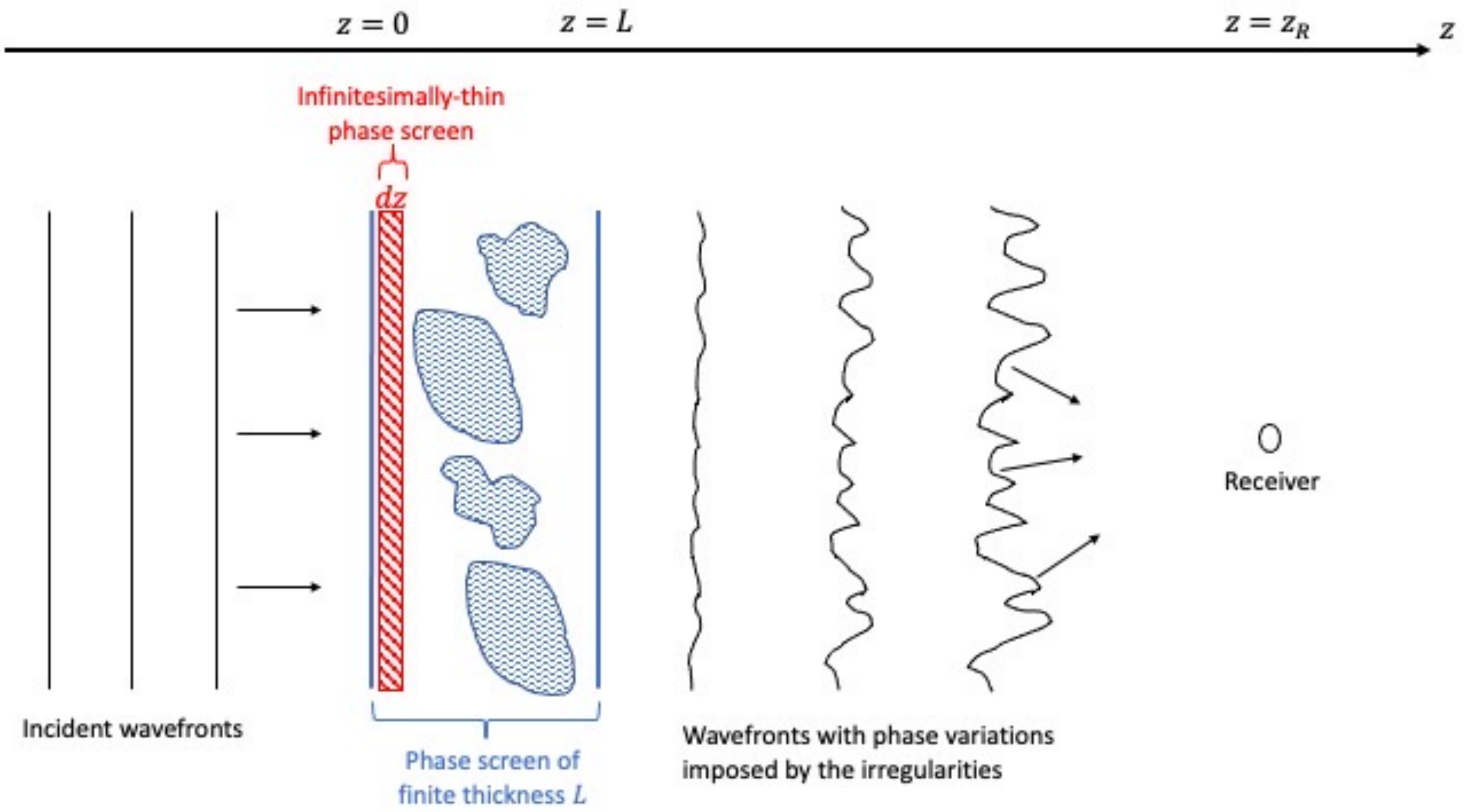
Examples of LOFAR and GNSS observations

Conclusions

Ionospheric irregularities

- Irregularities can form in the ionosphere due to instability mechanisms.
- Radio wave scintillation originated by irregularities can be used to infer the state of the ionosphere and its response to various space weather conditions.
- Use of LOFAR to detect scintillation on VHF radio wave frequencies, thus informing on ionospheric irregularities forming over different spatial scales.
- How do LOFAR VHF scintillation observations compare with traditional ionospheric observations (e.g., GNSS)?

The radio wave scintillation mechanism



Credit: Forte et al., ApJS, 2022

LOFAR scintillation observations

Zero-mean normalised intensity fluctuations $I_f(t)$

$$I_f(t) = \frac{I(x_R, y_R, z_R, \omega, t)}{\langle I(x_R, y_R, z_R, \omega, t)\rangle} - \left\langle \frac{I(x_R, y_R, z_R, \omega, t)}{\langle I(x_R, y_R, z_R, \omega, t)\rangle} \right\rangle = \frac{I(x_R, y_R, z_R, \omega, t)}{\langle I(x_R, y_R, z_R, \omega, t)\rangle} - 1$$

Proportional to the log-amplitude (Rytov solution) under weak scattering approximation

Scintillation index:

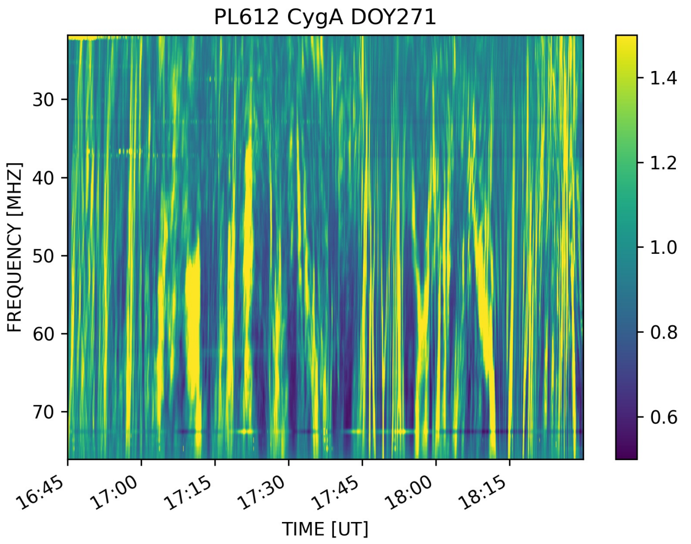
$$S_4 = \sqrt{\frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2}}$$

where

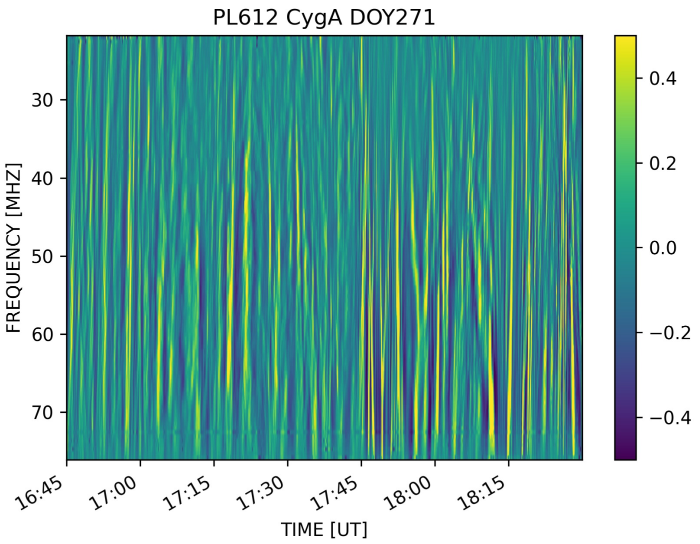
I radio-wave intensity

$\langle \quad \rangle$ temporal averaging in lieu of ensemble averaging

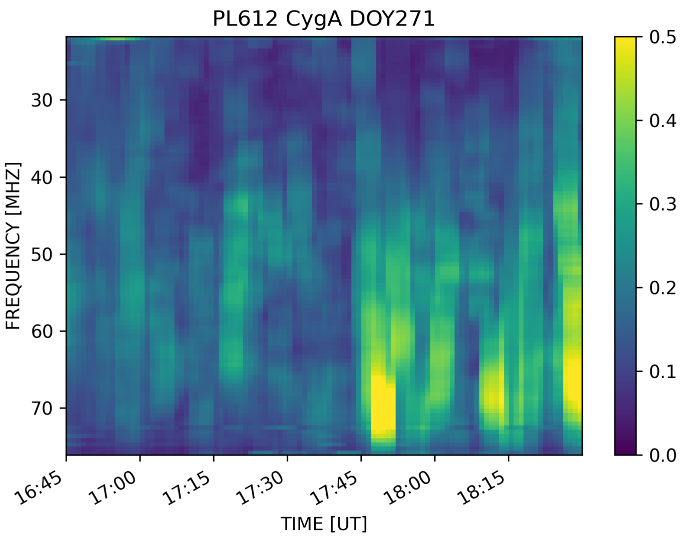
Raw intensity observations



Zero-mean, detrended intensity



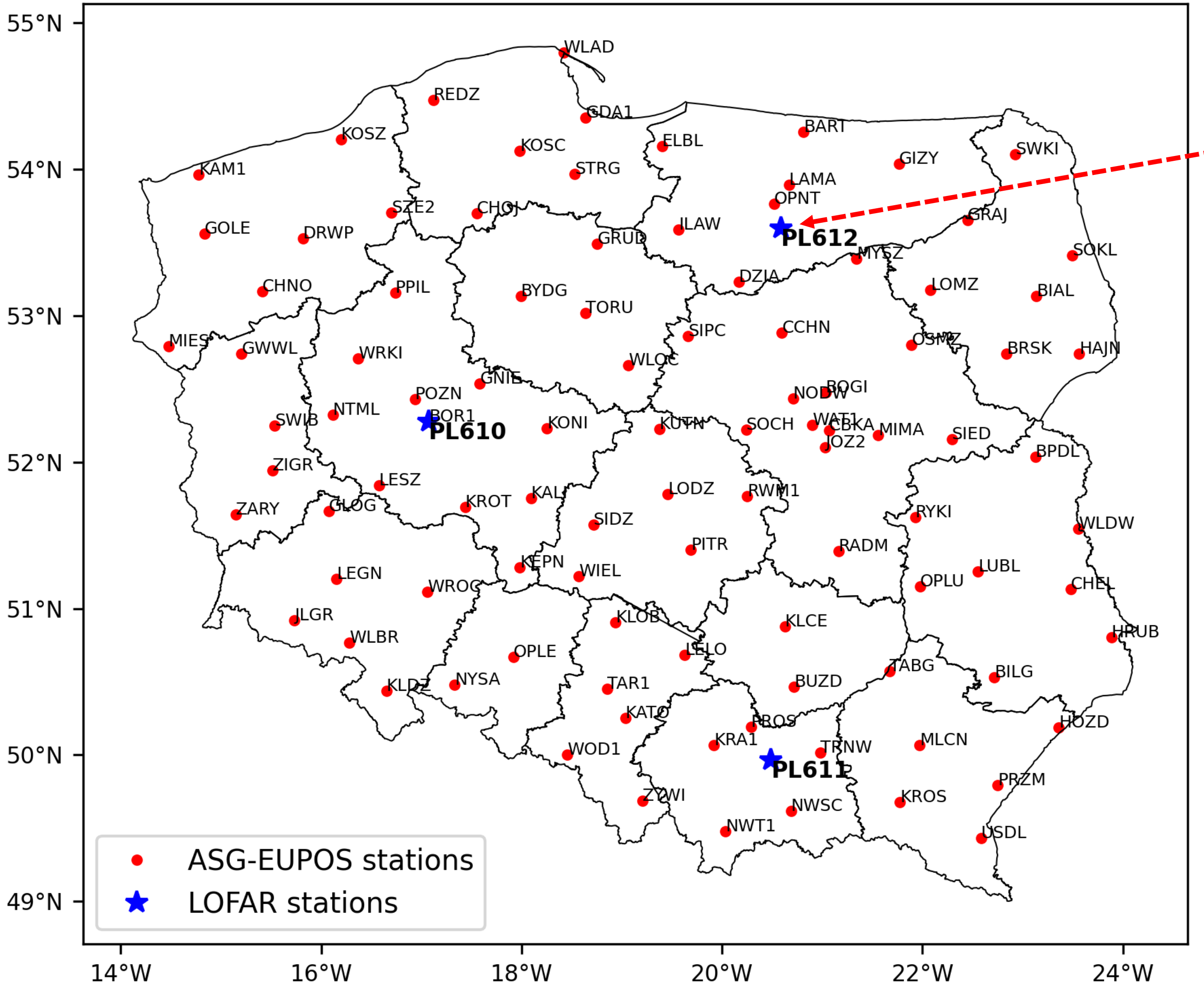
S_4 index



Some case studies from POLFAR

Dense network of GNSS geodetic stations

Three LOFAR stations



One GNSS Ionospheric station

Credit: Flisek et al., JSWSC, 2023

Example: DOY271 2017

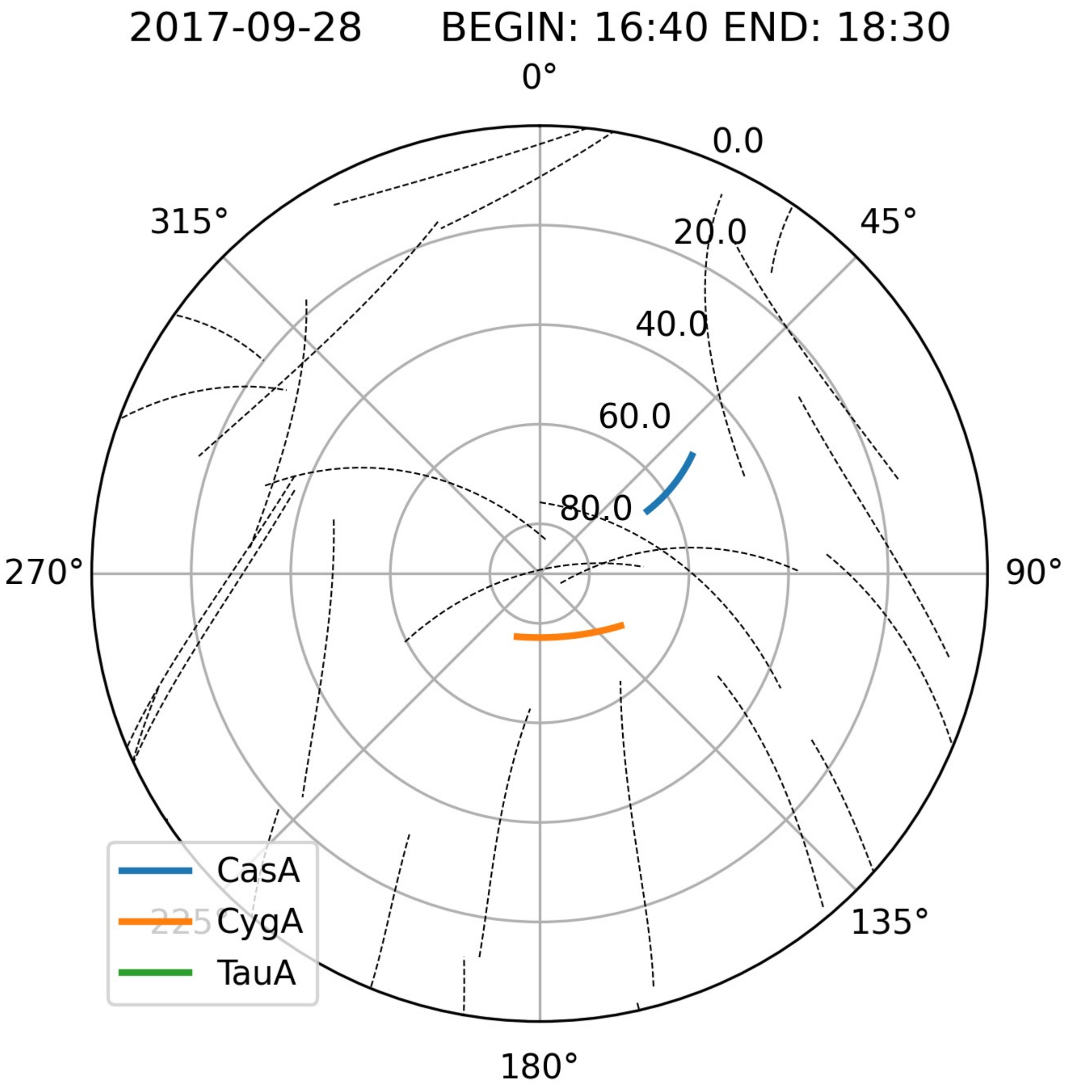
GNSS satellites

LOFAR:

Cassiopeia A

Cygnus A

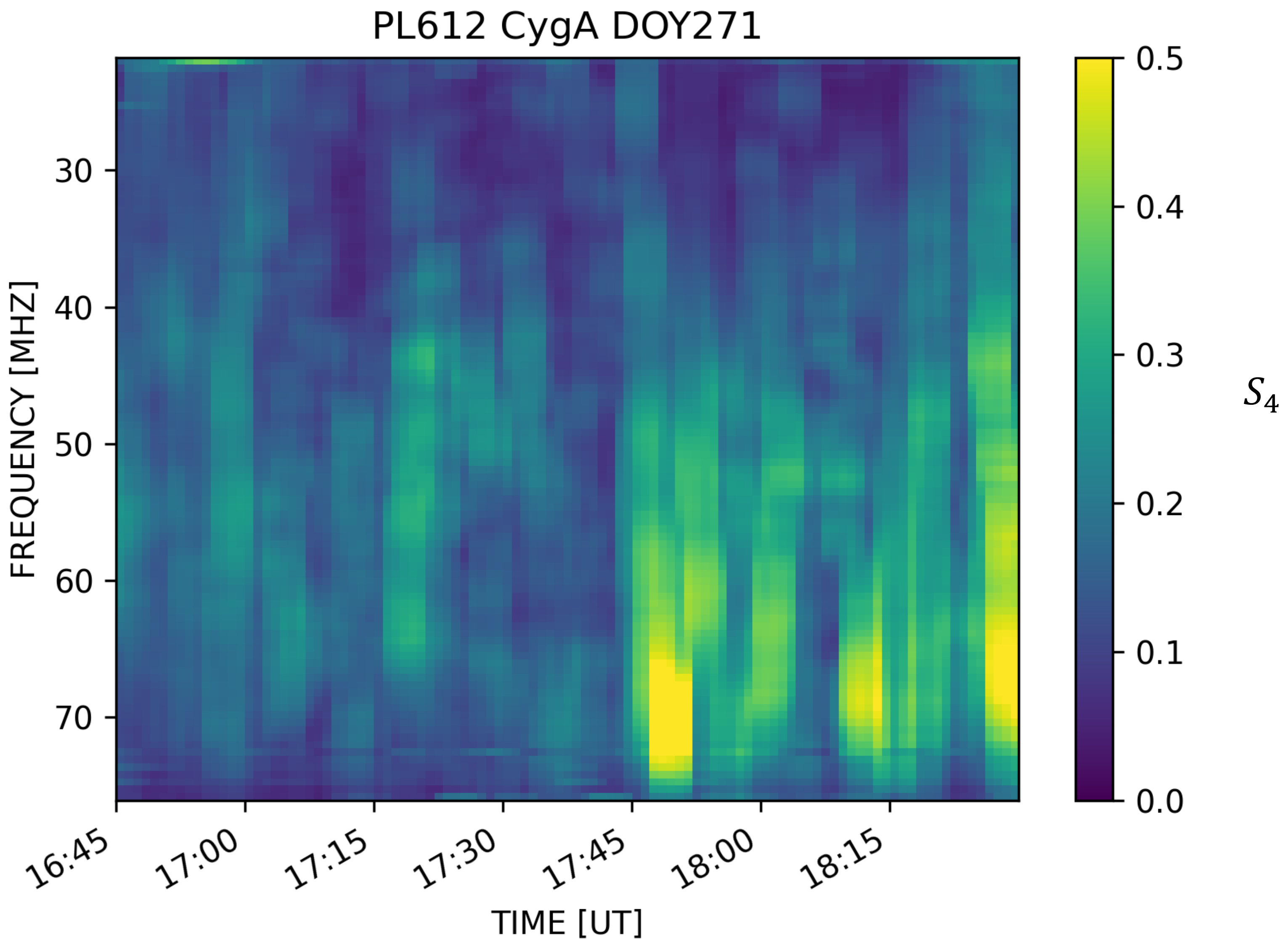
Taurus A



Credit: Flisek et al., JSWSC, 2023

Example: DOY271 2017

LOFAR scintillation index estimated over various VHF radio-wave frequencies



Credit: Flisek et al., JSWSC, 2023

Example: DOY271 2017

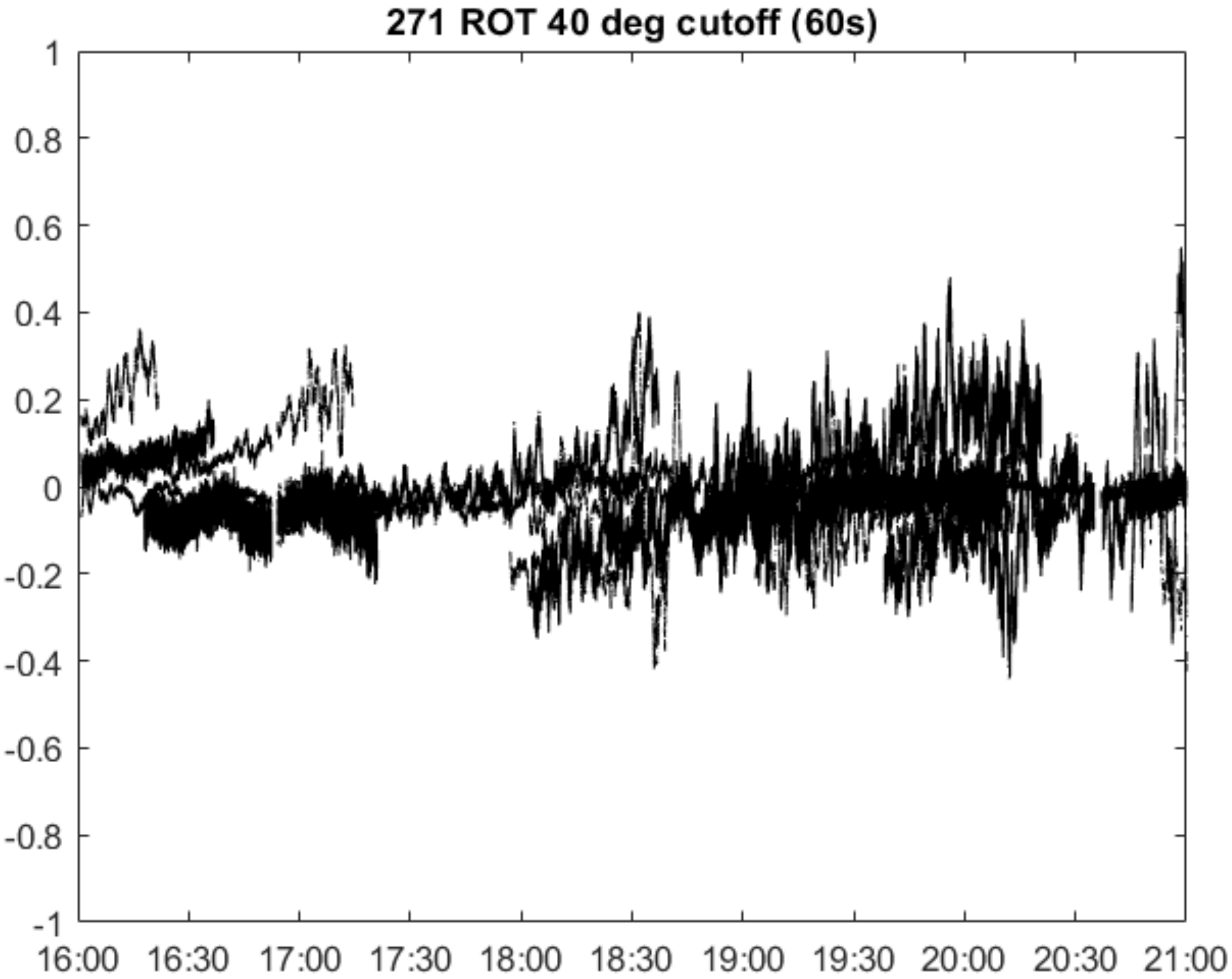
ROT
$[TECU/min]$

$$ROT_k = \frac{TEC_{k+1} - TEC_k}{t_{k+1} - t_k}$$

TEC: Total Electron Content

$t_{k+1} - t_k = 1\ \mathrm{min}$

GNSS Rate of Change of Total Electron Content (ROT) over 60 s temporal intervals



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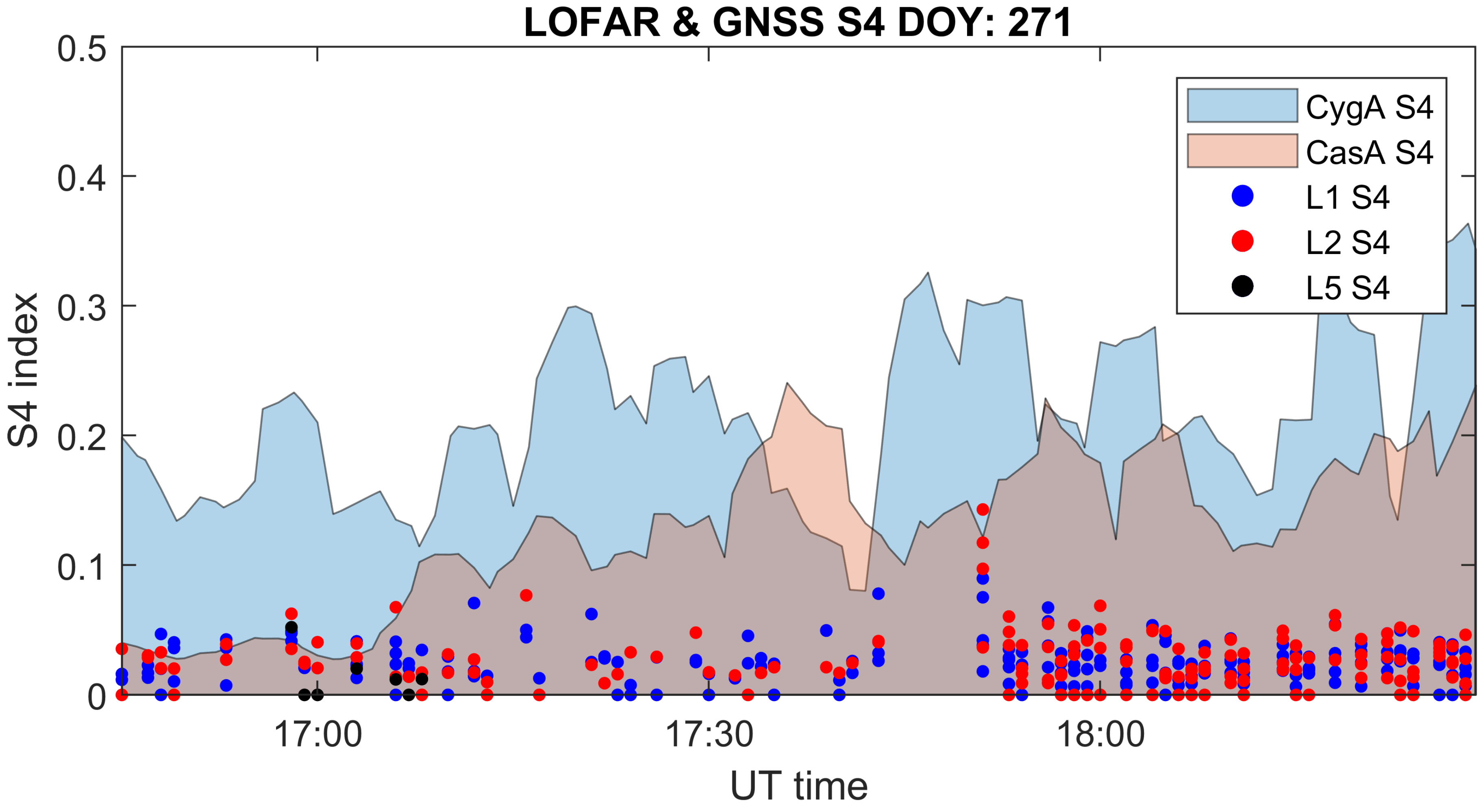
Credit: Flisek et al., JSWSC, 2023

Example: DOY271 2017

LOFAR VHF

GNSS L-band



Credit: Flisek et al., JSWSC, 2023

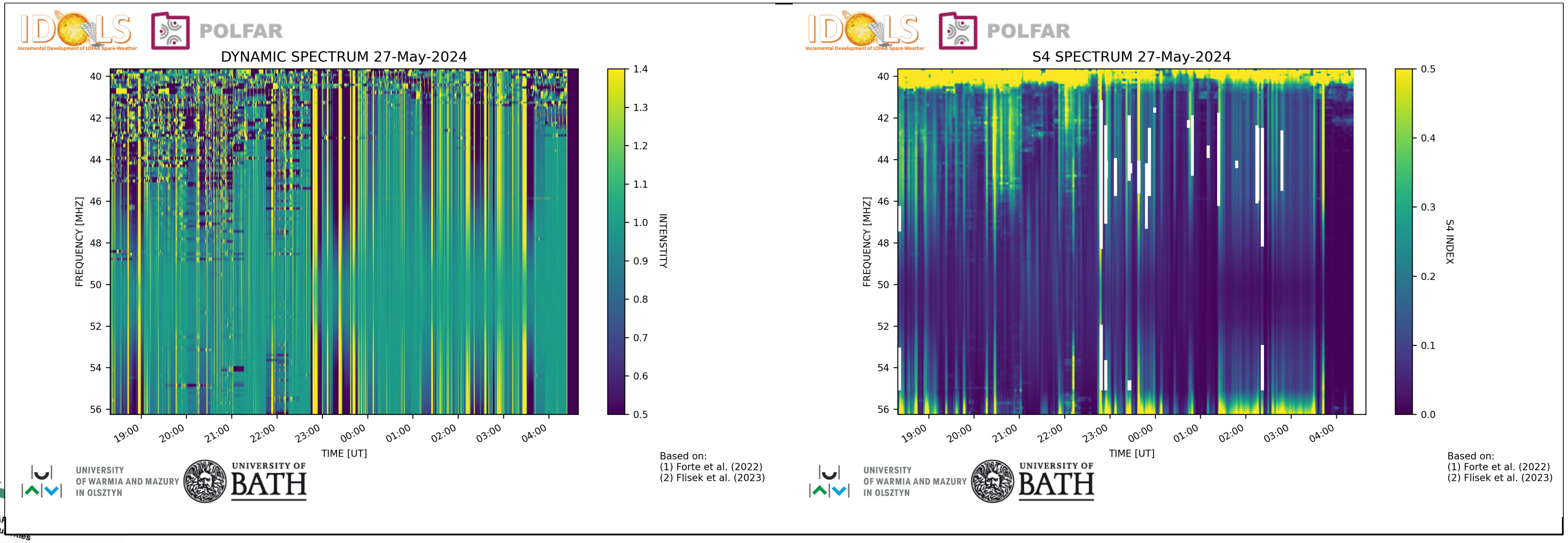
Pipeline for S4 scintillation index

S_4 spectrum figure:

- Based on the zero-mean, RFI-free, normalised intensity
- Method described in Forte et al. (2022) and Flisek et al. (2023)
- Available for nighttime scintillation observations on IDOLS (Incremental Development of LOFAR Space-weather)

Developed by University of Warmia and Mazury and University of Bath

Example outputs:



S_4 pipeline currect status:

- Working for nighttime observations on IDOLS
- Stable and reliable solution for calculating S_4
- Data stored in PNG and FITS formats
- 3, 4 and 5 minutes S_4 available in FITS

S_4 pipeline future plans:

- Working in realtime with a delay of 15 minutes
- S_4 classification for low, moderate and strong scintillation
- Multiple stations availability

Conclusions

- LOFAR enables the observation of scintillation on a wider interval of VHF radio waves frequencies: useful to infer different gradients in the ionosphere.
- For example, LOFAR can detect irregularities in the ionosphere which are not necessarily detected through GNSS.
- A pipeline for the routine calculation of the S4 index is available and can be used to inform astronomical observations.

Credit: Flisek et al., JSWSC, 2023

Credit: Forte et al., ApJS, 2022

Acknowledgments

Data obtained with the International LOFAR Telescope (ILT) under project codes LC7 001 and LC8 001. LOFAR (van Haarlem et al., 2013) is the Low Frequency Array designed and constructed by ASTRON. It has observing, data processing, and data storage facilities in several countries, that are owned by various parties (each with their own funding sources), and that are collectively operated by the ILT foundation under a joint scientific policy. The ILT resources have benefitted from the following recent major funding sources: CNRS-INSU, Observatoire de Paris and Universite d'Orleans, France; BMBF, MIWF-NRW, MPG, Germany; Science Foundation Ireland (SFI), Department of Business, Enterprise and Innovation (DBEI), Ireland; NWO, The Netherlands; The Science and Technology Facilities Council, UK; Ministry of Science and Higher Education, Poland.

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References

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Thank you for the attention.

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