DANTE – Science Requirements

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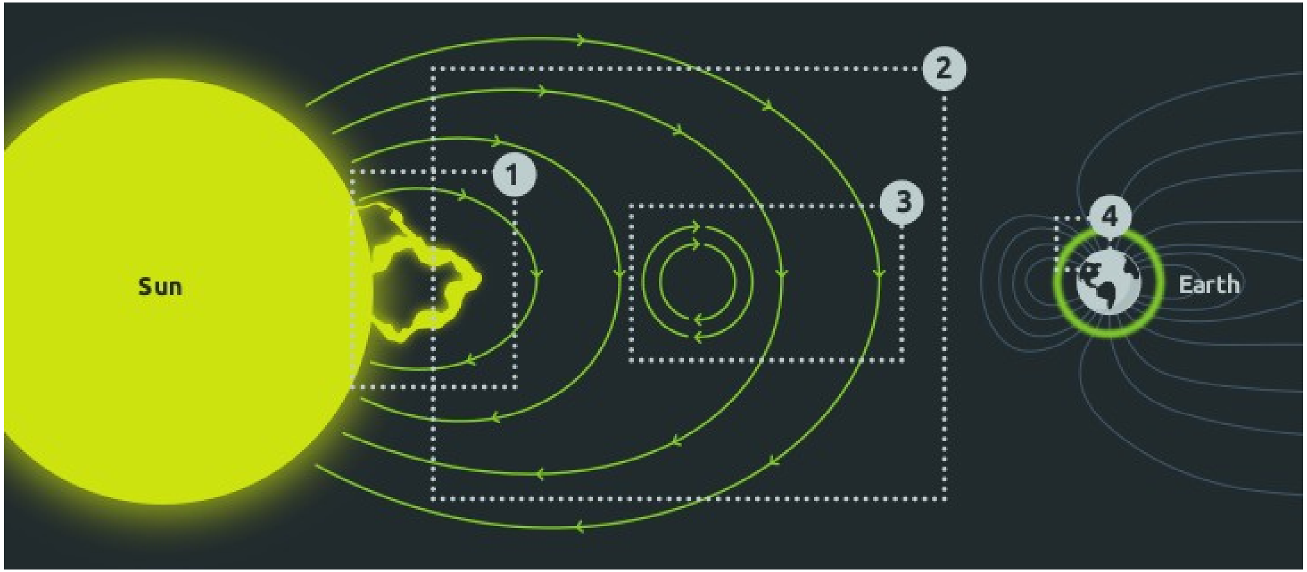
Towards Space-Weather Monitoring with Europe's Largest Radio Telescope

Richard Fallows

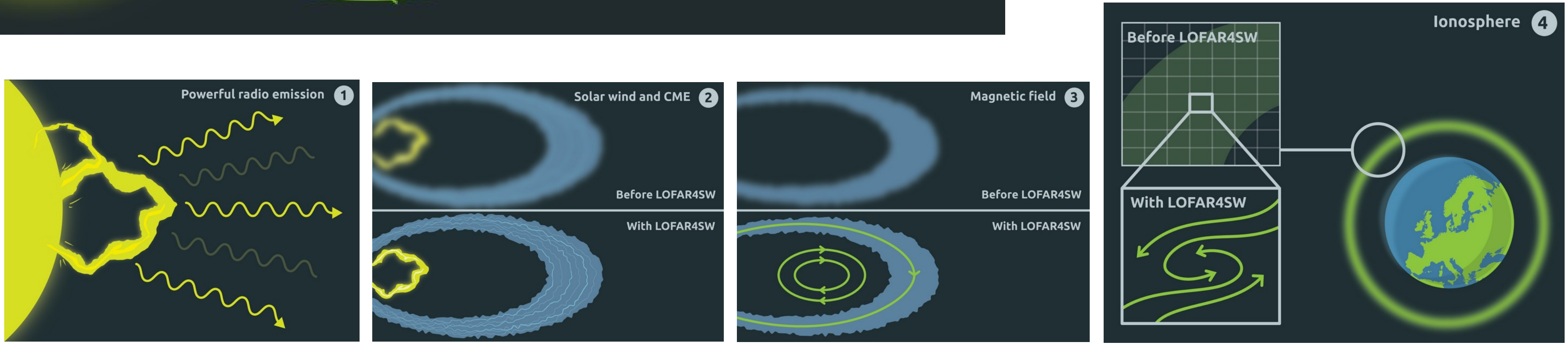
On behalf of the LOFAR4SW consortium

This project has received funding from the European Community's Horizon 2020 Programme H2020 INFRADEV-2017-1under grant agreement 777442.

LOFAR4SW: A Comprehensive Space Weather Observatory

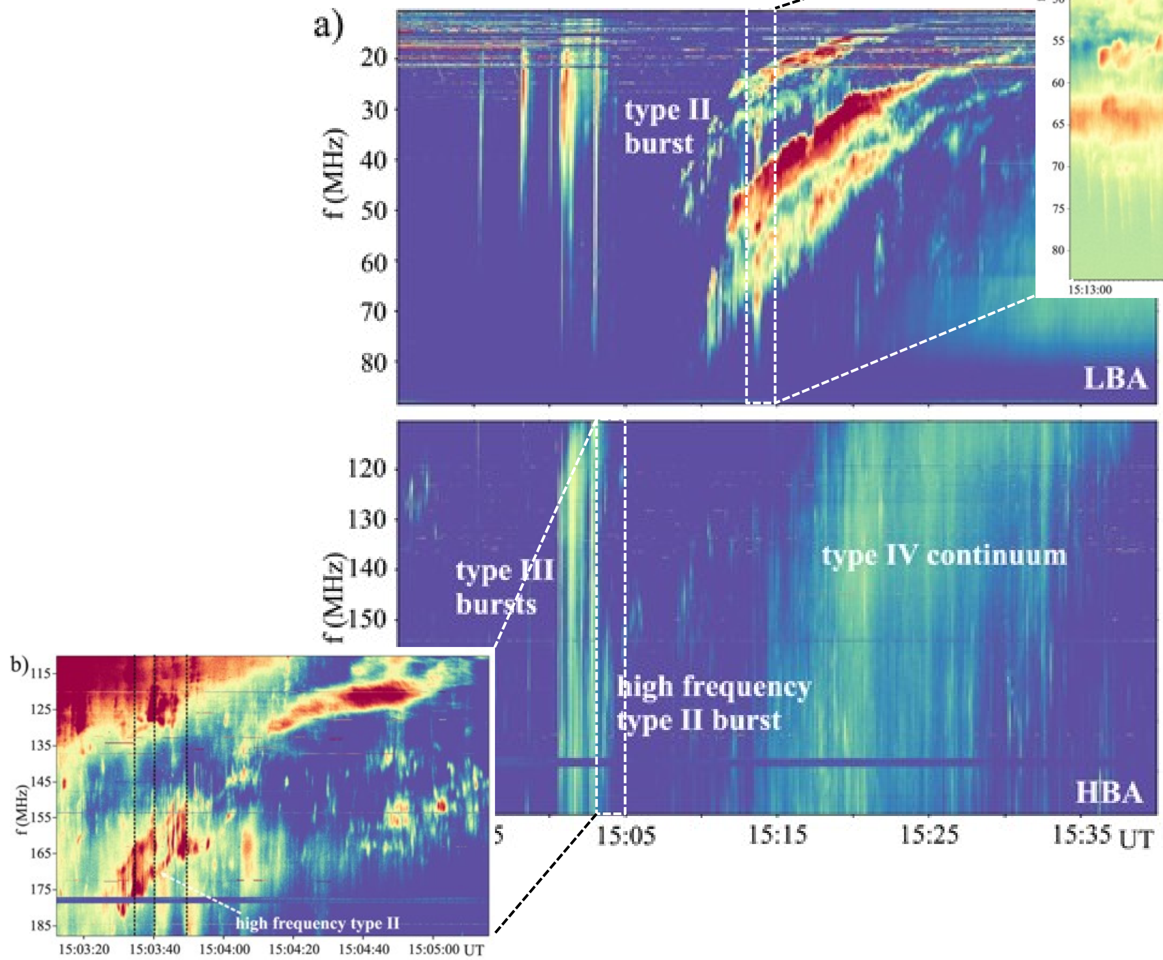


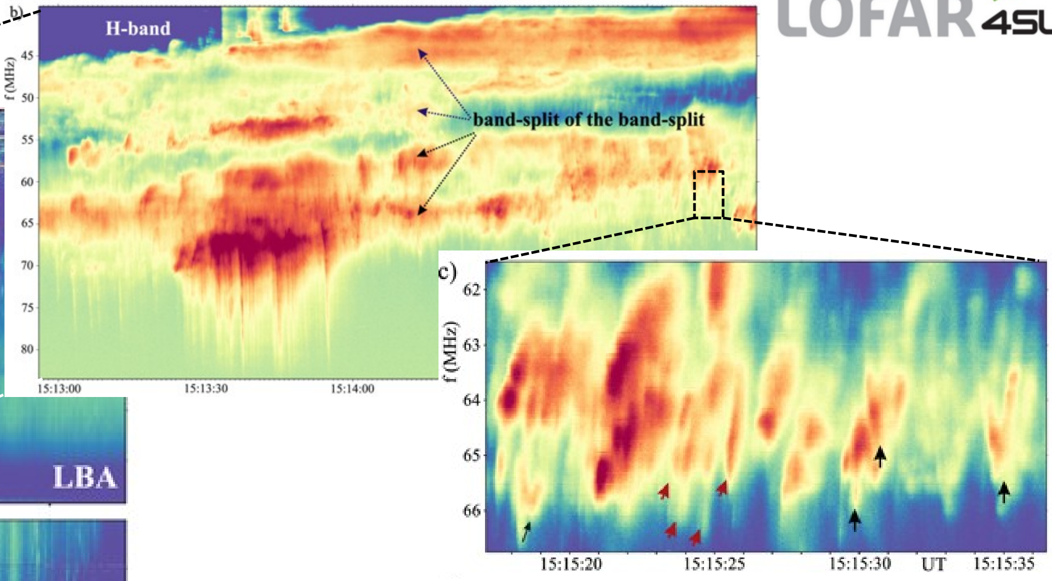
LOFAR is a fully-capable instrument for the observation of several aspects of space weather from solar flares to the solar wind to the Earth's ionosphere, with the ability to make significant scientific advances in these fields and provide global remote-sensing measurements to complement space-based observations.



Solar Radio Bursts

Magdelenic+ 2019





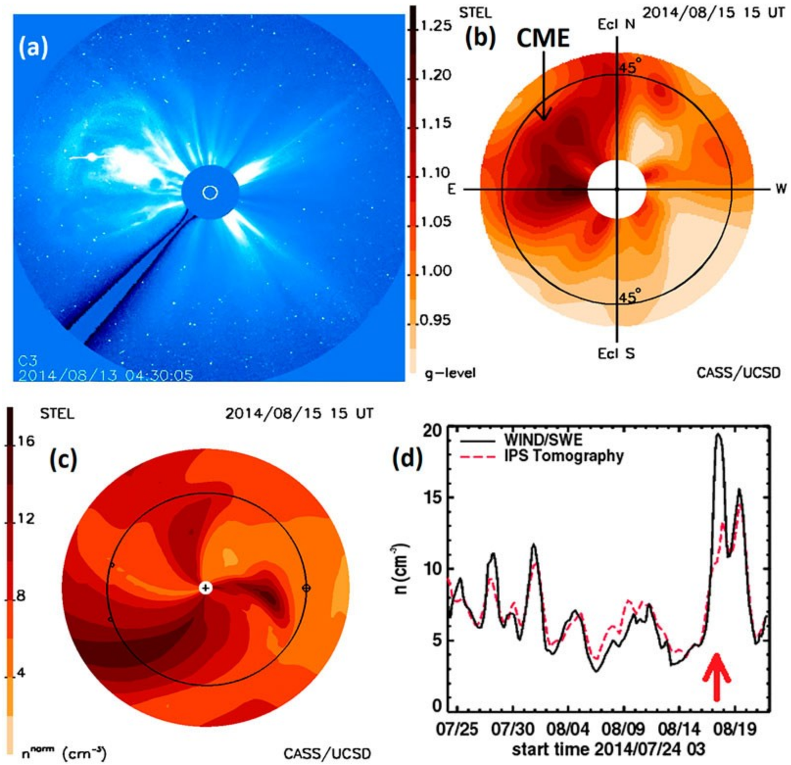
Radio bursts are indicators of activity within the solar corona, and act as tracers of material flowing along magnetic field structures.

LOFAR can take high-resolution dynamic spectra across a wide observing band to observe radio bursts in detail not seen before.

Studying these leads to a more fundamental understanding of the physical processes taking place within the corona, and how these processes lead to the eruption of material as a Coronal Mass Ejection.

The Solar Wind

Observations of the scintillation of any compact radio source due to density variations in the solar wind can be used to measure solar wind velocity and density throughout the inner heliosphere.

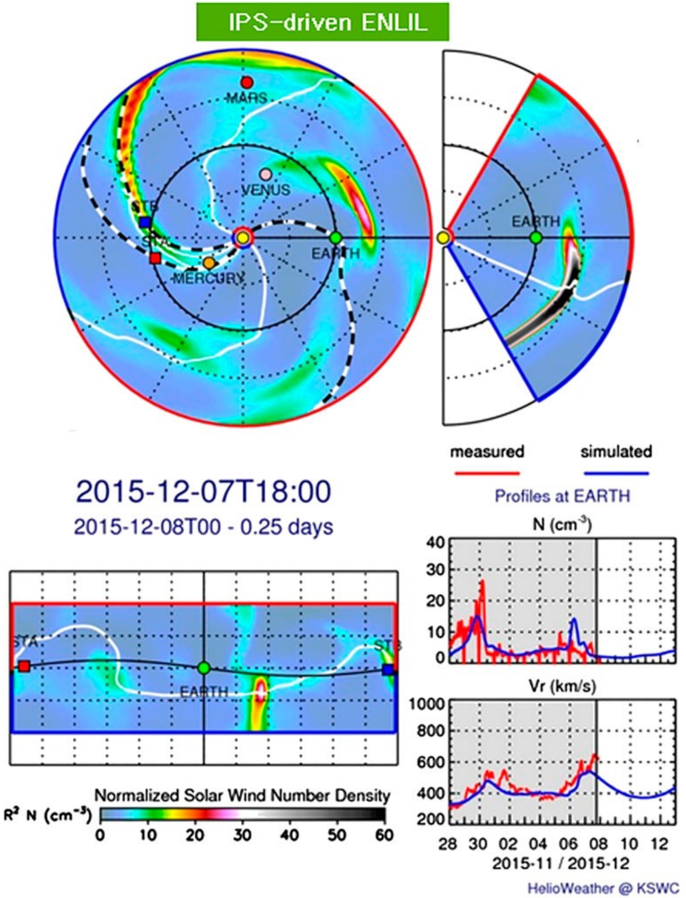


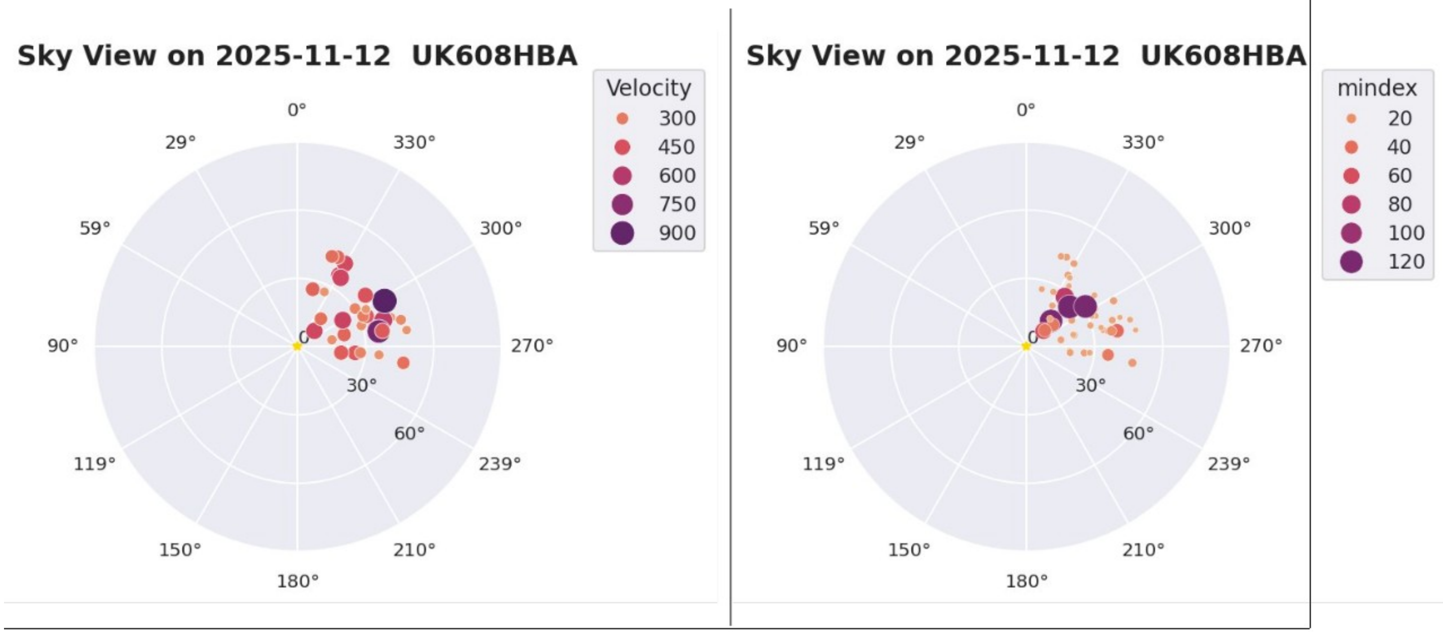
Jackson+, 2020

3-D tomographic modelling of ground-based remote-sensing observations provides forecasts of conditions near Earth (left).

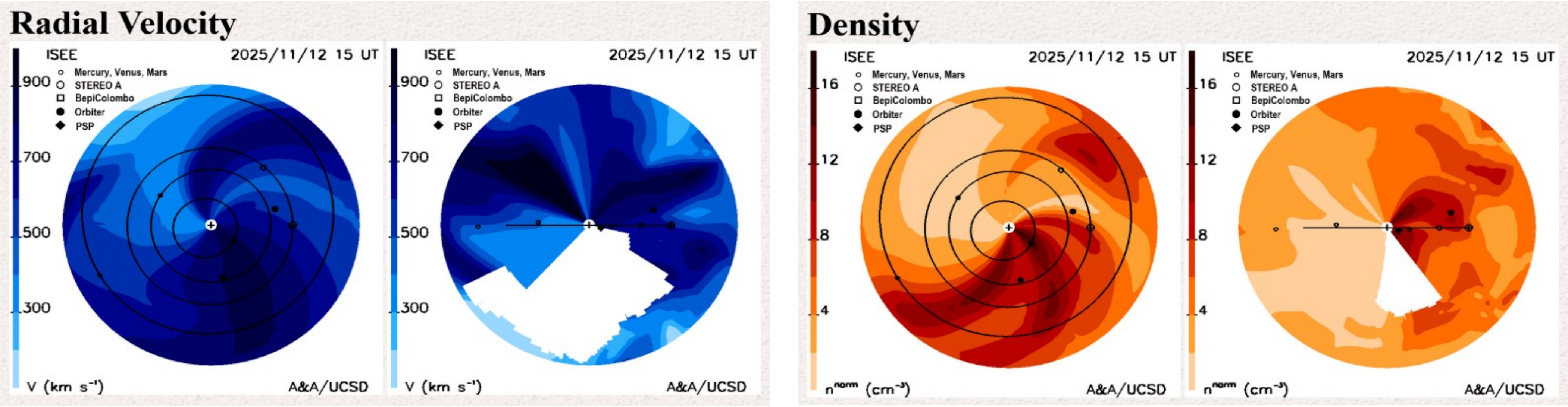
An ENLIL variant which uses this tomography as the solar wind input has been developed, **replacing solar surface extrapolation with real-world observation**.

This plots model velocity and density alongside values measured at Earth, and **forecasts a further five days into the future** (right).





Sky View on 2025-11-12 UK608HBA
Velocity
300
450
600
750
900
mindex
20
40
60
80
100
120
0°
29°
330°
59°
300°
90°
270°
119°
239°
150°
210°
180°
30°
60°



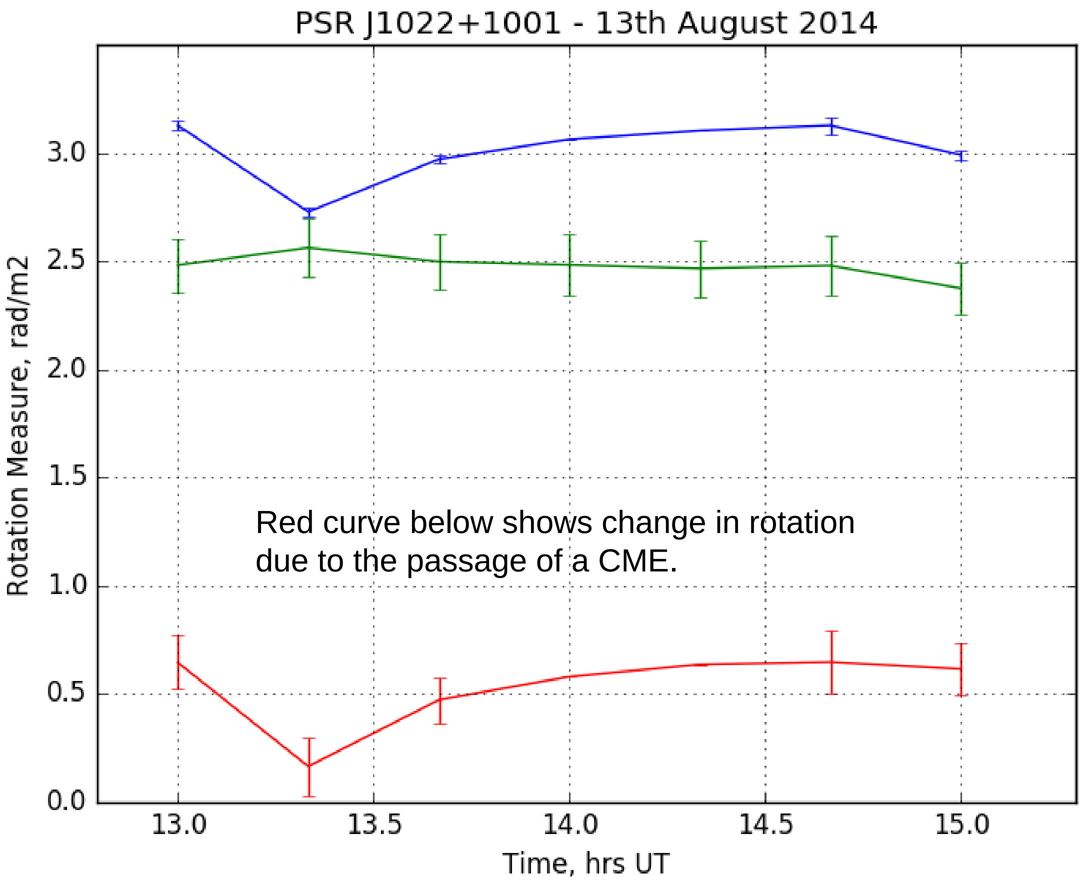
Radial Velocity
Density
ISEE
2025/11/12 15 UT
Mercury, Venus, Mars
STEREO A
BepiColombo
Orbiter
PSP
900
700
500
300
V (km s⁻¹)
16
12
8
4
n^norm (cm⁻³)
A&A/UCSD

Interplanetary Magnetic Field

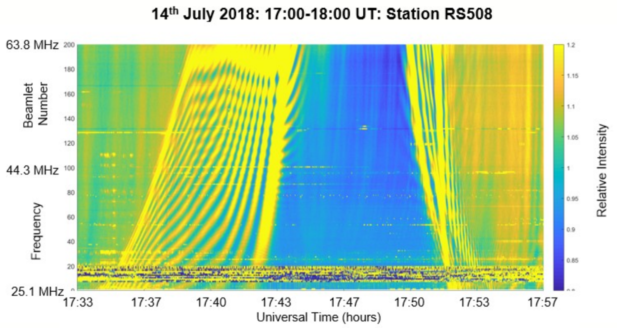
Measurement of the strength and direction of the interplanetary magnetic field is the “holy grail” of space weather.

Measurement of the Faraday rotation of pulsar signals shows **considerable promise in being able to observe the magnetic field in a CME**.

Such measurements would best be used to help prune ensemble model runs, as with the pulsar column density measurements.



Ionospheric Scintillation

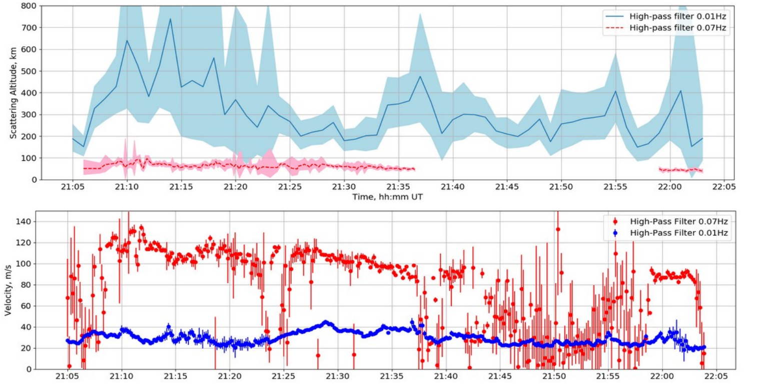


Weird feature of ionospheric scintillation seen only once so far. Cause under investigation, *Wood+.*

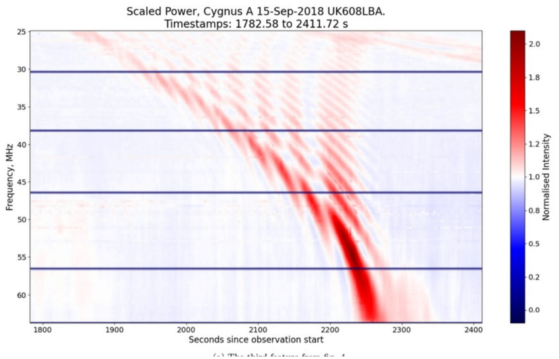
LOFAR observations of ionospheric scintillation expand the possibilities beyond anything available with GNSS measurements.

Features are seen in dynamic spectra which would be invisible to discrete-frequency measurements, some are seen only rarely, and sometimes only by one LOFAR station.

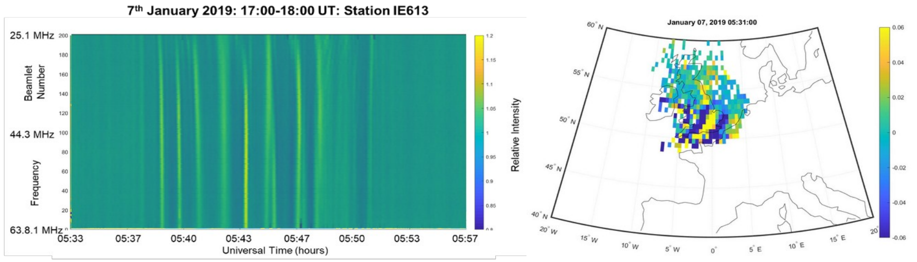
Such observations lead to new insights into the causes of the scintillation and offer new possibilities to advance modelling beyond the current state of the art.



Velocity and altitude of scattering pattern found to be due to two simultaneous Travelling Ionospheric Disturbances moving in perpendicular directions, *Fallows+, 2020.*



Another feature seen only once; modelling suggests that this is due to a small-scale feature in an otherwise stable ionosphere, *Boyde+, in prep, 2022.*



Intensity scintillation linked to horizontally-propagating plasma waves inferred from Global Navigational Satellite Systems (GNSS), *Dorrian+, in prep, 2022.*

Primary requirement:

The dual-beam system shall not interfere with regular astronomy operations.

This means effective, interference-free, separation between the two HBA beams.

LOFAR4SW: Towards space weather monitoring with LOFAR

Solar Use Cases

Case 1 title: Monitoring Solar Activity for Space Weather Operations

Case 2 title: CME Imaging for CME Physics Research

Case 3 title: Type II and Shock Analysis

Case 4 title: Type IIIs and Flares (Particle Acceleration and Coronal Propagation)

Case 5 title: Quiet Sun and Coronal Holes

Case 6 title: Long-term Particle Acceleration, Trapping, and their Relationship to Flares and CMEs

Case 7 title: Fine Structure and Fundamental Physics of Space Weather Properties

Case 8 title: Type I Noise Storms and Active Region Physics

Case 9 title: Long-term Monitor / Trigger for Flares

Case 10 title: Planetary Space Weather

Nearly 30 Use Cases generated in Science Requirements Workshop in Paris in May 2018.

Now distilled into a limited number of "observing modes".

Heliosphere Use Cases

Case 1 title: Multi-Stations IPS for Space Weather Science (includes comparison with NASA-ESA S/C) .

Case 2 title: Using g-levels from Observations of IPS to Characterise Solar Wind Density

Case 4 title: Space Weather g-levels and Cross Correlations

Case 5 title: All-Sky Snapshot of g-level and Single-Site Velocities

Case 6 title: Exploring Spatial and Temporal Solar Wind Turbulence Scales

Case 7 title: Inner Heliosphere Density Exploration (pulsar dispersions vs g-level conversion)

Case 3 title: Observations of IPS via interferometric imaging

Case 7 title: Inner Heliosphere Density Exploration (pulsar dispersions vs g-level conversion)

Case 8 title: FR with Pulsars

Case 9 title: FR with Polarised Galactic Background

Ionosphere Use Cases

Case 1 title: Imaging spectral riometers for space-weather science and forecasting

Case 2 title: Monitoring of ionospheric S4 index to track scintillation above LOFAR

Case 3 title: Monitoring scintillation pattern flows above LOFAR

Case 4 title: Single-station all-sky scintillation monitoring

Case 5 title: Wide-bandwidth monitoring of scintillation structure

Case 6 title: High-resolution all-sky monitoring of scintillation and refractive shifts above the LOFAR core

Case 7 title: Characterisation of Travelling Ionospheric Disturbances over Europe

Case 8 title: Mesospheric and Lower Thermospheric (MLT) wind fields for atmospheric/ionospheric coupling studies at mid latitudes

Case 9 title: Passive radar capabilities for multiple target studies in the LBA frequencies

Case 10 title: Observing TIDs with combined LOFAR interferometry and GNSS

Case 11 titile: Passive radar capabilities below 10 MHz using LOFAR

These cases cover scientific and operations-based uses across each of the three primary domains of solar, heliosphere, and ionosphere. An additional use case focuses on space weather at Jupiter.

LOFAR4SW: Towards space weather monitoring with LOFAR

Sub-array core stations, split bandwidth

Solar imaging:

Use full LBA plus 2(?) HBA tiles per station

Pulsar observations?:

Use full LBA plus all non-solar HBA tiles per station.

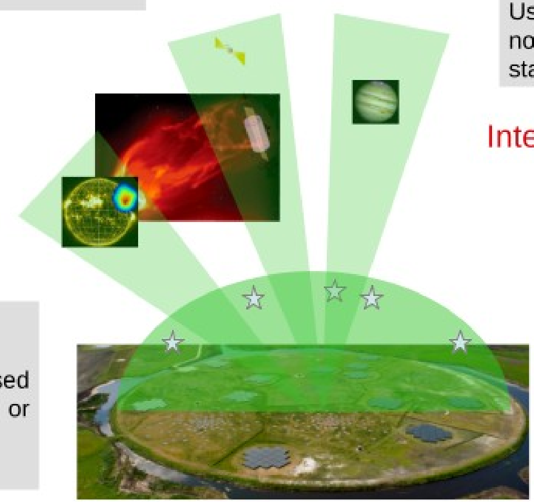
Interleave observations

Jupiter:

- Use LBA 15-45MHz for dynamic spectra;
- Take LBA+HBA snapshot images once per hour, interleaved with pulsar observations.

Trigger modes:

Switch to increased resolutions or between modes.



Core+remote stations

Observe with different stations

IPS:

Use full HBA at all remaining international/remote stations for full-resolution dynamic spectra.

Solar dynamic spectra:

Use full LBA plus HBA at 1-2 international/remote stations only for full-resolution dynamic spectra.

Pulsar observations?:

Use full LBA plus all HBA tiles at single international station(s).

International stations may not have the sensitivity needed for this; under investigation.

International stations

Ionosphere:

Piggy-back

- Observe intensity scintillation and source movement in all-sky images with individual stations.
- At night, when stations are not used for IPS/pulsar observations, observe wide bandwidth scintillation.

LBA only during solar/pulsar observations; HBA all-sky imaging may be possible at other times.

However, we have to work with the number of stations which are currently envisaged to be upgraded to dual-beam:

- 8 international stations
- 2 remote stations(?)

LOFAR4SW: Towards space weather monitoring with LOFAR

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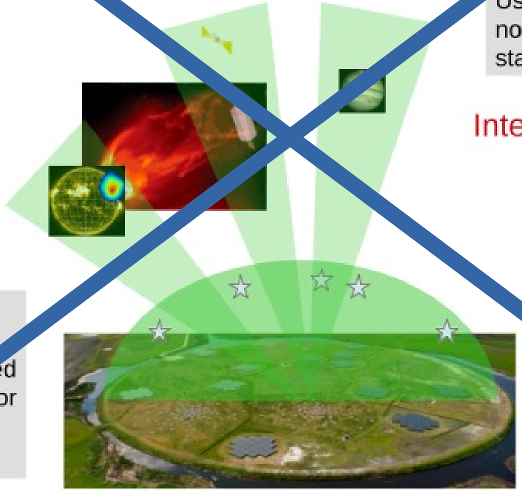

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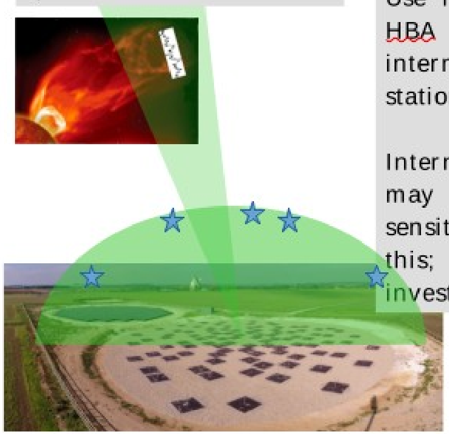

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LBA only during solar/pulsar observations; HBA all-sky imaging may be possible at other times.

Final LOFAR4SW Priority Remainder

Use Case	Subject	Final Priority (across all domains)	Final Priority (across all domains)
H8	Faraday rotation from pulsars (R2O)	Top	1
[redacted]	[redacted]	[redacted]	[redacted]
H2	G-levels from IPS	Top	1
H4	Space weather IPS	Top	1
H5	All-sky snapshot IPS	Top	1
[redacted]	[redacted] ~40MHz]	[redacted]	[redacted]
S1	SW monitoring	Top	1
H6	Solar wind turbulence (R2O)	High	2
[redacted]	[redacted]	[redacted]	[redacted]
I5	Wide-bandwidth scintillation (R2O)	High	2
[redacted]	High-resolution all-sky [redacted] scintillation (core)	[redacted]	[redacted]
P1	Jupiter Space Weather	Medium	2
[redacted]	[redacted]	[redacted]	[redacted]
H1	Multi-station IPS (R2O)	High	3
H2	G-levels from IPS (R2O)	High	3
[redacted]	[redacted]	[redacted]	[redacted]
S3	Type II/shocks (R2O)	High	3
[redacted]	[redacted]	[redacted]	[redacted]
I2	Monitoring S4	High	3
H7	Solar wind density from pulsar DM (R2O)	High	4

Use Case	Subject	Final Priority (across all domains)	Final Priority (across all domains)
[redacted]	[redacted]	[redacted]	[redacted]
S6	Long term sources (R2O)	High	4
[redacted]	[redacted]	[redacted]	[redacted]
H1	Multi-station IPS	High	5
S2	CME imaging	Medium	6
H8	Faraday rotation from pulsars	Medium	7
I4	All-sky scintillation (single station)	Medium	8
H7	Solar wind density from pulsar DM	Medium	9
[redacted]	[redacted]	Not Classi- [redacted] Skies	[redacted]
[redacted]	[redacted]	Not Classi- [redacted] Skies	[redacted]
I9	Passive radar (> 40MHz)	Not Classi-fied/Blue Skies	-

Additional Science Possibilities

- These come down to what is possible to achieve with [multiple] single stations, i.e., observations performed in Local mode.
  - Pulsar observations for timing etc;
  - Planetary observations, such as Jupiter bursts and Saturn lightning;
  - Olaf’s project.
- Understanding from LOFAR4SW: science motivations for funding each individual station upgrade dictate the priority for use of that station’s second beam. For the UK, that’s space weather; for others, it may be different.

Scope of the DANTE Project

- The limited number of stations to be upgraded limit the science cases to those which can be accomplished via single stations.
  - Processing can be done locally, as for Local station usage. (Possible exception for Dutch remote stations).
  - Scope of DANTE can be limited to signal chain into the second-beam DUPPLO rack. Data transport and processing from there can be the responsibility of individual stations, as for Local mode operations.

One Final Plea to Station Owners

With the advent of LOFAR2.0 and ultimately DANTE, can we please agree on a common control system and processing which produces common data products?!?