The Low-Frequency Array (LOFAR) interferometer: a unique tool for Solar-Earth interaction studies. Possibilities and perspectives

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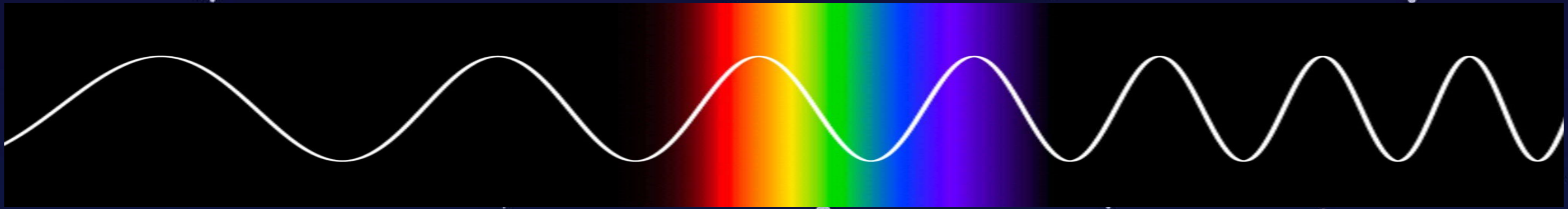
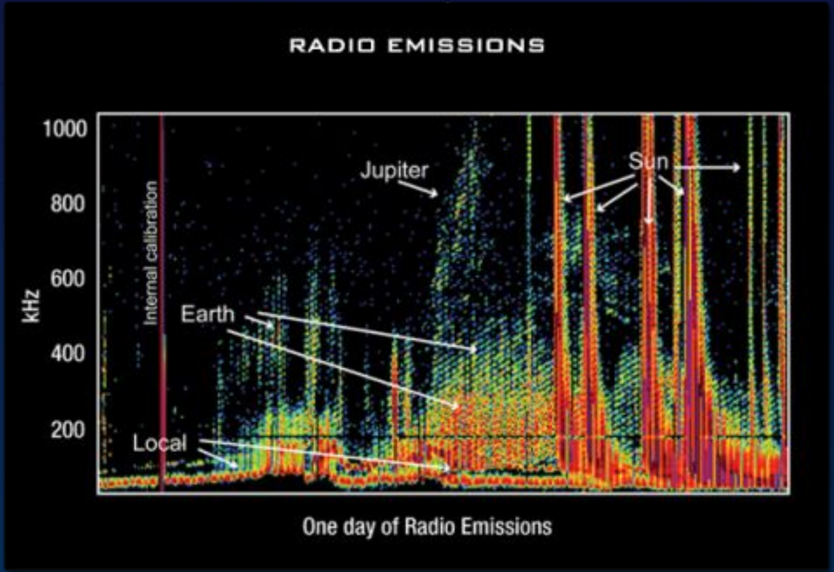


Extragalactic	51%
Pulsars and transients	15%
Instrumentation and methods	12%
Galaxy	7%
Solar	7%
Cosmic Rays	4%
Lightning	2%
Ionosphere	1%
Exoplanets	1%



Credit: NASA/GSFC Wind Waves Michael L. Kaiser

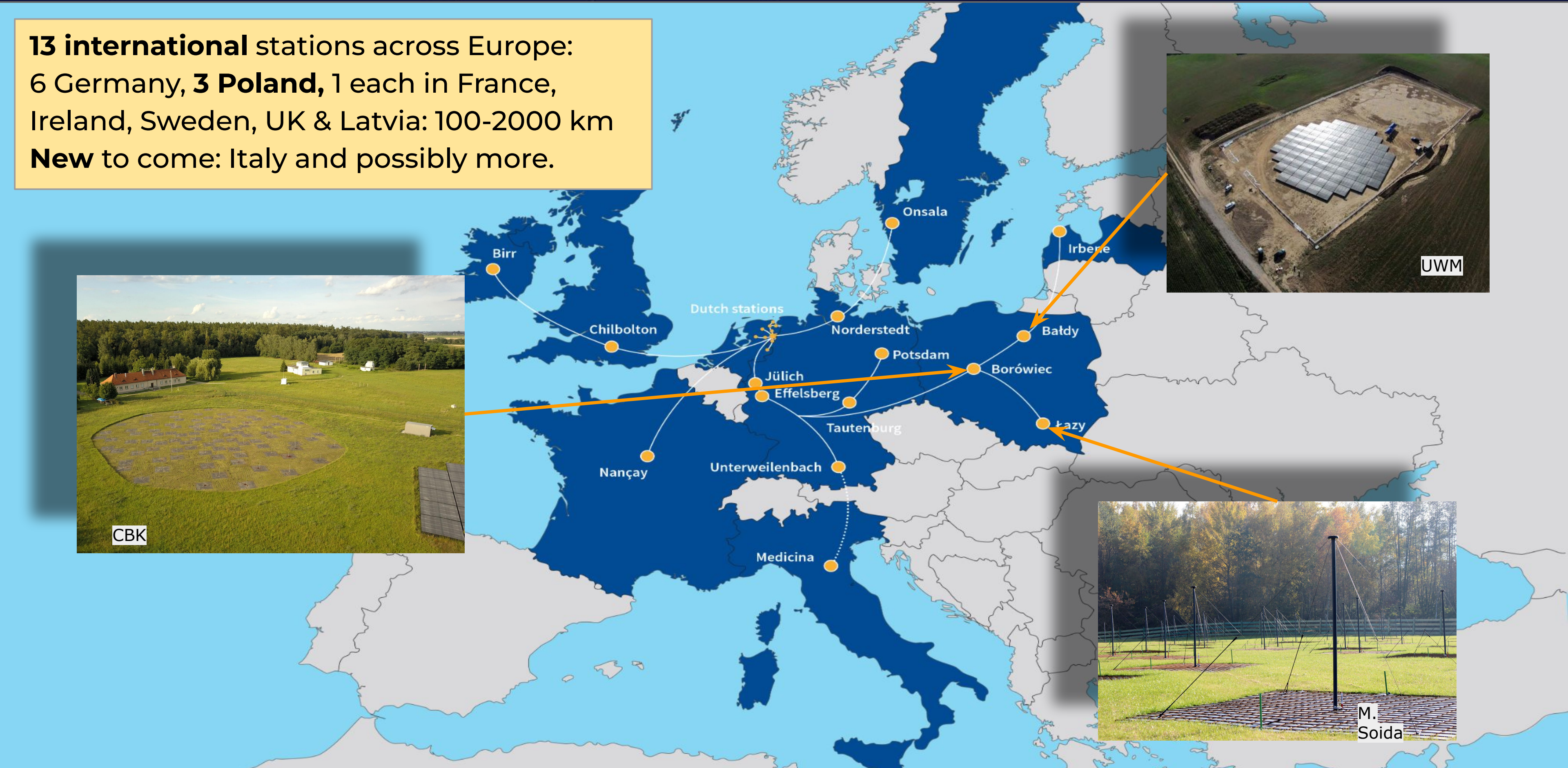
LOFAR: World's largest and most flexible low frequency radio telescope

24 core stations, Exloo: distances of 30 m – 3 km, 3 km diameter.
14 remote stations in the Netherlands: ~ 5-200 km

LOFAR core stations at Exloo

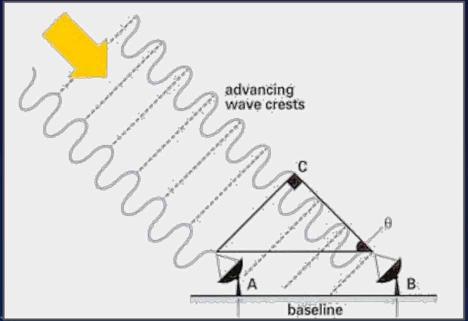
LOFAR: World's largest and most flexible low frequency radio telescope

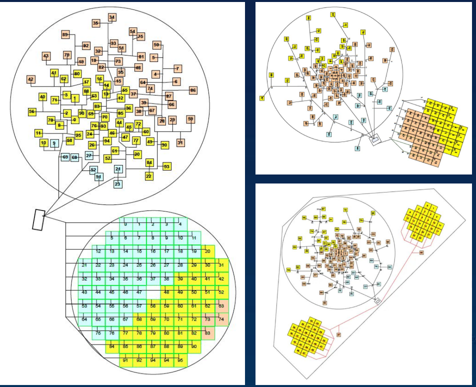
13 international stations across Europe:
6 Germany, **3 Poland,** 1 each in France,
Ireland, Sweden, UK & Latvia: 100-2000 km
New to come: Italy and possibly more.



LOFAR: World’s largest and most flexible low frequency radio telescope

Interferometry





Left:
Configurations of single LOFAR station: (left) international, (top right) remote, (bottom right) core.

Source: ASTRON

LOw Frequency ARray:
frequency range: **10 - 240 MHz**.

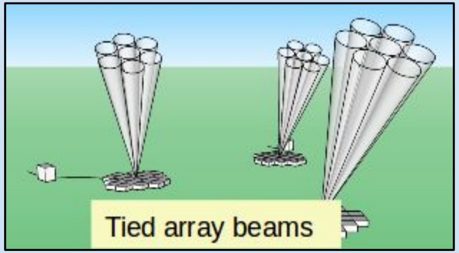
Stations consist of multiple “simple” dipole antennas

Antenna signals are coherently added to form a “beam”

Different modes:
- Single station data
- Tied array beams
- Interferometric mode

LBA: 10 -80 MHz:
- Dipole: all sky
- Station beam: ~10 degrees

HBA: 110-240 MHz:
- Tiles of 4x4 antennas: ~20 degree beam
- Station beam: ~ 4 degrees

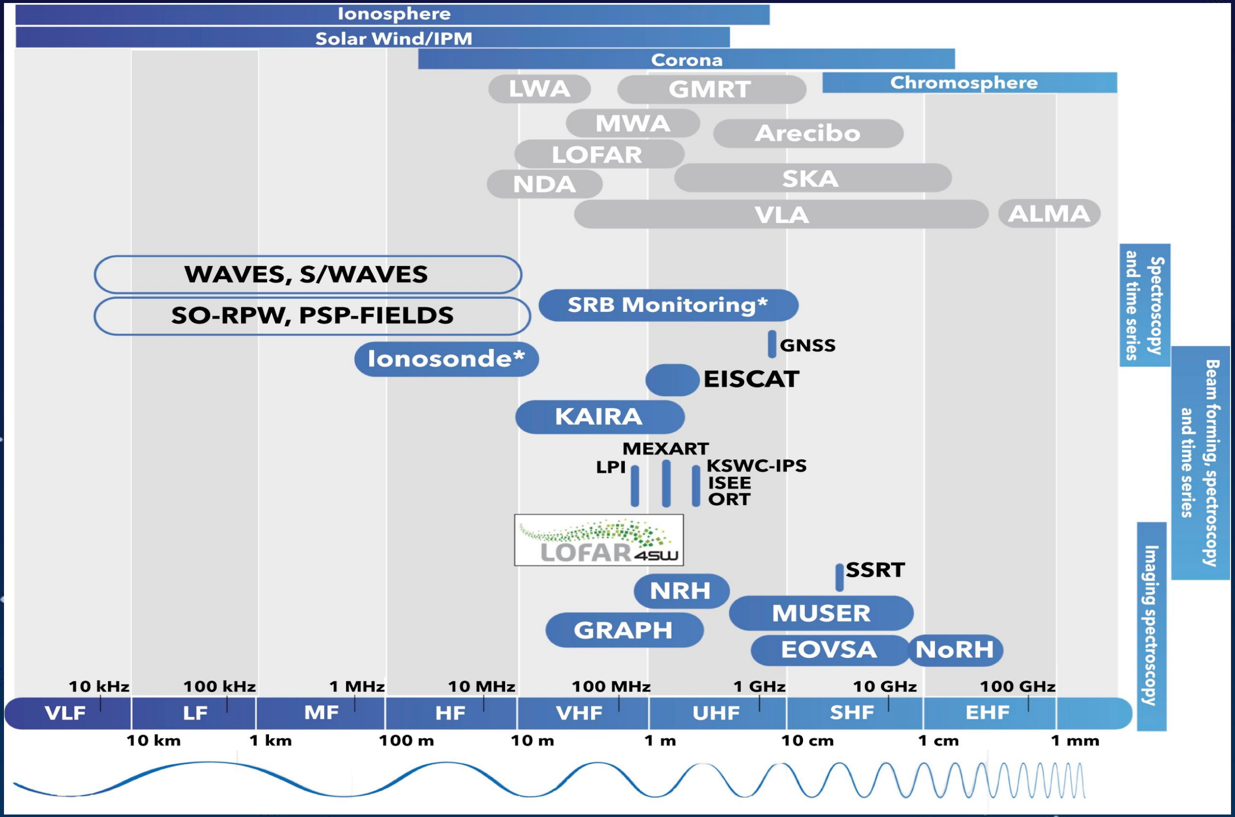


Core & Remote stations: 48 HBA, 96 LBA.
International stations: 96 HBA, 96 LBA

LOFAR in the landscape of radio instruments

Might observe SW related effects, but not dedicated to it.

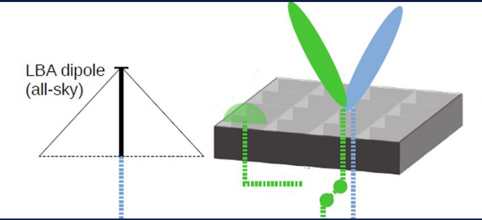
Dedicated to solar/heliospheric/ ionospheric studies

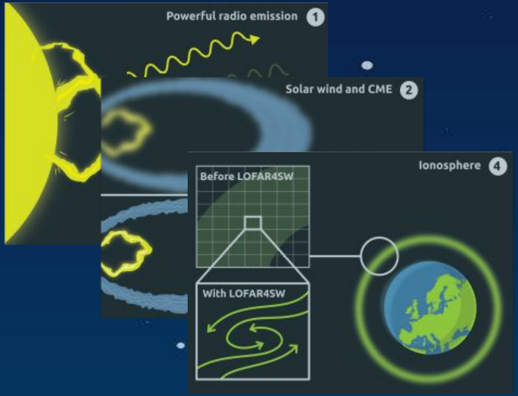


E.P. Carley et al. (https://doi.org/10.1051/swsc/2020007)

What is LOFAR4SpaceWeather and what is its goal?

- The LOFAR4SW was a Horizon 2020 (H2020) INFRADEV **design study** which ran from Dec 2017 to Feb 2022.
- It aimed to **design a full conceptual and technical description** of the LOFAR upgrade **allowing simultaneous operations** as a radio telescope designed for **astronomical research** as well as a infrastructure working 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.**

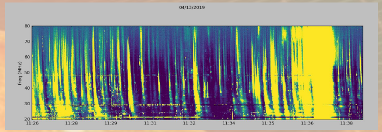




LOFAR4SW: A comprehensive Space Weather Observatory
Sun, Heliosphere and Ionosphere observations

Sun

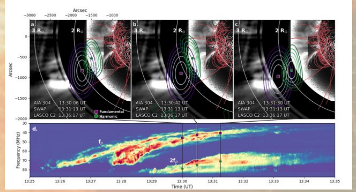
➔ **Monitoring Solar Radio Activity**



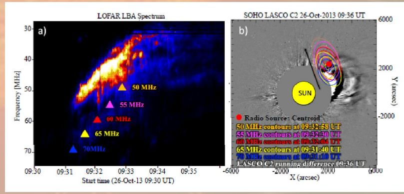
Zucca @ *Twitter*

➔ **Imaging of Radio Emissions**

Maguire et al., 2021



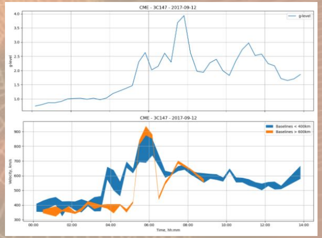
➔ **Solar radio bursts**



Zucca *et al.*, 2018

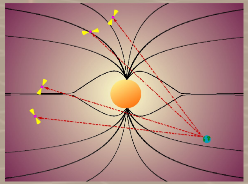
Heliosphere

➔ **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.

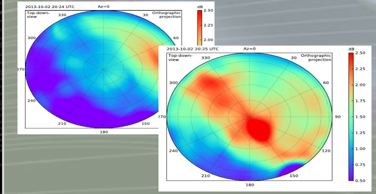
➔ **Faraday Rotation**



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

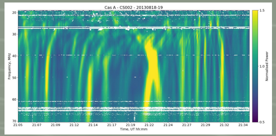
Ionosphere

➔ **Spectral riometer**



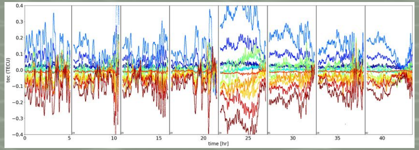
KAIRA data: McKay *et al.* (2015), Radio Science 50

➔ **Ionospheric scintillation**



Single station Scintillation spectrum CasA

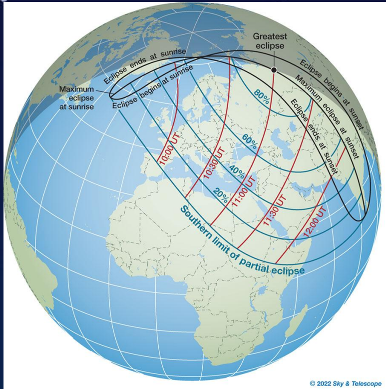
➔ **TIDs**

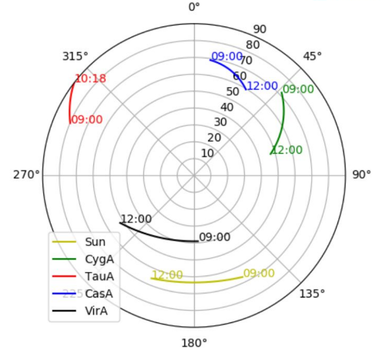


differential TEC vs time, all Dutch stations

Credit: NASA

Ionosphere: Looking for the solar eclipse signature



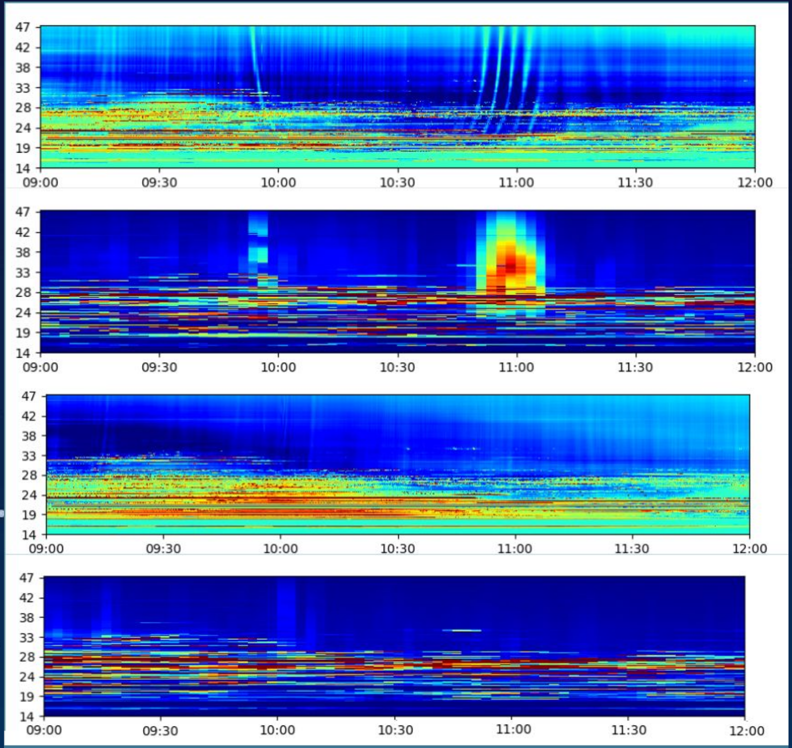


The solar eclipse of October 25, 2022, was a partial solar eclipse visible from Europe, the Urals and Western Siberia, Central Asia, Western Asia, South Asia and from the north-east of Africa. (Left top)

- ➔ **left bottom:** During the event, the observation of strong radiosources - CasA, CygA, and VirA - has been carried out, depending on their availability . We used bands in range 14-47 MHz. The Sun was observed in range 5-99 MHz.

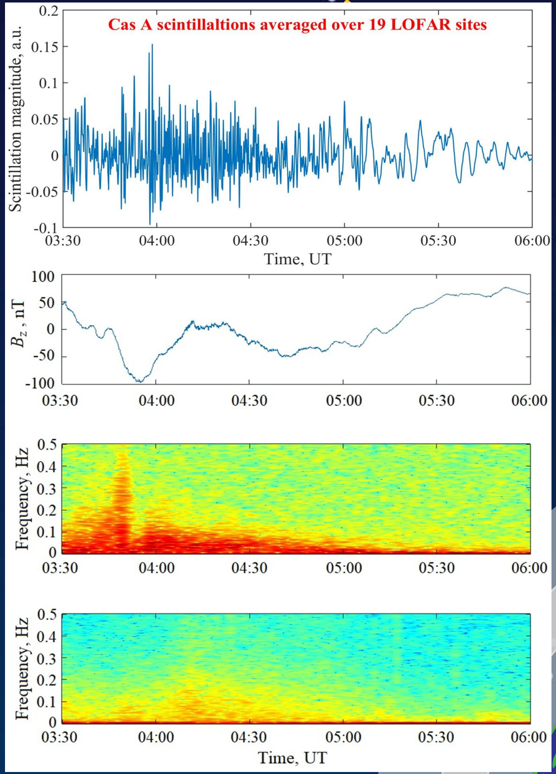
- ➔ **Right, numbered from top :** (1) Intensity of CasA, the diffraction structure is clearly visible. The pattern is caused by a small-scale structure passing through the ionosphere. It is possible to see the dispersion and the difference in the time of its transition. There is no direct connection between the eclipse and ionospheric scintillation, but scintillation intensifies with passing diffraction structure (2). (3) & (4) Dynamic spectrum and calculated scintillation index for CygA, respectively.

- ➔ Information in LOFAR single station is limited but is an opportunity to get additional information and should be used with other data



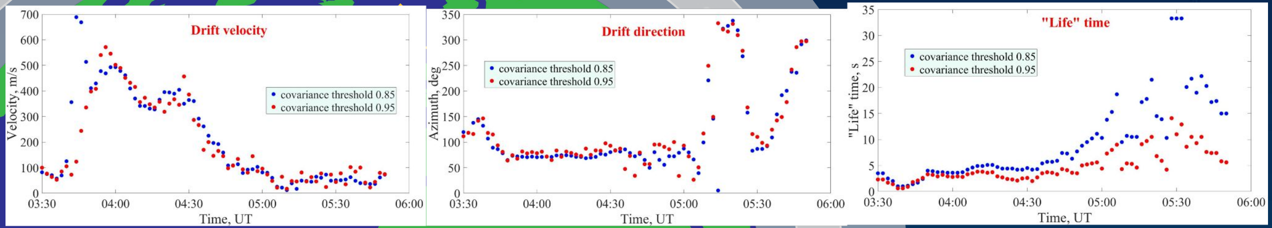
M. Pozoga et al.

Ionosphere: LOFAR to study ionospheric scintillations



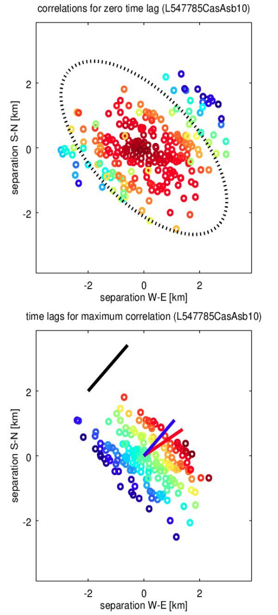
Analysis of selected Cassiopeia A signal records (19 stations) during the magnetic storm recovery phase on September 25, 2016

- ➔ **left:** Cas A signal averaged over all the records from 19 LOFAR stations whose envelope demonstrates a rather noticeable decrease near 03:45 UT(1 from top). A similar specific trough, delayed by ~ 10-15 min (2), can be observed in the magnetic field component recorded by the Abisko station. Hypothesis is also supported by a fairly high similarity in the dynamic spectra of the scintillations and magnetic field variations shown in 3 and 4 from top, respectively.
- ➔ **bottom:** the drift velocity magnitude (left), azimuth (middle) and decay (“life”) time for two correlation function thresholds (right). As can be seen, the drift has the zonal direction with its maximum magnitude about 700 m/s, which supports our hypothesis since such velocity gives a similar delay of structures in the magnetic signal with respect to the LOFAR observations



V. Galushko & M. Grzesiak

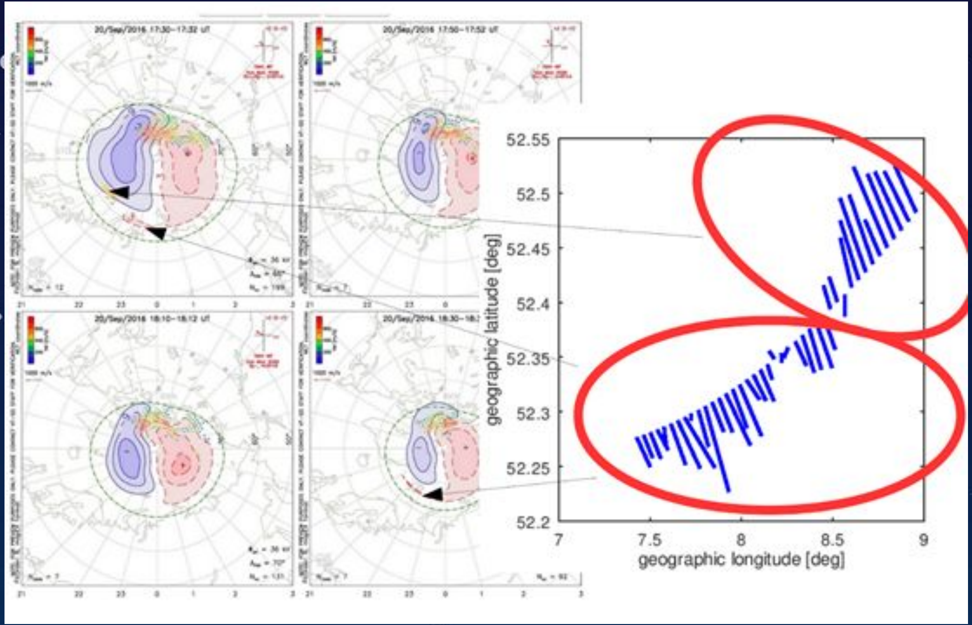
Ionosphere: LOFAR to study ionospheric scintillations



Left: (top) cross-correlation function, (bottom) time lags for maximum correlation.

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

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



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

Use of a model with the diffraction pattern 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.

Calibration solutions - phases vs. images

We analyze ionospheric phases extracted during calibration routine with wavelet transform and determine the wave-like disturbances parameters; the input dTEC is the difference in TEC between stations

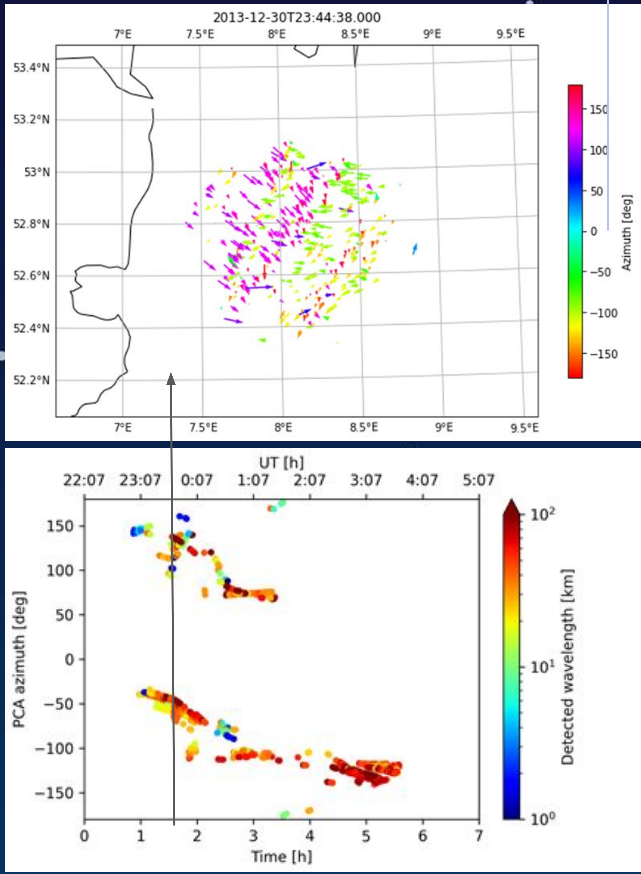
We then create snapshot images (2 minutes), extract positions of all sources in the FOV, and calculate offsets of this positions with their average positions- these offsets are a function of local plasma density gradient

both from calibration phases and images we detect similar directions

- analyzing phase solutions gives insight into distortions within images
- can save processing time (creating images) if the ionosphere is very active
- reveals plasma structures in the ionosphere on many spatio-temporal scales

de Gasperin et al., 2019

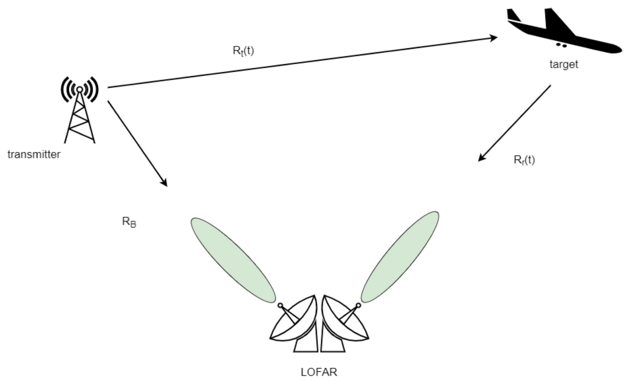
Beser et al.



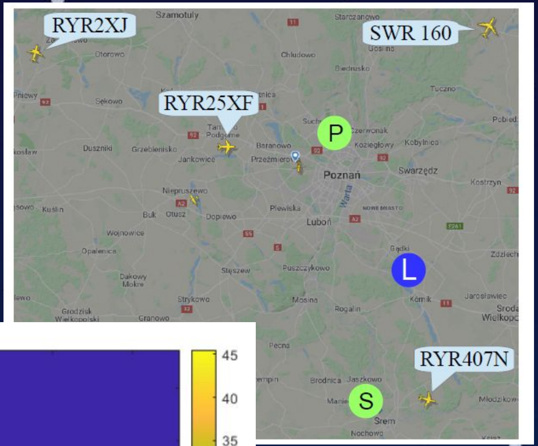
Additionally: LOFAR as a passive radar

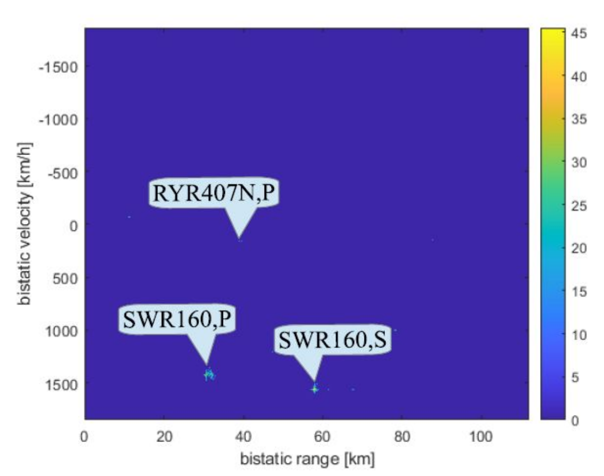
Project led in collaboration with Warsaw University of Technology (Politechnika Warszawska),

- 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 LOFAR station was used as a surveillance receiver and reference receiver.



Passive radiolocation setup.





Top left: Cross-ambiguity function obtained for 64 tiles combined into a beam steered in the direction of SWR160 plane

Top right: Map with planes around the LOFAR station in Borowiec in the moment of the registration, L – the LOFAR station in Borowiec, S – the broadcasting station in Srem, P – the broadcasting station in Piatkowo (A. Droszcz et al., 2020)

H2020 project officially ended in Feb 2022

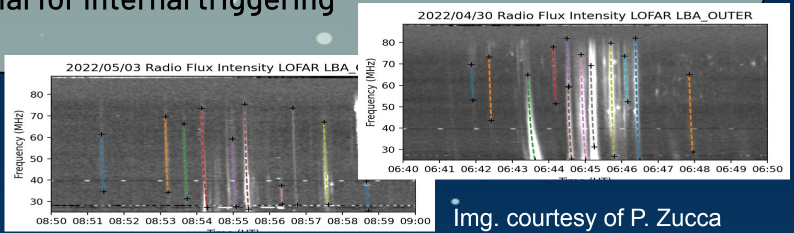
DANTE (Development of an Advanced HBA Frontend) - hardware focused

- a production-ready hardware design for the next-generation LOFAR HBA front-end boards
- a new HBA tile summator-beamformer design producing two independent HBA tile beams when operated with the new HBA-FE boards

IDOLS (Incremental Development of LOFAR Space-Weather) - operation focused

prototyping observing schemes, pipelines, data transport, and data processing on-station and centrally

- Simulates the use of an independent second HBA beam, which will be available once stations are upgraded on one of the LOFAR core stations
- Real-time observations of Sun and scintillation and testing of pipelines and operation scenario
- Implementation of preliminary detection algorithm - potential for internal triggering



Img. courtesy of P. Zucca

LOFAR ERIC

LOFAR ERIC will provide a coordinating organisation to optimise the joint exploitation and to maximise the science output of the LOFAR facilities. Importantly, LOFAR ERIC will also ensure a united approach to ongoing and future upgrades to the facility. Maintaining the common vision and policies requires appropriately aggregated long-term membership and funding stability.

The staged upgrade called LOFAR2.0 will hugely enhance the capabilities of LOFAR, particularly at the lowest frequencies.

LOFAR ERIC

defines and implements a common long-term strategy, joint fundraising, and consistent prioritisation of the development effort for LOFAR2.0, as well as optimising the availability of the collective partner and LOFAR ERIC owned facilities (including sensor, compute, and data storage resources) that form the LOFAR research infrastructure.

LOFAR ERIC

is the appropriate vehicle to attract and consolidate partners with a range of levels of involvement, and to establish and maintain clear long-term policies and funding stability for the organisation and its infrastructure as a whole.

LOFAR ERIC

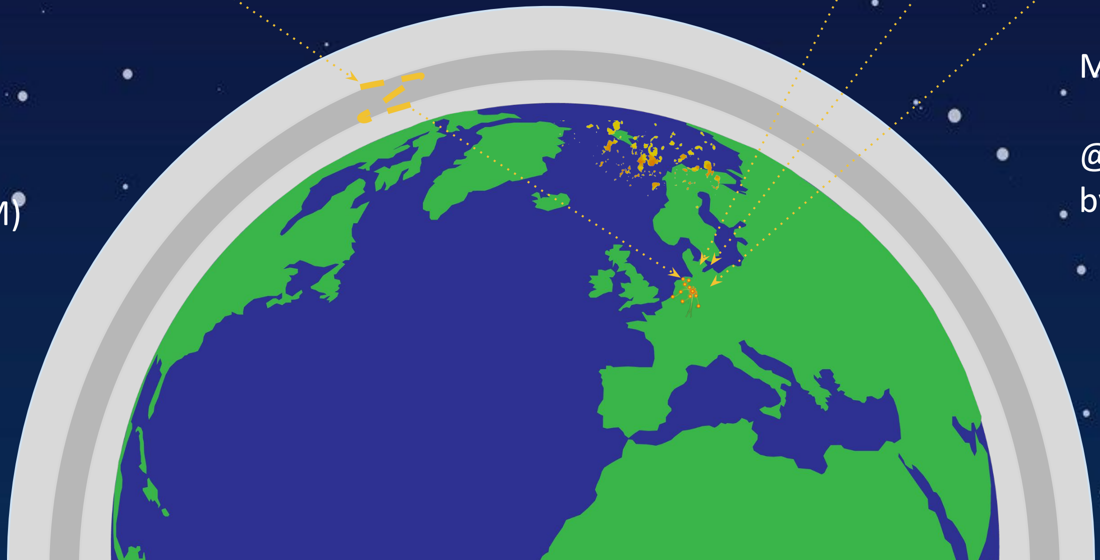
cohered at the (multi-)national level, brings appropriate visibility and recognition at national and European levels, facilitating a dialogue with science policy makers and funders across its working domain.

LOFAR ERIC

with its unique and cutting-edge facilities, has a continuing role in assuring and stimulating the vitality of the European science community.

Source: https://www.lofar.eu/

Thank you!



More about ERIC

@ 12:45 (FRI)
by A. Krankowski (UWM)

More about LOFAR

@ 13:00 (FRI)
by M. Olech (UWM)