# Possibilities and perspectives of the Space Weather program through the use of innovative tools developed on the basis of the European LOFAR interferometric radio telescope

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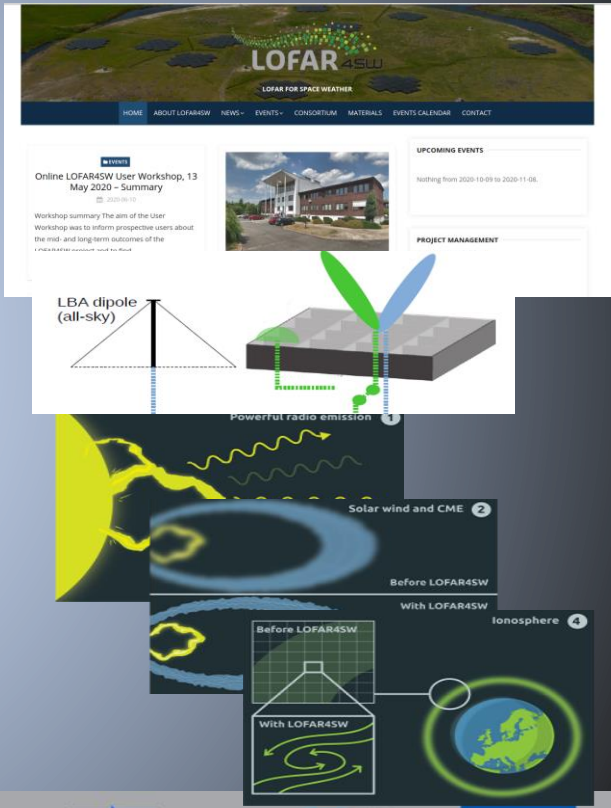
LOFAR4SW consortium

# LOFAR4SW  H2020  program finished

- The LOFAR4SW, Horizon 2020 (H2020) INFRADEV **design study** - completion in Feb 2022, **delivery of complete design from use cases  to working prototypes of hardware and software.**

- The acttivity  should be **continue** after the project completion and still some **efforts was taken for the implementation** of the project outcomes and to upgrade LOFAR to infrastructure for **space weather studies.**

- A fully implemented LOFAR4SW will be one of **Europe's most comprehensive space weather observatories**, shedding new light on several aspects of the space weather system, from **the Sun** through **the solar wind** to **the ionosphere.**

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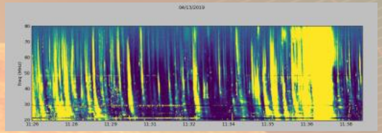
# **LOFAR4SW:** A comprehensive Space Weather Observatory
## Sun, Heliosphere and Ionosphere observations

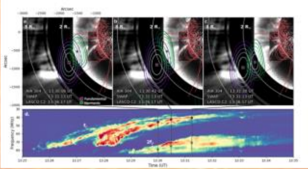
## Sun

### ➔ Monitoring Solar Radio Activity



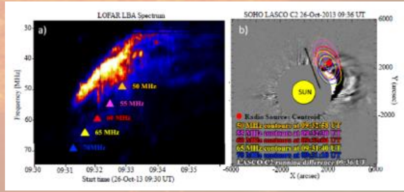
Zucca @ *Twitter*

### ➔ Imaging of Radio Emissions



Maguire et al., 2021

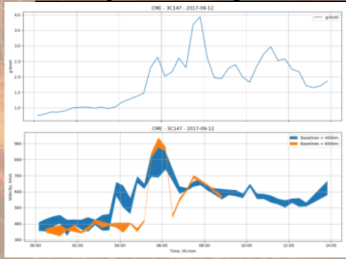
### ➔ Solar radio bursts




Zucca *et al.*, 2018

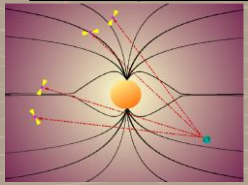
## Heliosphere

### ➔ Interplanetary Scintillation (IPS)



Beamformed observations of point-like, distant, astronomical radio sources - determine the plasma outflow velocity(ies) across each line of sight and single-site techniques.

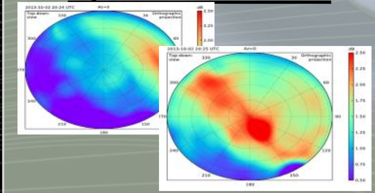
### ➔ Faraday Rotation



Determine the plasma density (and potentially the heliospheric magnetic field) using pulsars.

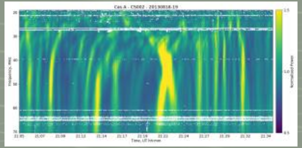
## Ionosphere

### ➔ Spectral riometer



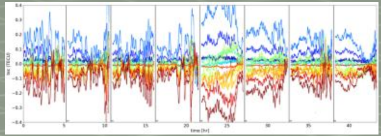
KAIRA data: McKay *et al.* (2015), Radio Science 50

### ➔ Ionospheric scintillations



Single station Scintillation spectrum CasA

### ➔ TIDs



differential TEC vs time, all Dutch stations

Credit: NASA

# LOFAR4SW Final Design

Architectural Design

Operational model

Hardware design

Science Use Cases

Software design

Data management plan

Governance model

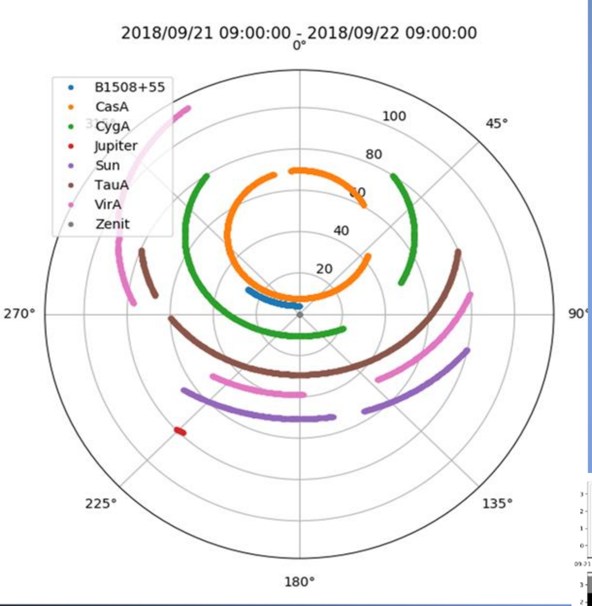
| Science | | | |
|---|---|---|---|
| **Use Case** | **Subject** | **Science Priority (within each domain)** | **Science Priority (across all domains)** |
| Ionospheric | | | |
| 1 | Imaging riometer (R2O) | High | 3 |
| 3 | Scintillation pattern flow | High | 2 |
| 5 | Wide-bandwidth scintillation (R2O) | High | 2 |
| 6 | High-resolution all-sky scintillation (core) | High | 2 |
| 7 | TID (R2O) | High | 4 |
| 8 | MLT wind fields | High | 4 |
| 10 | TID (LOFAR+GNSS) | High | 4 |

| Monitoring/Operations | | | |
|---|---|---|---|
| **Use Case** | **Subject** | **Monitoring/Operations Priority (within each domain)** | **Monitoring/Operations Priority (across all domains)** |
| Ionospheric | | | |
| 1 | Imaging riometer | Top | 1 |
| 2 | Monitoring S4 | High | 3 |
| 4 | All-sky scintillation (single station) | Medium | 8 |
| 7 | TID | High | 4 |
| 11 | Passive radar MHz) [Extend <10MHz to ~40MHz] | Top | 1 |

# What ionospheric studies are currently possible and what was done by help POLFAR for Ionosphere?


- Observations made in the frame of ‘Monitoring Ionospheric Scintillation Above LOFAR” proposals. Data available for selected time periods with different configurations of ILT stations.
- Local mode observations focused on ionospheric studies. Data available for selected time periods, only from selected stations.
- Post-processing of astronomy data

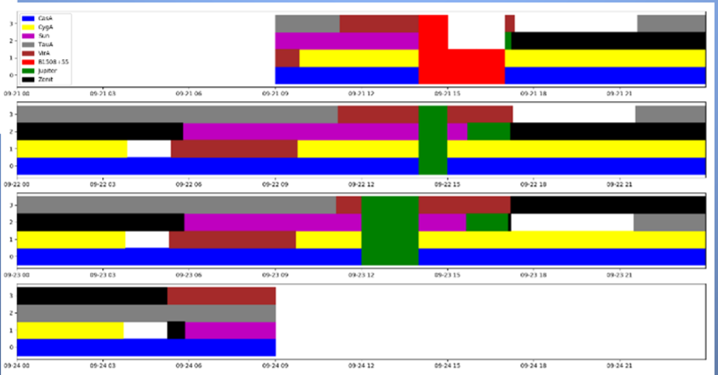
# What ionospheric studies are currently possible with LOFAR for Ionosphere?

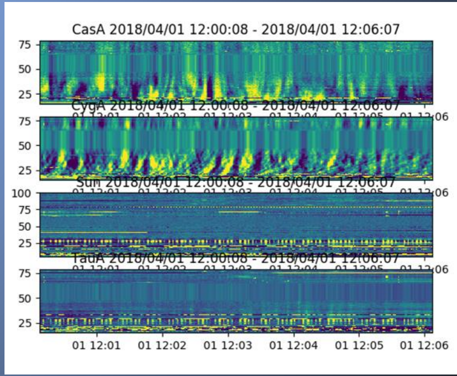



**Ionospheric diagnostic piggy back in majority**

**Already existing pipelines at international stations (PL610)**

- semi-automated (operator action needed to run the scheduler at the beginning of the local mode)
- simultaneous observations to 4 different objects
- different types of observations (change of bitmode, sources)
- observations are logged to the database – easier searching of files and better control over station work



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# An exemplary ionospheric observation scenario

## Normal observing → Trigger → Triggered observations

**Normal observing**

- Ionospheric scintillation S4 index
- all-sky imaging at each station (piggy back)

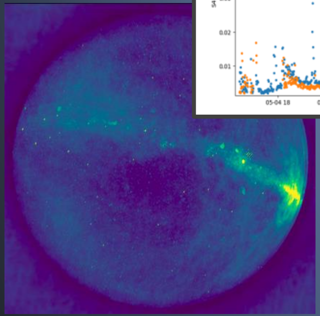
**Trigger**

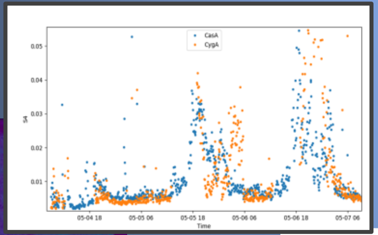
trigger example:

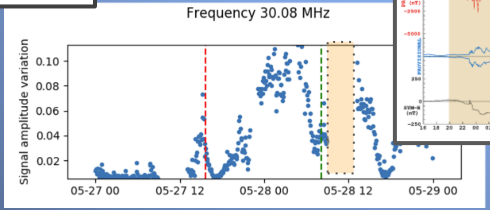
- internal: **elevated S4 index value**
- or external: **SYM-H/Dst** indicating geomagnetic disturbance, prediction of the **time of CME arrival** to the Earth's magnetosphere
- mix of both

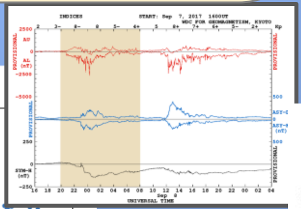
**Triggered observations**

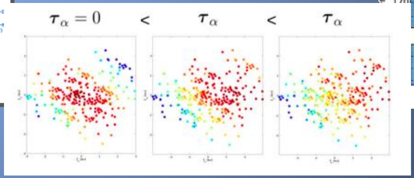
- Ionospheric scintillation -> wide-band dynamic spectras
- higher cadence and increased resolution versions of the normal observations
- core observations of moving structures

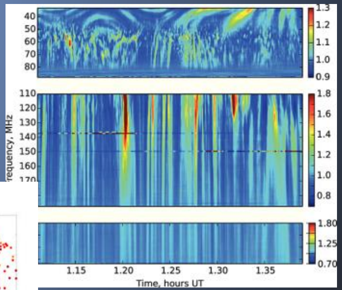




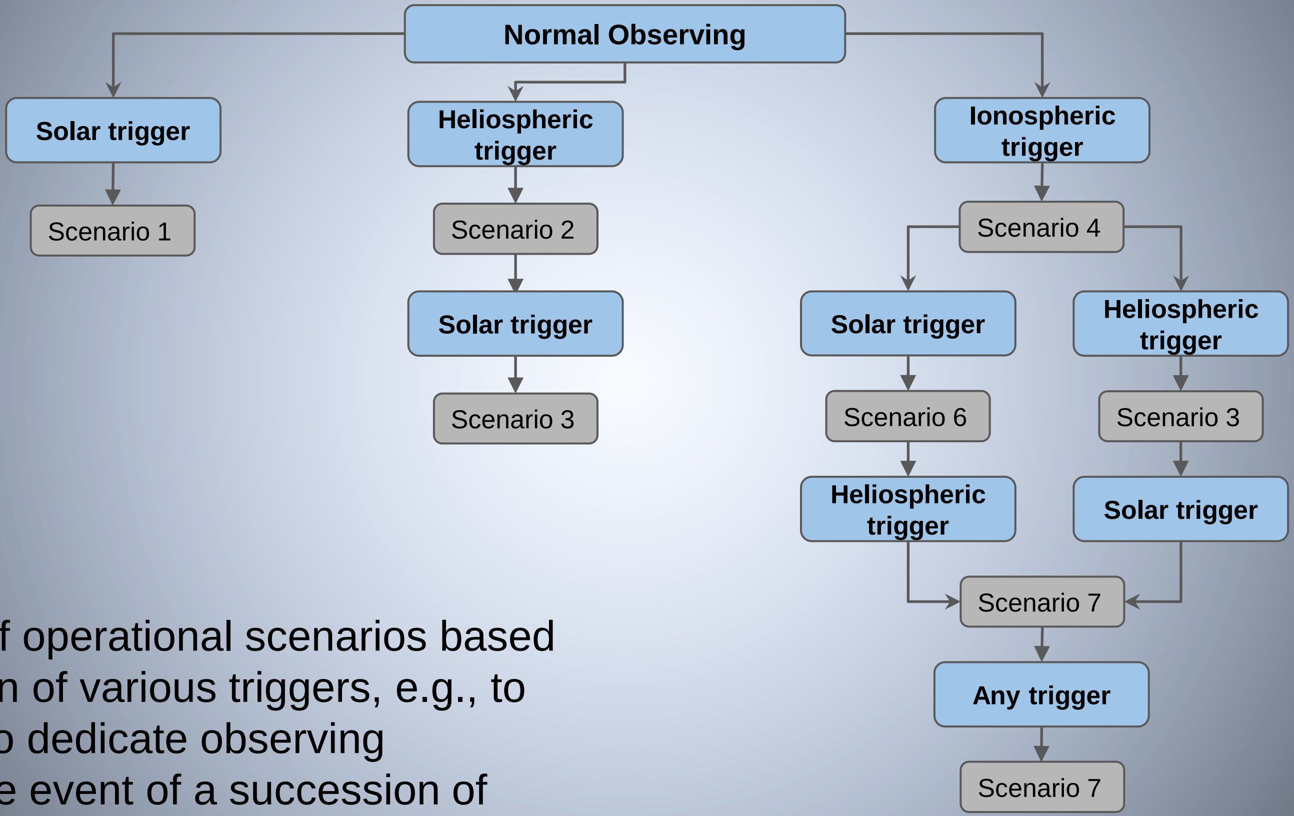





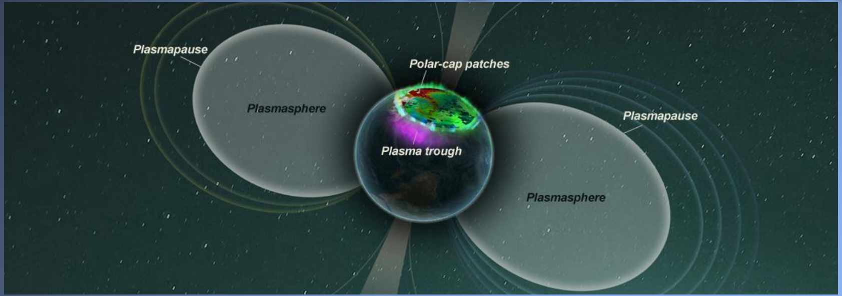


# How LOFAR4SW will operate



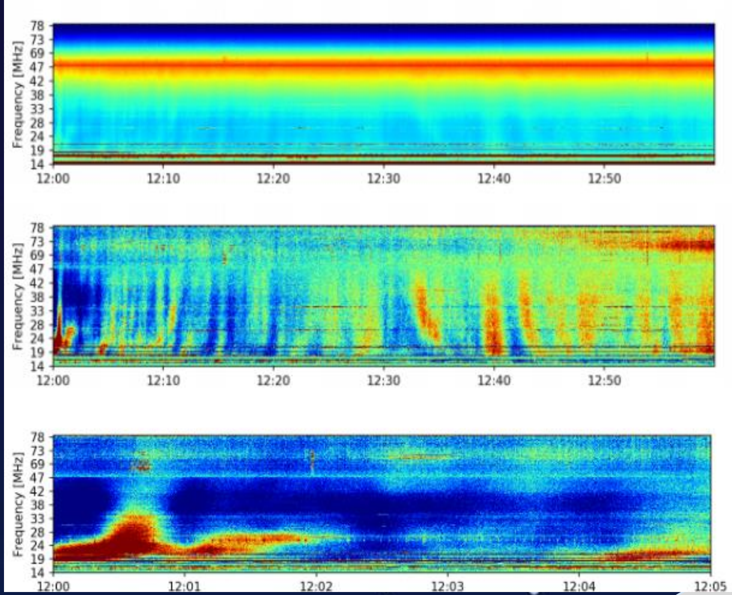

Decision tree of operational scenarios based on the reception of various triggers, e.g., to decide where to dedicate observing resources in the event of a succession of multiple flares or CMEs.

# ZOO of the ionospheric phenomena





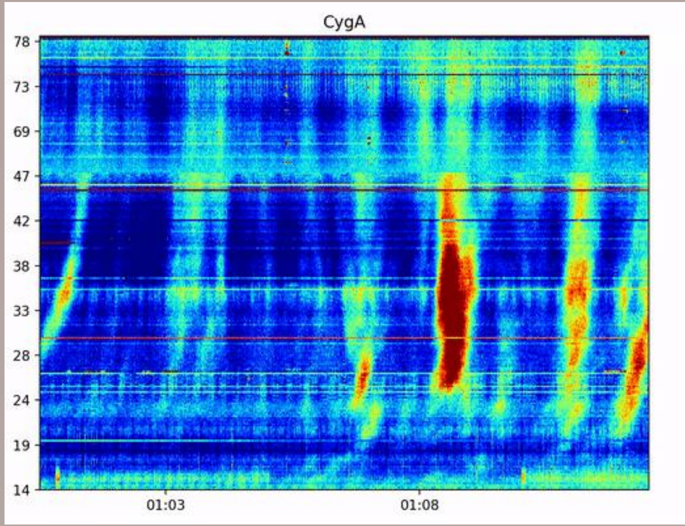
- ➢ Ionospheric irregularities – from small to large scales
- ➢ Monitoring the sub auroral and auroral region, Ionospheric trough, plasma depletion and mid-latitude region
- ➢ Scintillation activities
- ➢ Plasma absorption properties
- ➢ Neutral wind properties
- ➢ Monitoring EM noises and Thunderstorm activities, and vulcanic eruption .....

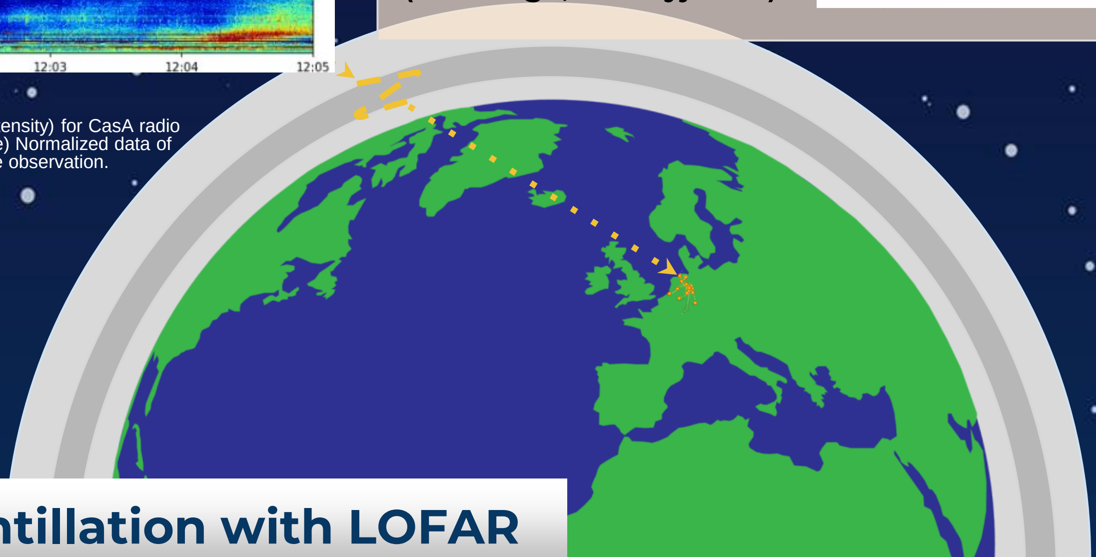



(top) the example raw data of 1h of I (signal intensity) for CasA radio source (2018/10/06, 12:00-01:00 pm). (middle) Normalized data of the top plot. (bottom) Short time scale observation.

Dynamic spectrum of measured intensity of Casiopea A signal with clearly visible scintillation pattern.

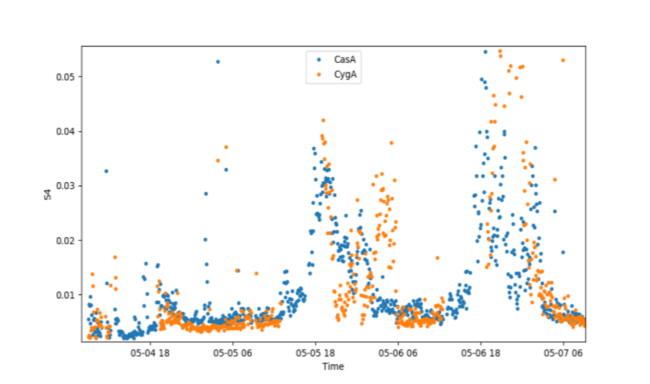
Observations made on 25.02.2018 at polish LOFAR station PL610.
Y axis: frequency in MHz, X axis: time.
(M.Pozoga, B.Matyjasiak)



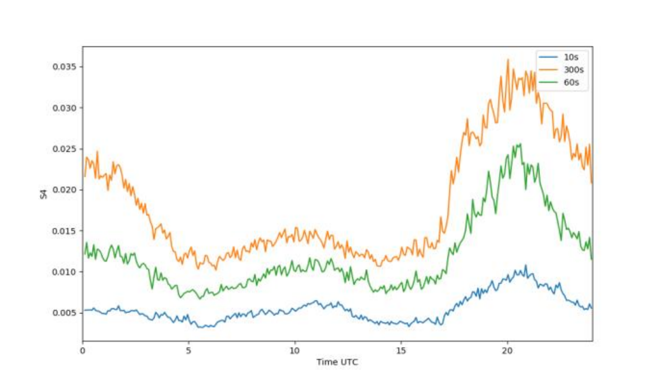



# Ionospheric scintillation with LOFAR

**Pipeline for S4 index computed from beamformed data was developed.**
**We use 100Hz amplitude recorded from single station PL610 We processed 8500 hour of observation for 4 brignest radio sources CasA, CygA, VirA, TauA**




S4 value computed from 60s segment of data frequency 30MHz for 2 s source CasA and Cyg A 4-7 May 2018




Comparison of daily median of s4 index at 30MHz for CasA for different length of data segment used to computation


Comparison of daily median course of s4 index at 20,40,70MHz for 60s segment for CasA

(Pożoga et al., 2021, DOI: 10.1109/SPSympo51155.2020.9593637)

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# $S_4$ index routine calculation

**Joint colaboration between: University of Warmia and Mazury in Olsztyn, University of Bath and RAL Space**

LOFAR

UNIWERSYTET WARMIŃSKO-MAZURSKI W OLSZTYNIE

Aims:

- Routine S4 calculation in order to characterize ionospheric irregularities,
- Estimating the ionospheric impact on the LOFAR observation for upcoming solar cycle maximum

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Topical Issue - Scientific Advances from the European Commission H2020 projects on Space Weather

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RESEARCH ARTICLE OPEN ACC

**A LOFAR observation of ionospheric scintillation from two simultaneous travelling ionospheric disturbances**

Richard A. Fallows[1,*], Biagio Forte[2], Ivan Astin[2], Tom Allbrook[2,a], Alex Arnold[2,b], Alan Wood[3], Gareth Dorrian[4], Maaijke Mevius[1], Hanna Rothkaehl[5], Barbara Matyjasiak[5], Andrzej Krankowski[6], James M. Anderson[7,8], Ashish Asgekar[9], I. Max Avruch[10], Mark Bentum[1], Mario M. Bisi[11], Harvey R. Butcher[12], Benedetta Ciardi[13], Bartosz Dabrowski[6], Sieds Damstra[1], Francesco de Gaspe Sven Duscha[1], Jochen Eislöffel[15], Thomas M.O. Franzen[1], Michael A. Garrett[16,17], Jean-Matthias Grießmeier[18,19], André W. Gunst[1], Matthias Hoeft[15], Jörg R. Hörandel[20,21,22], Marco Iacobelli[1], Huib T. Intema[17], Leon V.E. Koopmans[23], Peter Maat[1], Gottfried Mann[24], Anna Nelles[25,26], Harm P Vishambhar N. Pandey[1,23], Wolfgang Reich[28], Antonia Rowlinson[1,29], Mark Ruiter[1], Dominik J. Schwarz[30], Maciej Serylak[31,32], Aleksander Shulevski[29], Oleg M. Smirnov[33,31], Marian Soida[34], Matthias Steinmetz[24], Satyendra Thoudam[35], M. Carmen Toribio[36], Arnold van Ardenne[1], Ilse M. van Bemmel[37], Matthijs H.D. van der Wiel[1], Michiel P. van Haarlem[1], René C. Vermeulen Christian Vocks[24], Ralph A.M.J. Wijers[29], Olaf Wucknitz[28], Philippe Zarka[38], and Pietro Zucca[1]

sensors MDPI

Article

**Finding the Ionospheric Fluctuations Reflection in the Pulsar Signals' Characteristics Observed with LOFAR**

Leszek P. Błaszkiewicz [1,*], Paweł Flisek [1], Kacper Kotulak [1], Andrzej Krankowski [1], Wojciech Lewandowski [2], Jarosław Kijak [2] and Adam Froń [1]

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**Abstract:** Pulsars' signals reaching the atmosphere can be considered being stable under certain assumptions. In such a case the ionosphere remains the main factor distorting signal from the extraterrestrial sources, particularly if we observe them at long radio waves. In this article we present the results of the analysis of relative peak flux changes for two selected pulsars: PSR J0332+5434 (B0329+54) and PSR J1509+5531 (B1508+55), observed with the long radio wave sensor (The PL612

The Astrophysical Journal Supplement Series, 263:36 (15pp), 2022 December https://doi.org/10.3847/1538-4365/ac

OPEN ACCESS

**Interpretation of Radio Wave Scintillation Observed through LOFAR Radio Telescop**

Biagio Forte[1], Richard A. Fallows[2,3], Mario M. Bisi[3], Jinge Zhang[4], Andrzej Krankowski[5], Bartosz Dabrowski[5], Hanna Rothkaehl[6], and Christian Vocks[7]

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**Abstract**

Radio waves propagating through a medium containing irregularities in the spatial distribution of the electron density develop fluctuations in their intensities and phases. In the case of radio waves emitted from astronomical objects, they propagate through electron density irregularities in the interstellar medium, the interplanetary medium, and Earth's ionosphere. The LOFAR radio telescope, with stations across Europe, can measure intensity across the VHF radio band and thus intensity scintillation on the signals received from compact astronomical objects. Modeling intensity scintillation allows the estimate of various parameters of the propagation medium, for example, its drift velocity and its turbulent power spectrum. However, these estimates are based on the assumptions of ergodicity of the observed intensity fluctuations and, typically, of weak scattering. A case study of single-station LOFAR observations of the strong astronomical source Cassiopeia A in the VHF range is utilized to illustrate deviations from ergodicity, as well as the presence of both weak and strong scattering. Here it is demonstrated how these aspects can lead to misleading estimates of the propagation medium properties, for example, in the solar wind. This analysis provides a method to model errors in these estimates, which can be used in the characterization of both the interplanetary medium and Earth's ionosphere. Although the discussion is limited to the case of the interplanetary medium and Earth's ionosphere, its ideas are also applicable to the case of the interstellar medium.

*Unified Astronomy Thesaurus concepts:* Interplanetary scintillation (828); Ionospheric scintillation (861); Radio telescopes (1360)

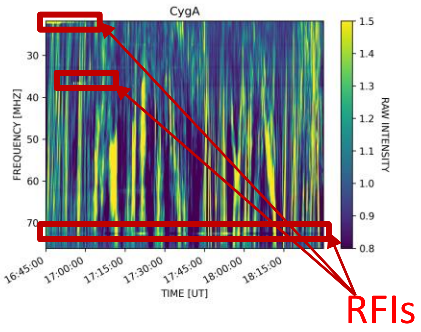
LOFAR

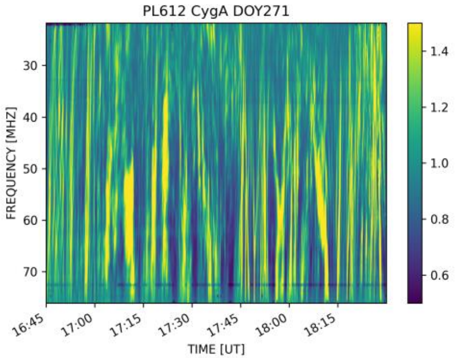
# Processing scintillation data

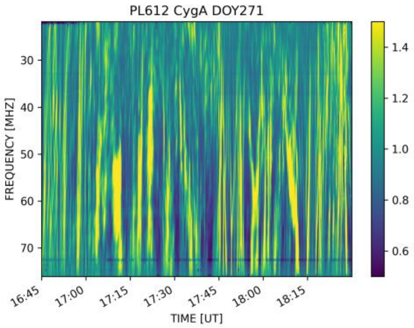
LOFAR

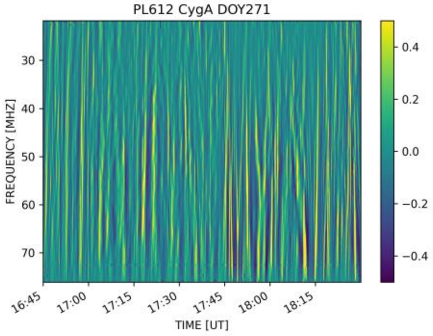
LOFAR observations of radio waves intensities utilised in this analysis were sporadically affected by RFI.

In the RFI-mitigation process, the median filter for each frequency band is applied. The threshold for the RFI detection is set on the level of the 10th percentile (5 threshold) for each channel. Spikes remaining after the filtering and larger than the threshold are cut out from the dynamic spectra.



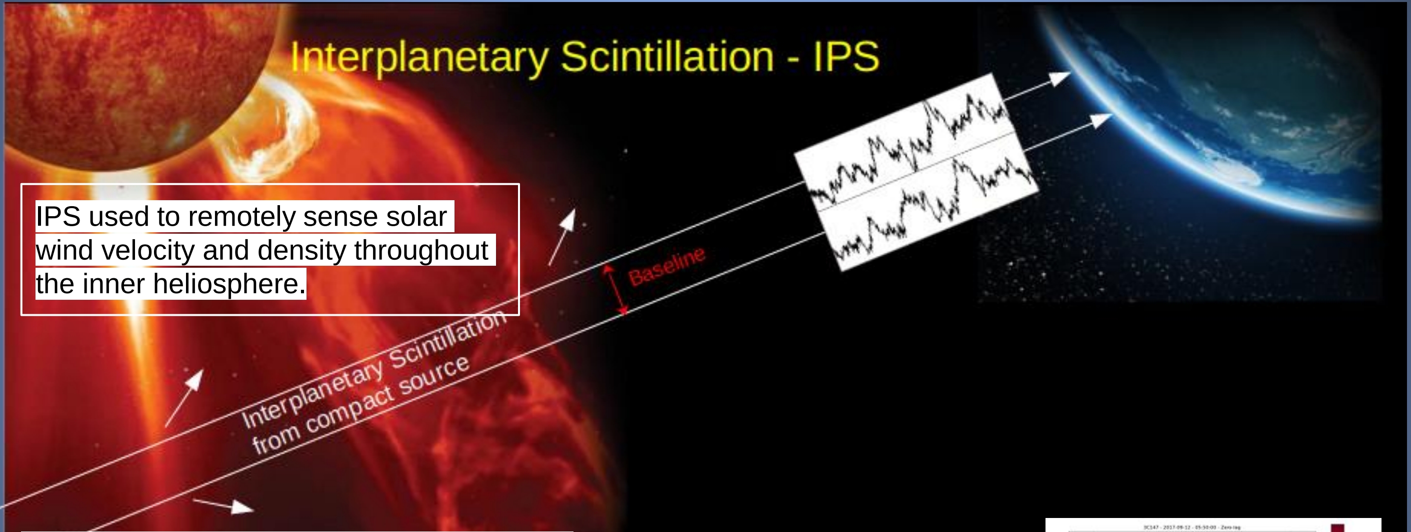

RFI-free intensities are detrended and normalized to zero-mean values.

Zero-mean normalized intensity allows to estimate the temporal fluctuations on the radio waves intensities induced by scintillation.

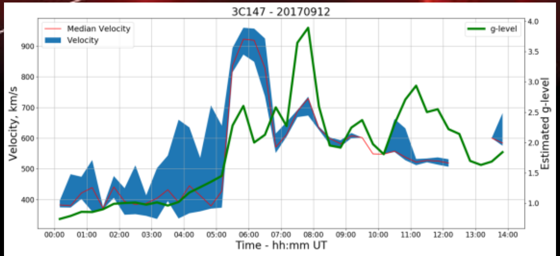
Detrending is done by subtracting a moving average with a 3-minute window.

LOFAR

# Monitoring the Inner Heliosphere

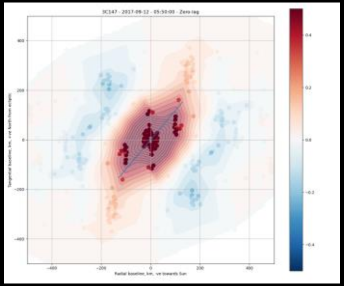



IPS used to remotely sense solar wind velocity and density throughout the inner heliosphere.

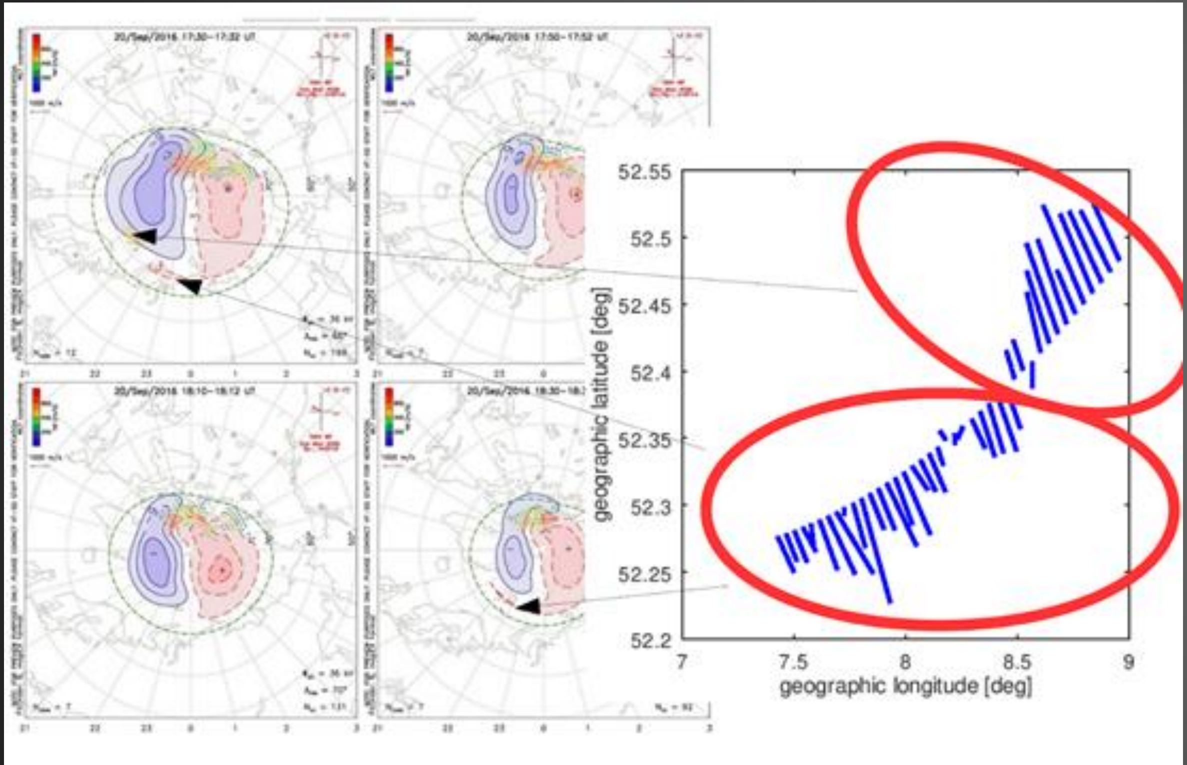



Left: Velocity and g-level (density) of a CME passage.

Right: NEW! Possibility to detect off-radial alignment of magnetic field from spatial pattern.



# Ionospheric studies with LOFAR




## Large-, Medium- and Small-scale ionospheric structures: Size and movement

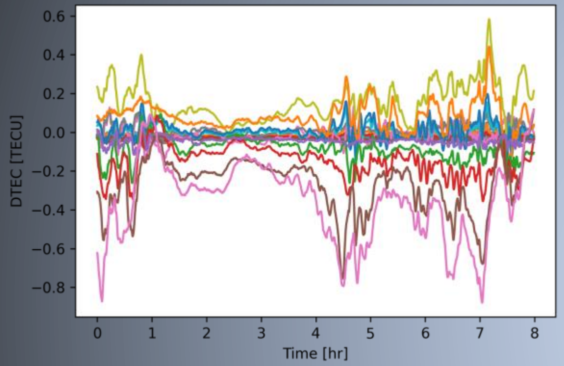
Use of a model with the diffraction pattern's temporal decorrelation to obtain drift velocity estimates. Accomplished by fitting a three-dimensional polynomial to the spatio-temporal correlations obtained from LOFAR's scintillation amplitude measurements

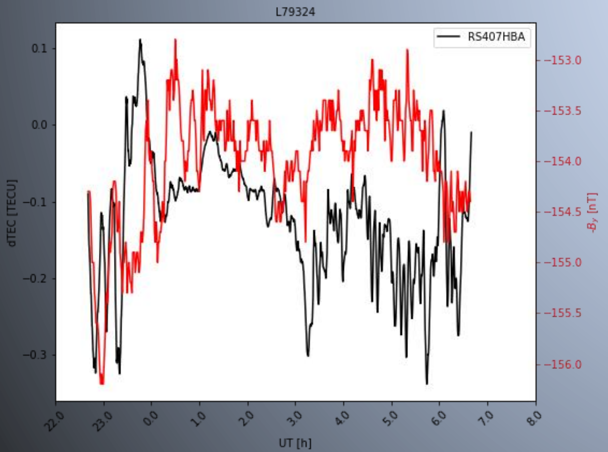
**Comparative plots between velocity observations from LOFAR (right) and SuperDARN (left).**

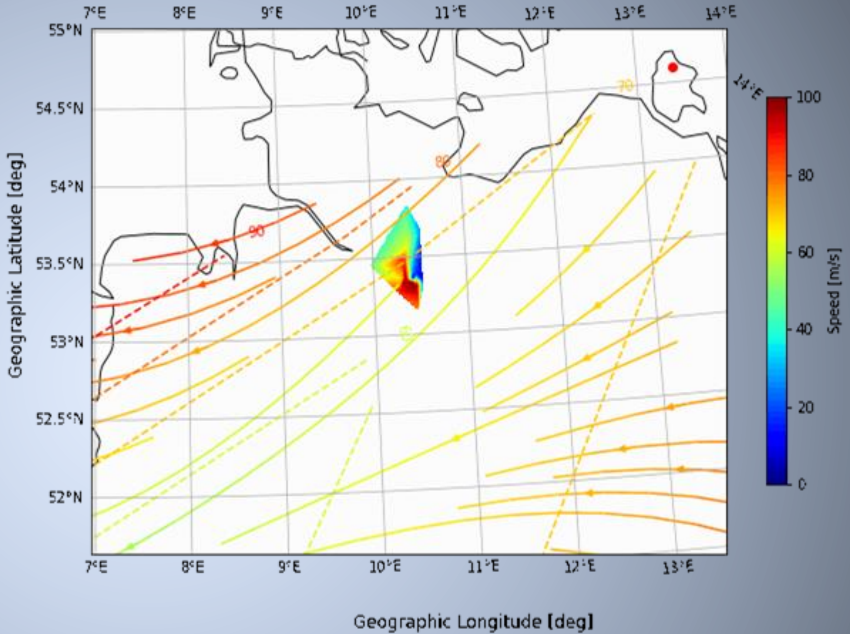
Grzesiak, M.et al., *Remote Sens.* **2022**, *14*, 4655. https://doi.org/10.3390/rs14184655

# Analysis of ionospheric signal in LOFAR calibration solutions

K. Beser



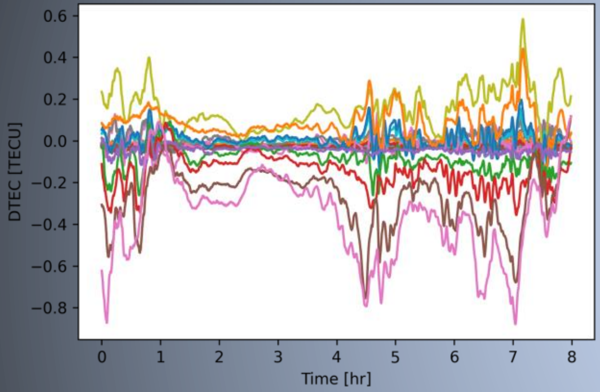



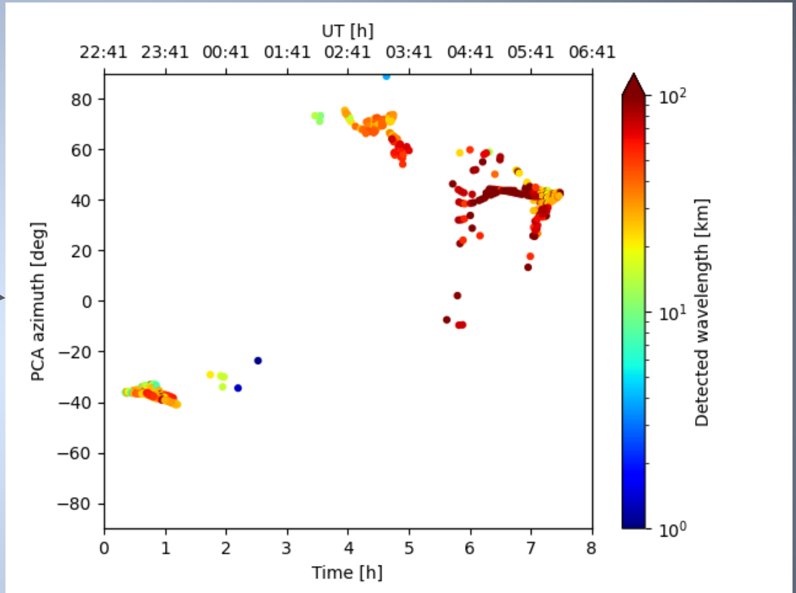




Investigations of LOFAR baselines' responses to dynamic changes in the ionosphere/plasmasphere.
Establishing quiet-time sensitivity levels.
Connection with geomagnetic field measurements from ground-based magnetometers and ionosondes.

# Analysis of ionospheric signal in LOFAR calibration solutions

K. Beser



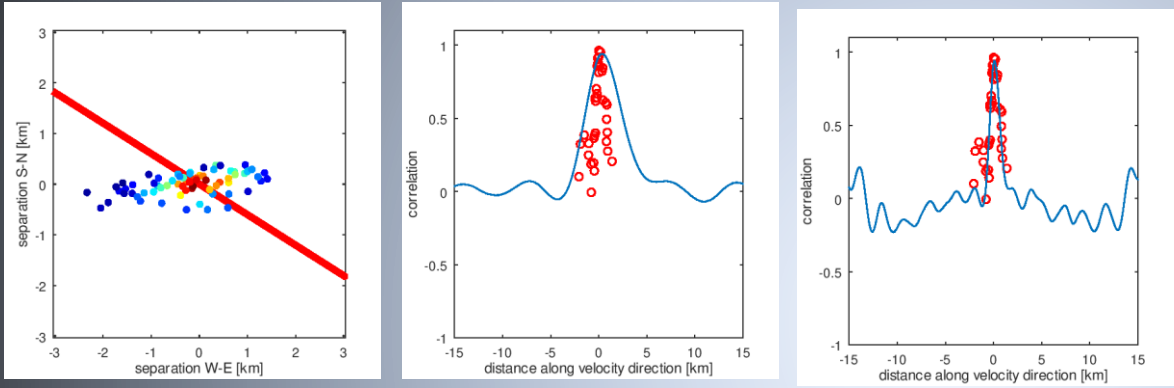




Detection of disturbances in ionospheric plasma density

Estimation of dominant direction and wave parameters of the wave-like disturbance signal

Characterization of medium- and small-scale disturbances in the ionosphere and their time evolution

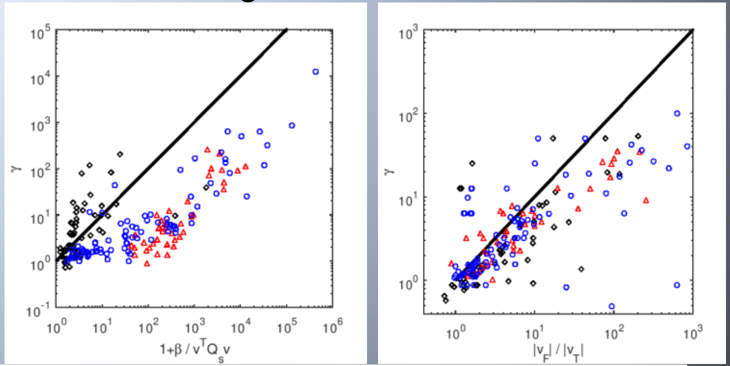
# Determining Ionospheric Drift and Anisotropy of Irregularities from LOFAR Core Measurements: Testing Hypotheses behind Estimation




An example of the procedure for obtaining the experimental velocity scaling factor: (a)—a bar containing spatial correlations taken for comparison, (b)—spatial correlations superimposed on temporal cross-correlation between a pair of stations (they do not overlap), (c)—spatial correlations superimposed on temporal cross-correlation between a pair of stations after the optimal speed scaling.

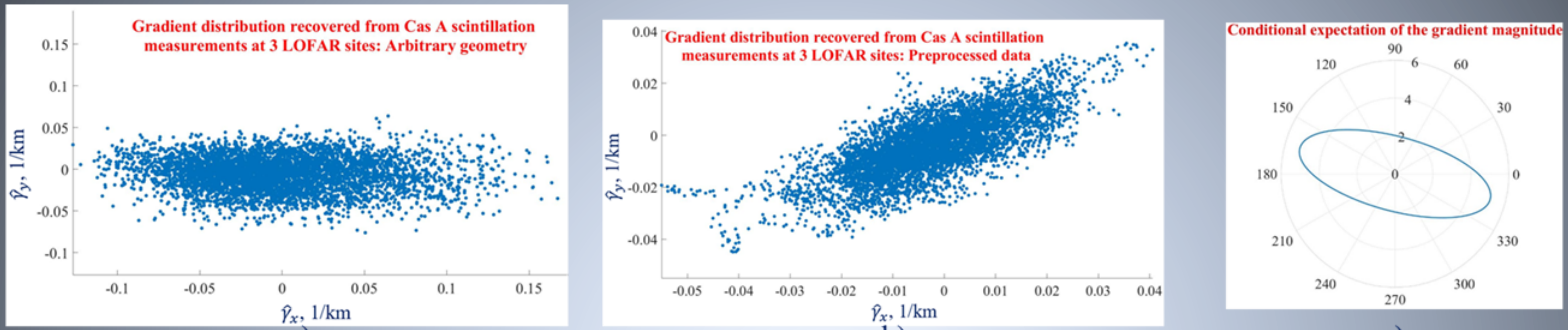
**Validation of assumptions made when estimating ionospheric drift.**

Left panel: experimental scaling factor γ vs scaling factor from Briggs model: $1+\beta/v^TQv$; right panel: experimental scaling factor γ vs ratio $|v_F|/|v_T|$. Different markers denote quantities for different geophysical conditions.



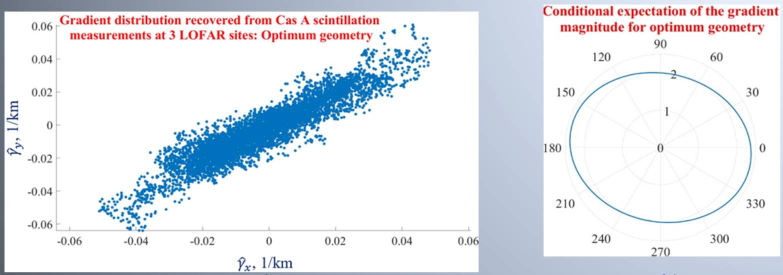

Grzesiak, M.et al., *Remote Sens.* **2022**, *14*, 4655. https://doi.org/10.3390/rs14184655

# Estimating scintillation pattern gradients from measurements at 3 spaced sites




a) b) c)

Fig. 1 Gradient distributions recovered from Cas A scintillations measured at 3 LOFAR stations before (a) and after (b) preprocessing for arbitrary geometry of the sites and conditional expectation of the gradient magnitude (c)

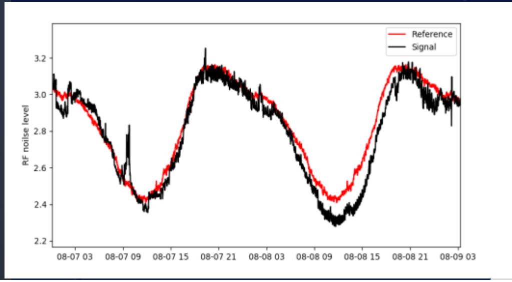


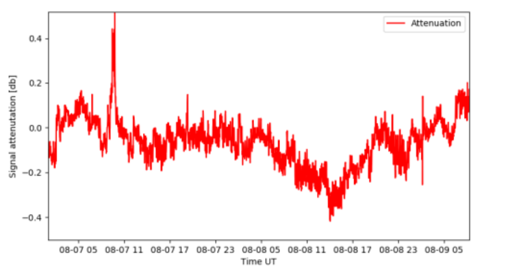

a) b)

Fig. 2 Gradient distribution recovered from Cas A scintillations measured at 3 optimally selected LOFAR sites (a) and conditional expectation of the gradient magnitude (b)

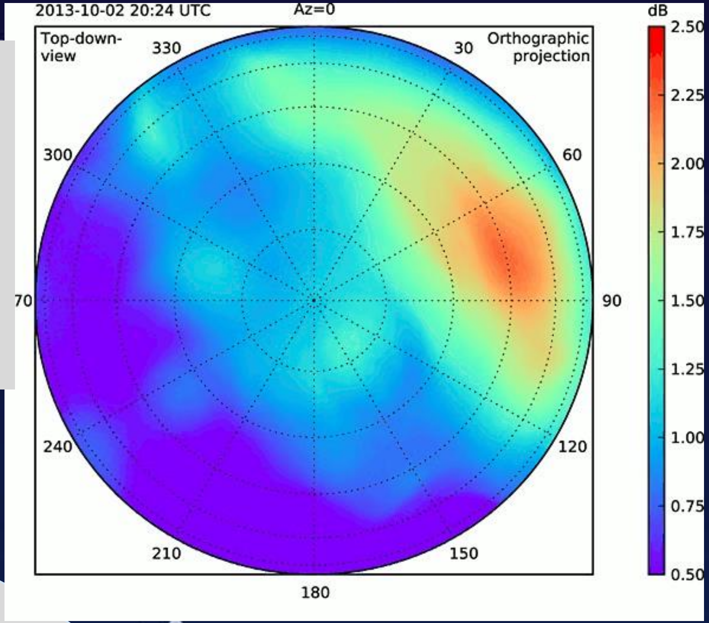
As was found, gradients recovered from cosmic source scintillation measurements at 3 spaced sites are dependent on the station allocation (see Figs. 1a and 2a), which effect can be due to noise and measurement inaccuracy. Based on analyzing the conditional expectation of the gradient magnitude (Figs. 1c and 2b), calculated for a model of a "white" noise, an optimum site selection criterion and data preprocessing algorithm have been suggested. The result of applying the suggested algorithm is shown in Fig. 1b. As can be seen, it differs significantly from that without preprocessing (Fig. 1a), being more consistent with the case of an optimum site allocation.

CBK PAN




A few 1 min frames of **all-sky interferometric riometry.** These reveal the true direction of the arrival of the absorption, sweeping from the northeast to the southwest. (McKay et al. 2015, Radio Science 50)




# All-sky interferometric riometry

# IONOSPHERIC TROUGH

**Ionospheric conditio during geomagnetic disturbancec**

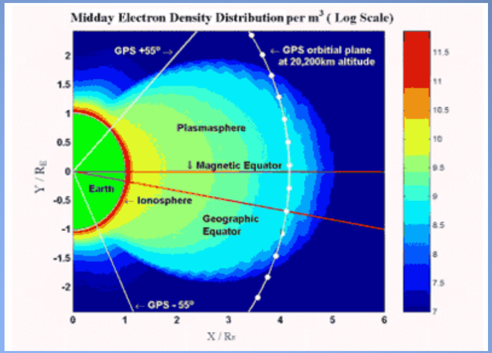
Ionospheric trough and plasmopause around 42-44 geographic latitude below Core and PL610 station.

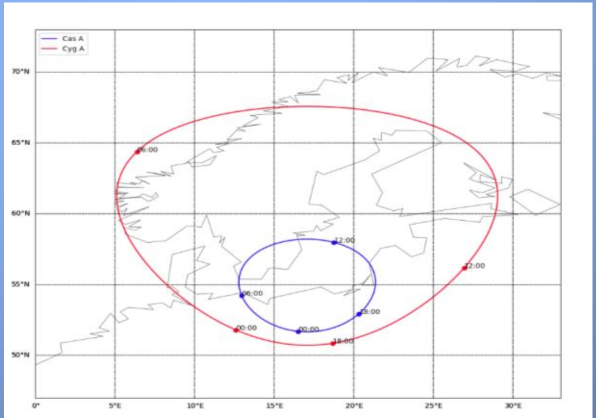
Field aligned current .

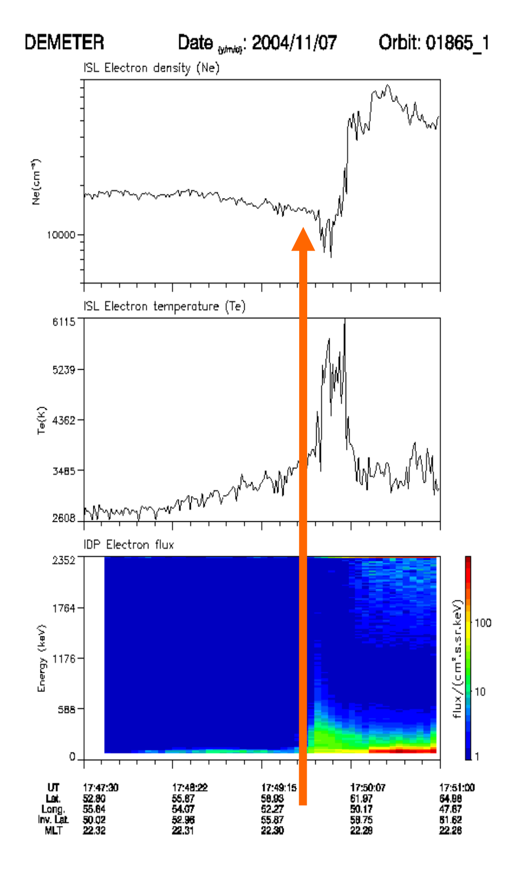
Absorption small scales

Enhancements of Spread-F layers

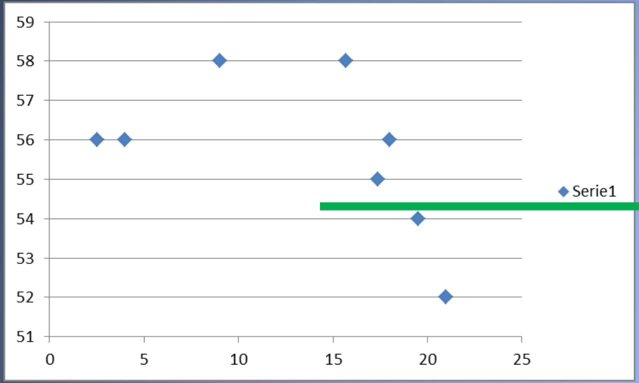
Turbulent structures of ionosphere structures

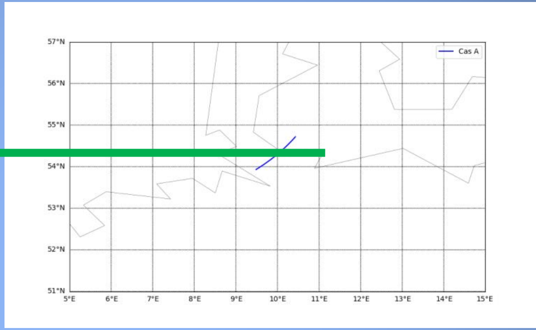


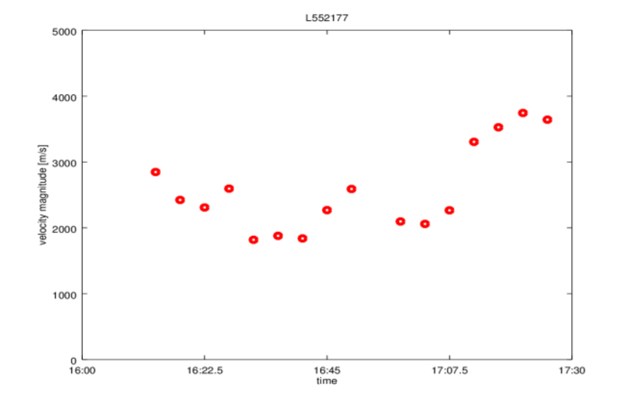



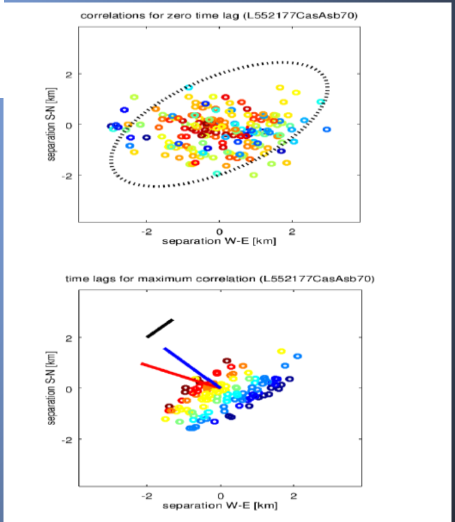



# The determination of main ionospheric trough by LOFAR and SWARM diagnostics



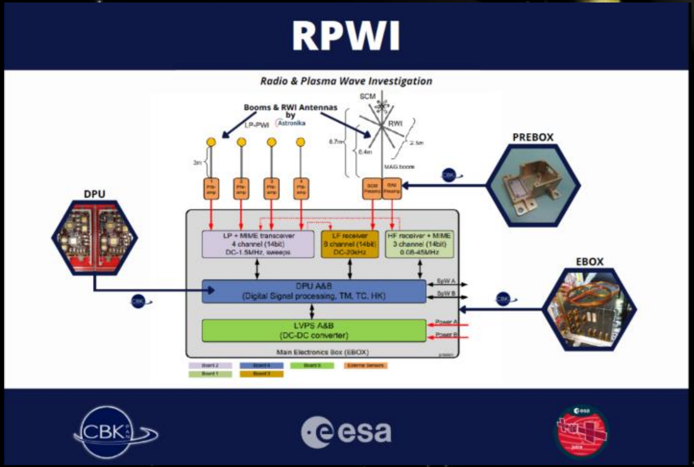




Geomagnetic storm
13 10 2016

14 04 2023 14:14
CET

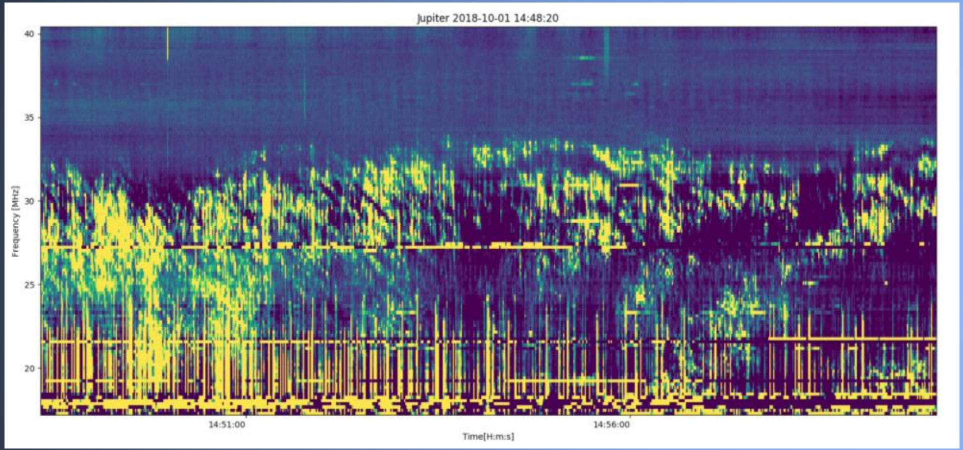


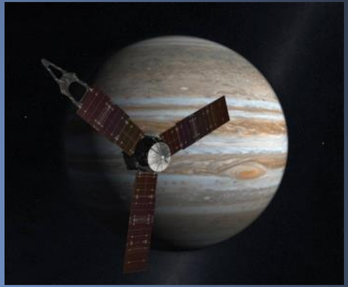

# Jupiter observations

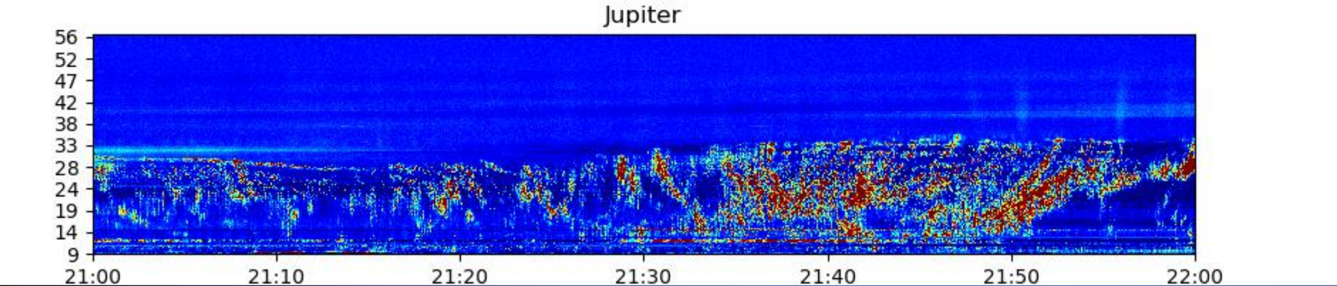
DAM emissions - Jovian decametric radio emission

Follow-up for JUNO and JUICE, EUROPA CLIPPER missions

Observations accessible by VO



# INVESTIGATION OF STRUCTURES PRODUCED BY THE QUASI-PERIODIC S-BURSTS IN JUPITER DAM EMISSION DYNAMIC SPECTRA

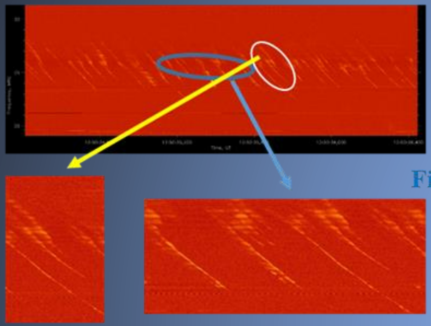
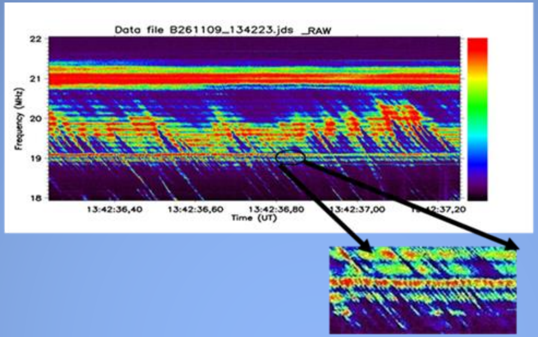
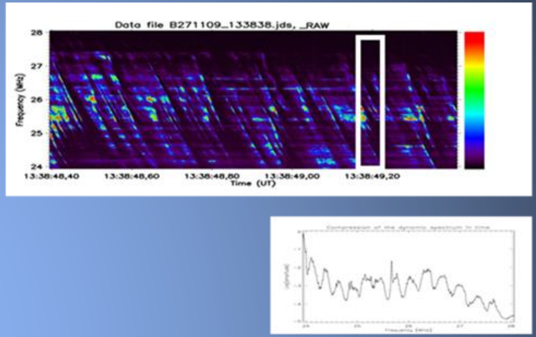


Fig 1



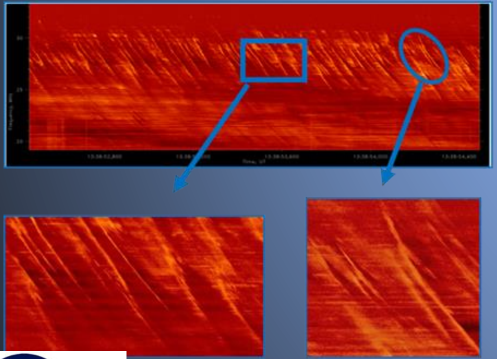



Fig 2

**It was identified in detail:**

- **Fig.1** **Time-shifted events in the same frequency range (narrow frequency band 1 ÷ 3 MHz );**
- **Fig.2** **Fast negative frequency drift 25 ÷ 35 MHz/s can change for two events coinciding in the frequency range;**
- **Fig.3** **Internal periodic structure with a time resolution corresponding to the resolution of the receiver;**
- **Fig.4** **More intensive Faraday fringes are also modulated in frequency by some plasma process with higher density of lanes.**

G. Lytvynenko

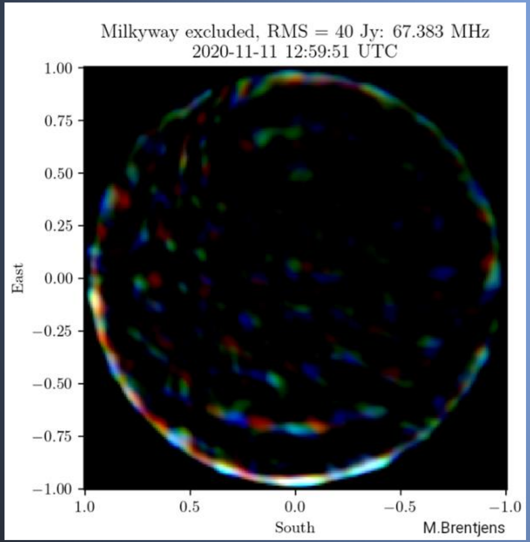
# What ionospheric studies are currently possible with LOFAR for Ionosphere?

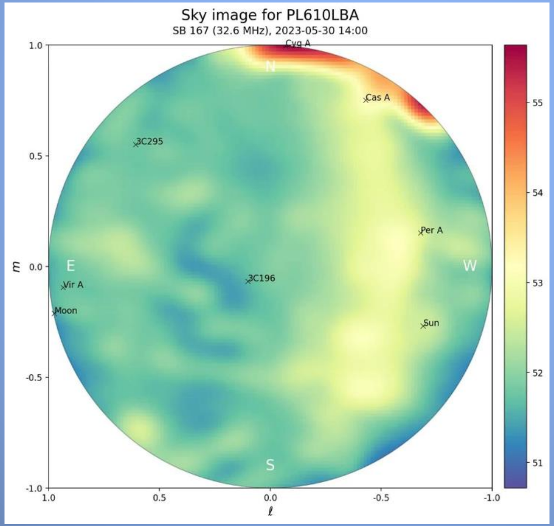
## Passive Radars

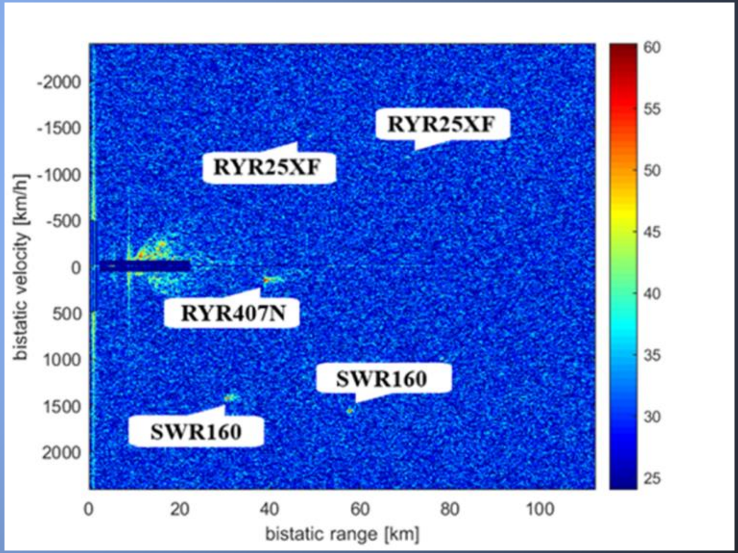
**Man made noises**

**Meteor /Neutral wind**

**Aircraft and ISS**



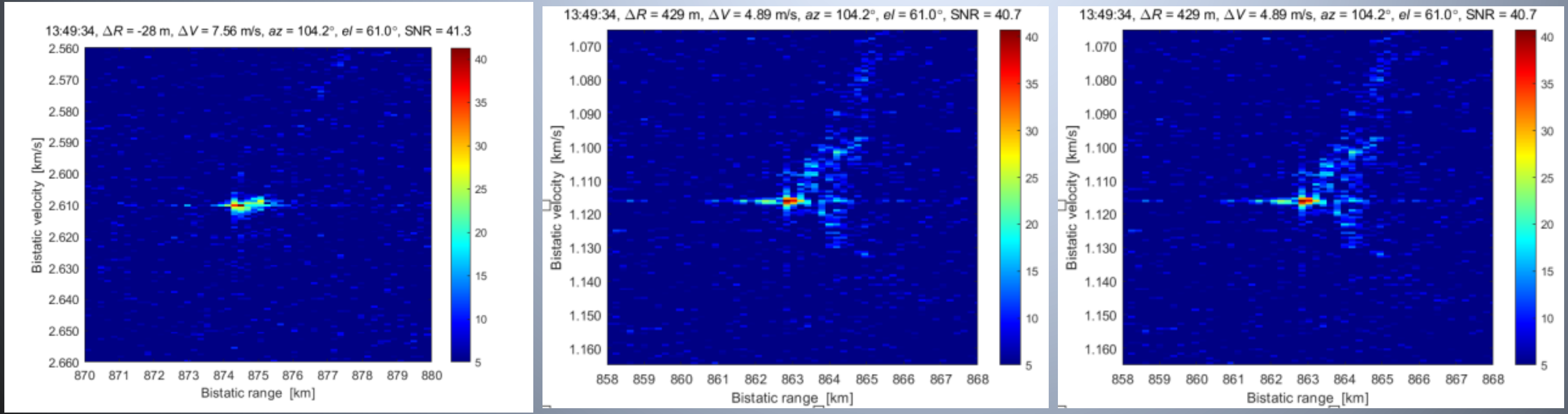




Preseid and Geminid

# Space Object Detection using LOFAR as a passive radar

- Project led in collaboration with Warsaw University of Technology (Politechnika Warszawska),
- Receivers, such as LOFAR,  can be used in **passive radiolocation systems** (aircraft detection, space targets detection),
- DAB+ commercial transmitters are being used as illuminators of opportunity, while two LOFAR stations were used as a surveillance receiver and as a reference receiver.

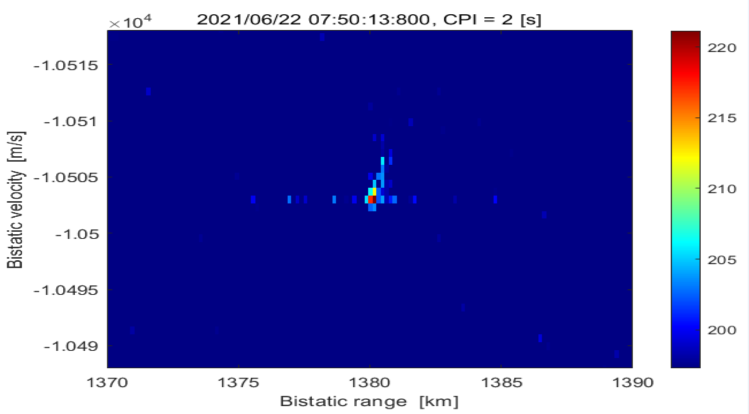

ISS (red line), surveillance receiver (SR), reference receiver (RR) and illuminator of opportunity (I) positions during measurements.

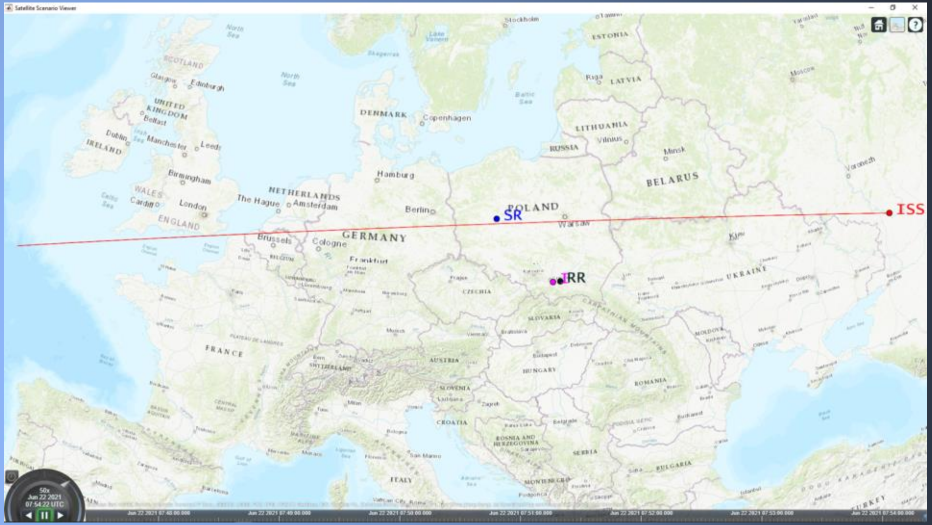



Zoom on the ISS echo in the range-velocity maps obtained for different transmitter.

# Space Object Detection using LOFAR as a passive radar

- Project led in collaboration with Warsaw University of Technology (Politechnika Warszawska),
- Receivers, such as LOFAR, can be used in **passive radiolocation systems** (aircraft detection, space targets detection),
- DAB+ commercial transmitters are being used as illuminators of opportunity, while two LOFAR stations were used as a surveillance receiver and as a reference receiver.




ISS (red line), surveillance receiver (SR), reference receiver (RR) and illuminator of opportunity (I) positions during measurements.

Zoom on the ISS echo in the range-velocity maps obtained for subsequent time moments.

# The solar radio bursts observations with LOFAR

UNIWERSYTET WARMIŃSKO-MAZURSKI W OLSZTYNIE

**Work within international cooperation under KSP “Solar Physics and Space Weather with LOFAR” team:**

B. Dabrowski, A. Wołowska, C. Vocks, P. Flisek, A. Krankowski, P. Zhang, J. Magdalenic, H. Rothkaehl, A. Warmuth, D. E. Morosan, M. Bröse, M. M. Bisi, B. Matyjasiak, L. Błaszkiewicz, E. P. Carley, R. A. Fallows, A. Froń, P. T. Gallagher, M. Hajduk, K. Kotulak, G. Mann, P. Rudawy, T. Sidorowicz, Y. Wu, P. Zucca, and K. Mikuła

Space Radio-Diagnostics Research Centre, University of Warmia and Mazury in Olsztyn, Poland

**LOFAR**
Solar and Space Weather
**KSP**

NATIONAL SCIENCE CENTRE POLAND

DFG Deutsche Forschungsgemeinschaft German Research Foundation

**Beethoven Classic 3**
LOFAR observations of the solar corona during Parker Solar Probe perihelion passages

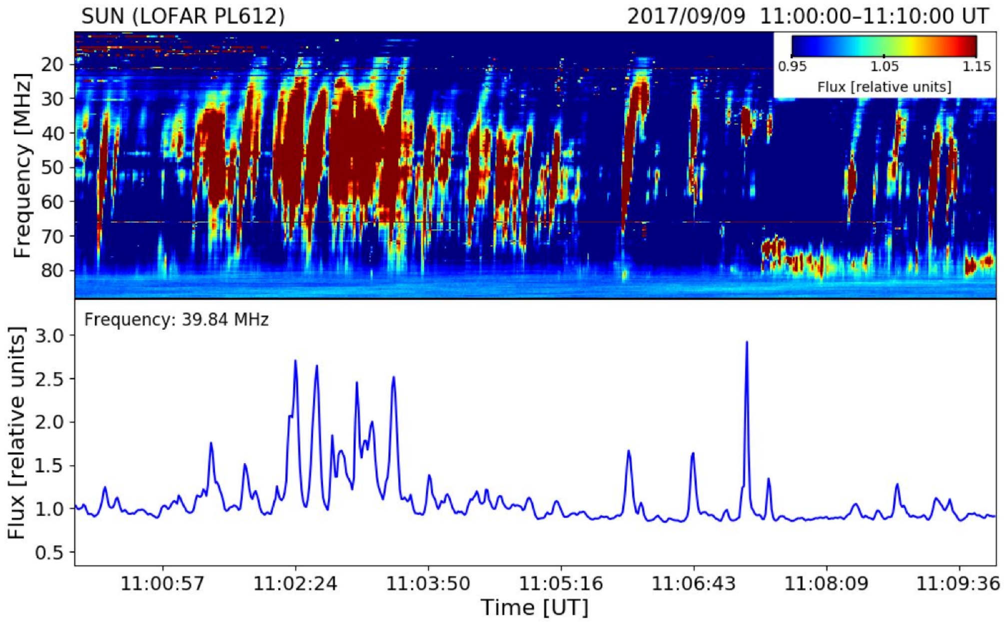
UNIWERSYTET WARMIŃSKO-MAZURSKI W OLSZTYNIE

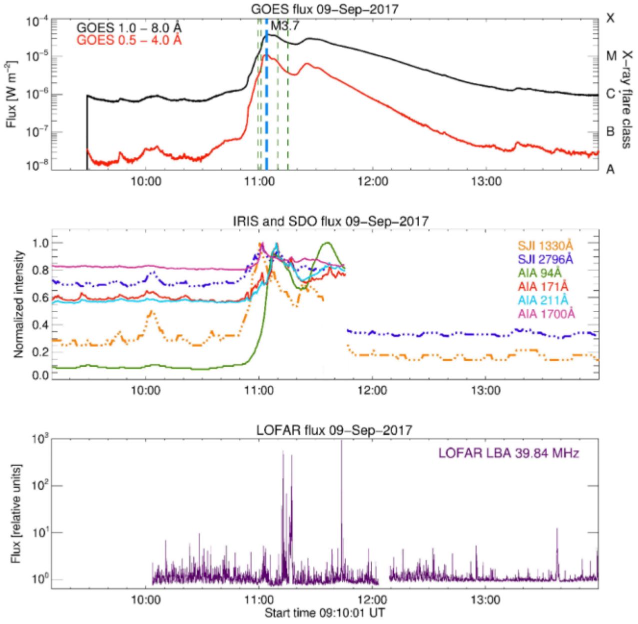
AIP Leibniz-Institut für Astrophysik Potsdam

LOFAR

# Storm of type III radio bursts recorded on 9th September 2017

In this work we presented study of the two solar radio events consisting of type III bursts, observed by LOFAR telescope in Bałdy in the single mode.




**Dabrowski** et al., *Type III Radio Bursts Observations on 20th August 2017 and 9th September 2017 with LOFAR Bałdy Telescope*, 2021, Remote Sens., **13**, 148

# Interferometric imaging of the type IIIb and U radio bursts

LOFAR

UNIWERSYTET WARMIŃSKO-MAZURSKI W OLSZTYNIE

In this study the source size of type IIIb and U solar bursts in a relatively wide frequency band from 20 to 80 MHz was determined (LC8_013: Interferometric Observations of the Active Regions in Radio Domain Before and After the Total Solar Eclipse on 21 August 2017, PI: B. Dabrowski).

TYPE U BURST
burst #1

TYPE IIIb BURST
burst #2

TYPE IIIb BURST
burst #3

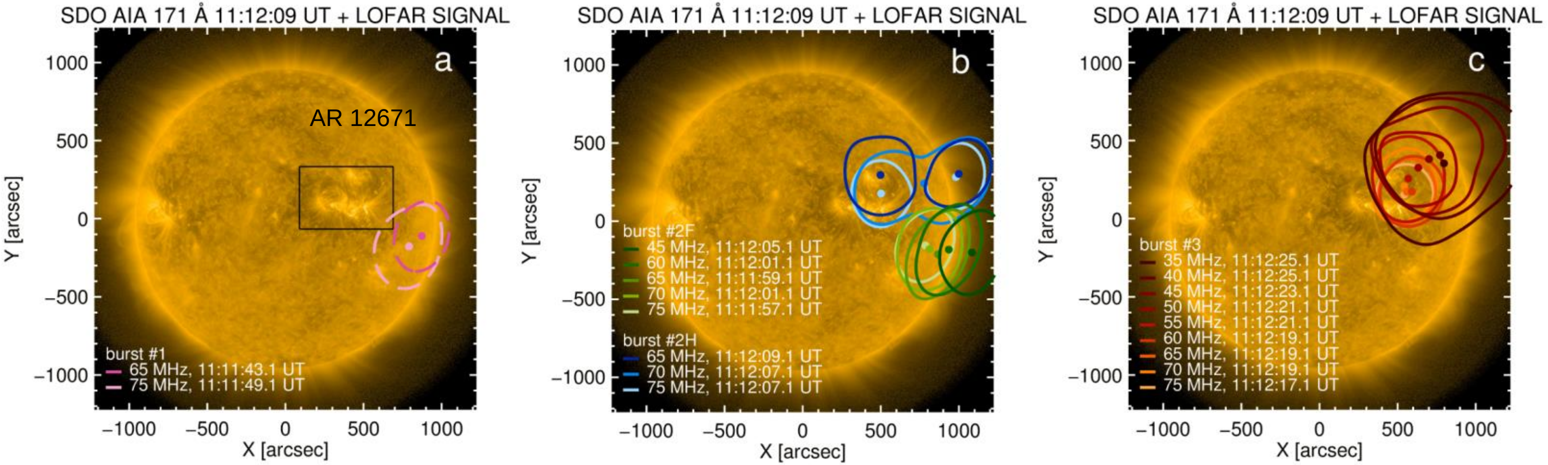
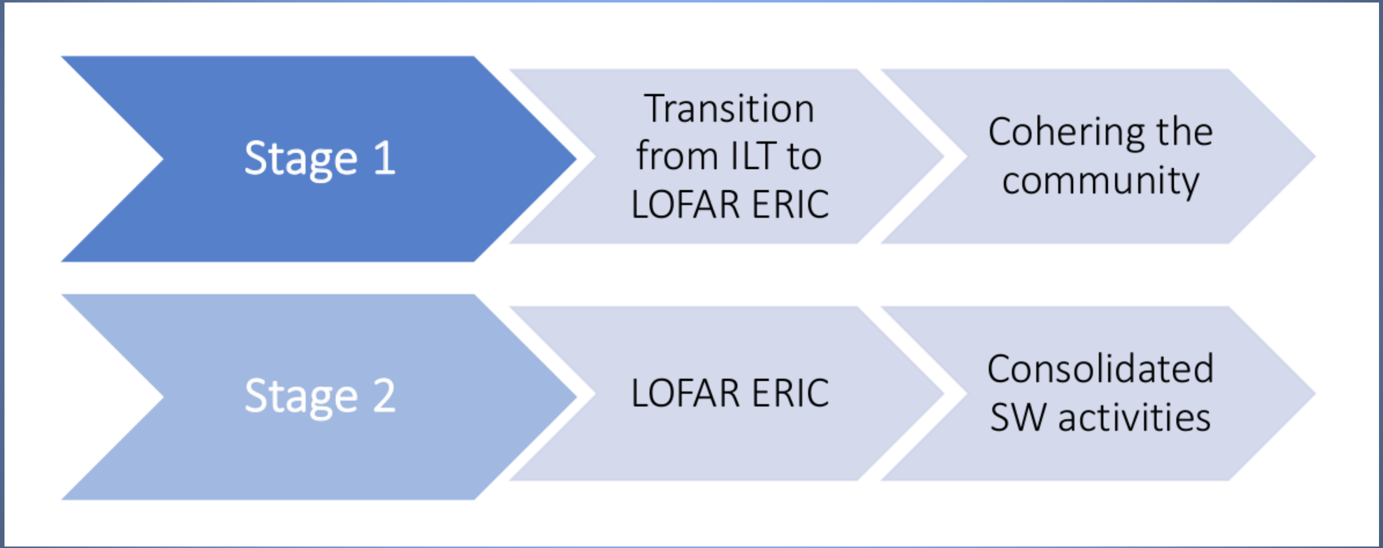



Image of the Sun received in the AIA 171 Å channel by SDO with superimposed color contours showing bursts #1, #2, and #3, at a range of frequencies.


**Dabrowski** et al., *Interferometric imaging of the type IIIb and U radio bursts observed with LOFAR on 22 August 2017*, 2023, A&A, **669**, A52

# Space weather in LOFAR ERIC

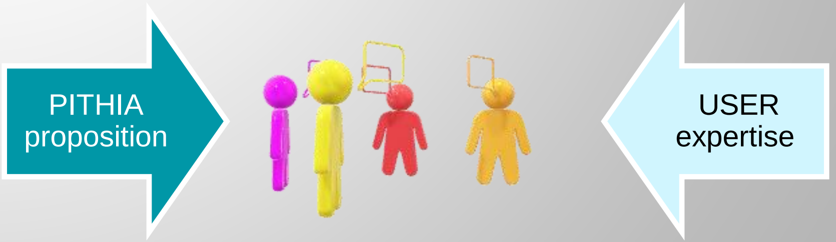



C. Baldovin

# PITHIA-NRF facilities for testing novel instruments

**The goal  is to enhance and promote cooperation with the space agencies, the aerospace industry, SMEs, and non-governmental organizations.**

**The innovation platform** is another important mechanism that lead to the integration of PITHIA-NRF research Currently, the operation of the participating Research Infrastructures is not coordinated and its networking is very
limited. For the first time, PITHIA-NRF integrates on a European scale, key national and regional research infrastructures tools to future development plans of the business/industrial sector

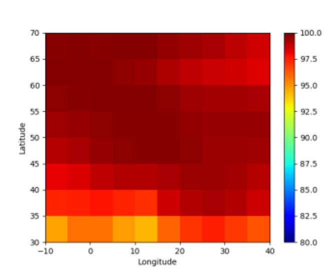


# Access to CBK PAN node

WP7: Access to PITHIA-NRF facilities

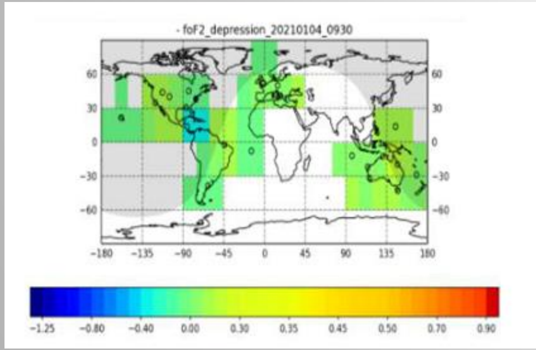
## Products/models

### Ionosphere model Helgeo2PT (H2PT):

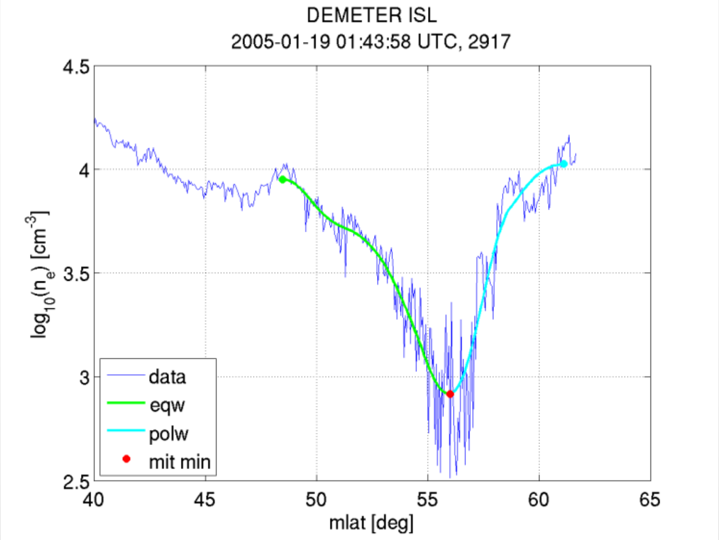



Spatial data availability plot for H2PT model (time period from 2020-07-01 to 2020-09-30)

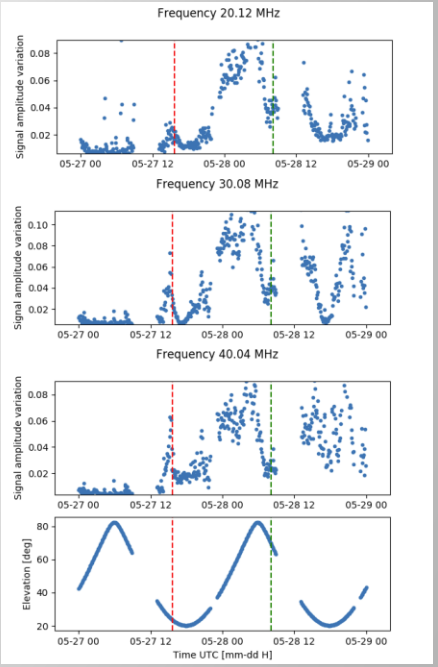
### Post-storm foF2 depression




### MIT parametrization: MIT position, borders and slope of the equatorial and polar walls

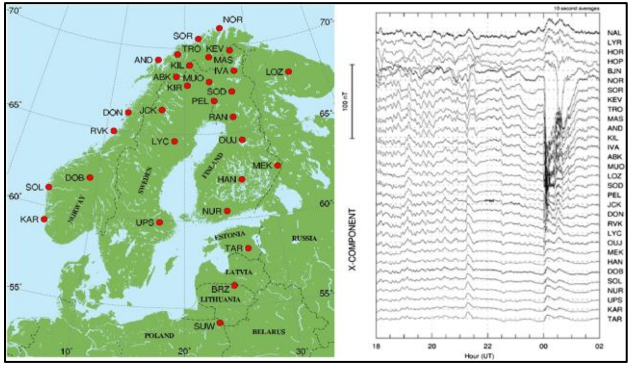


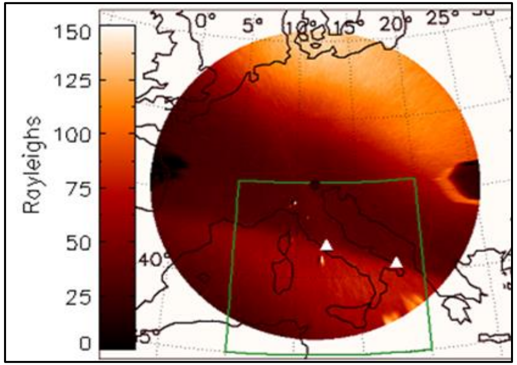

### Scintillation index from LOFAR PL610 :

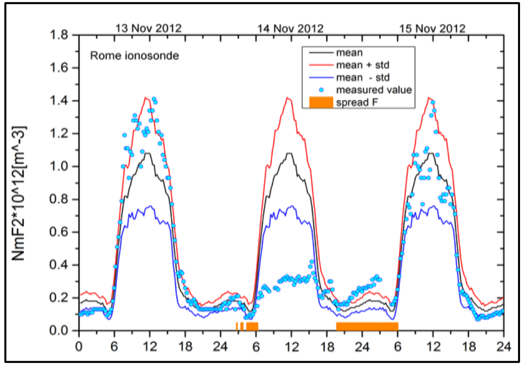


# Proposals for joint experiments among several nodes

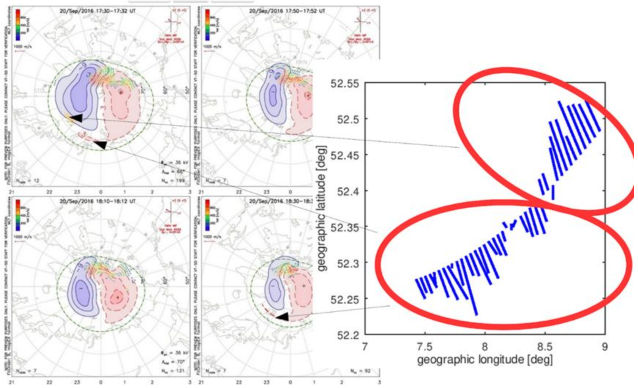
## LSTID morfology and propagation by help of optical, GNSS, magnetometer, LOFAR, EISCAT and HF

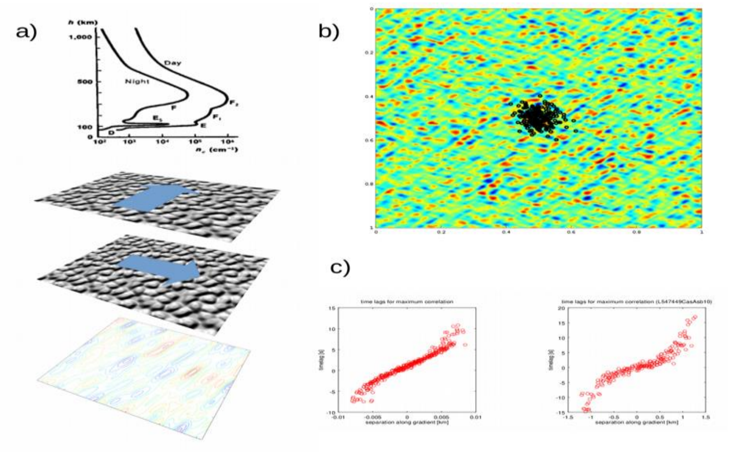



*Cesaroni et al., JGR 2017*




*Grzesiak et al. 2021*