Ionospheric predictions for low frequency radio astronomical observations

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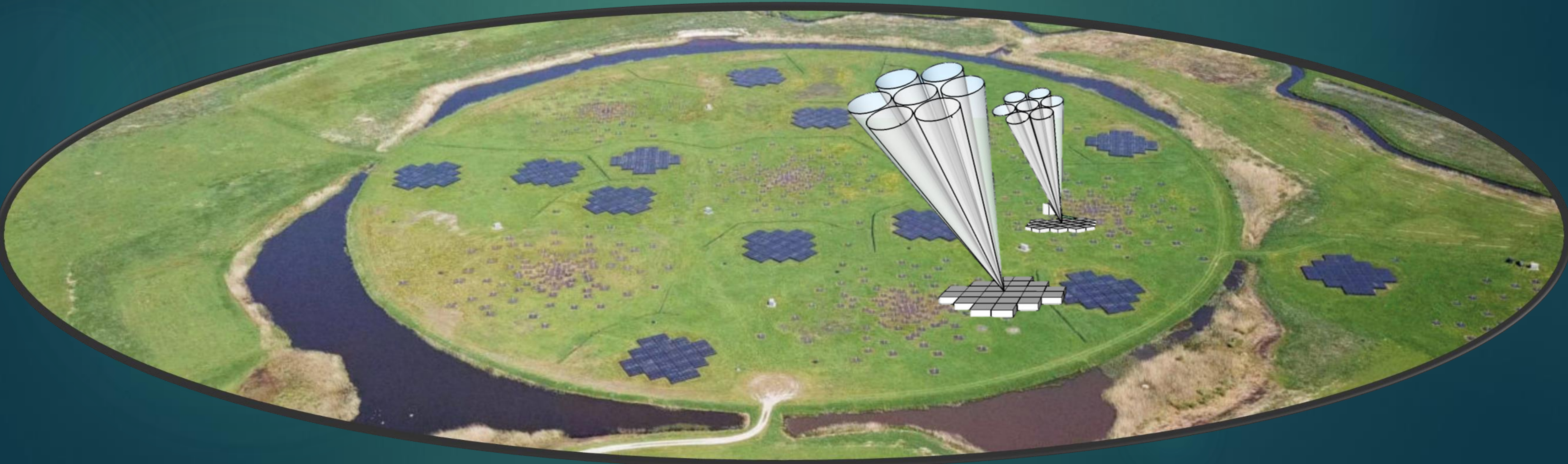
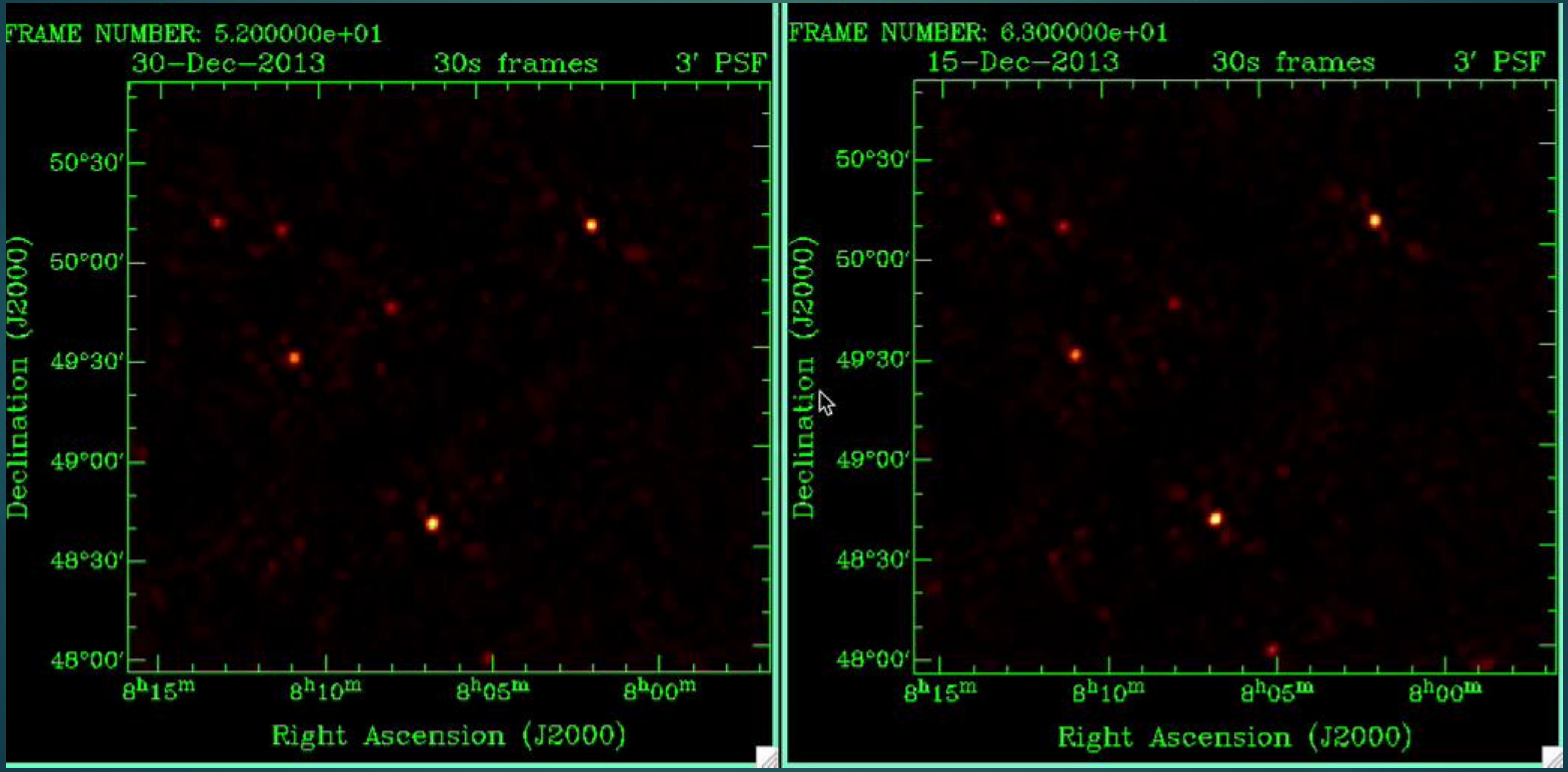


Low Frequency radio telescopes

- MWA (Australia)
- LWA (US)
- LOFAR (Europe)
- GMRT (India)
- SKA (Low-> Australia, Mid-> South Africa)
- ...
- In general: Radio telescopes make images of the radio sky
- Ionospheric gradients corrupt these images
- Low frequency -> Wide field of view. Variations of the ionosphere over the field of view are hard to remove
- Strong frequency dependence: decorrelation if integrating over wider bands
- Longer integration times -> time variability of ionosphere can decorrelate the signal

Low frequency radio astronomy and the ionosphere

LOFAR data
Image credit: G. de Bruyn

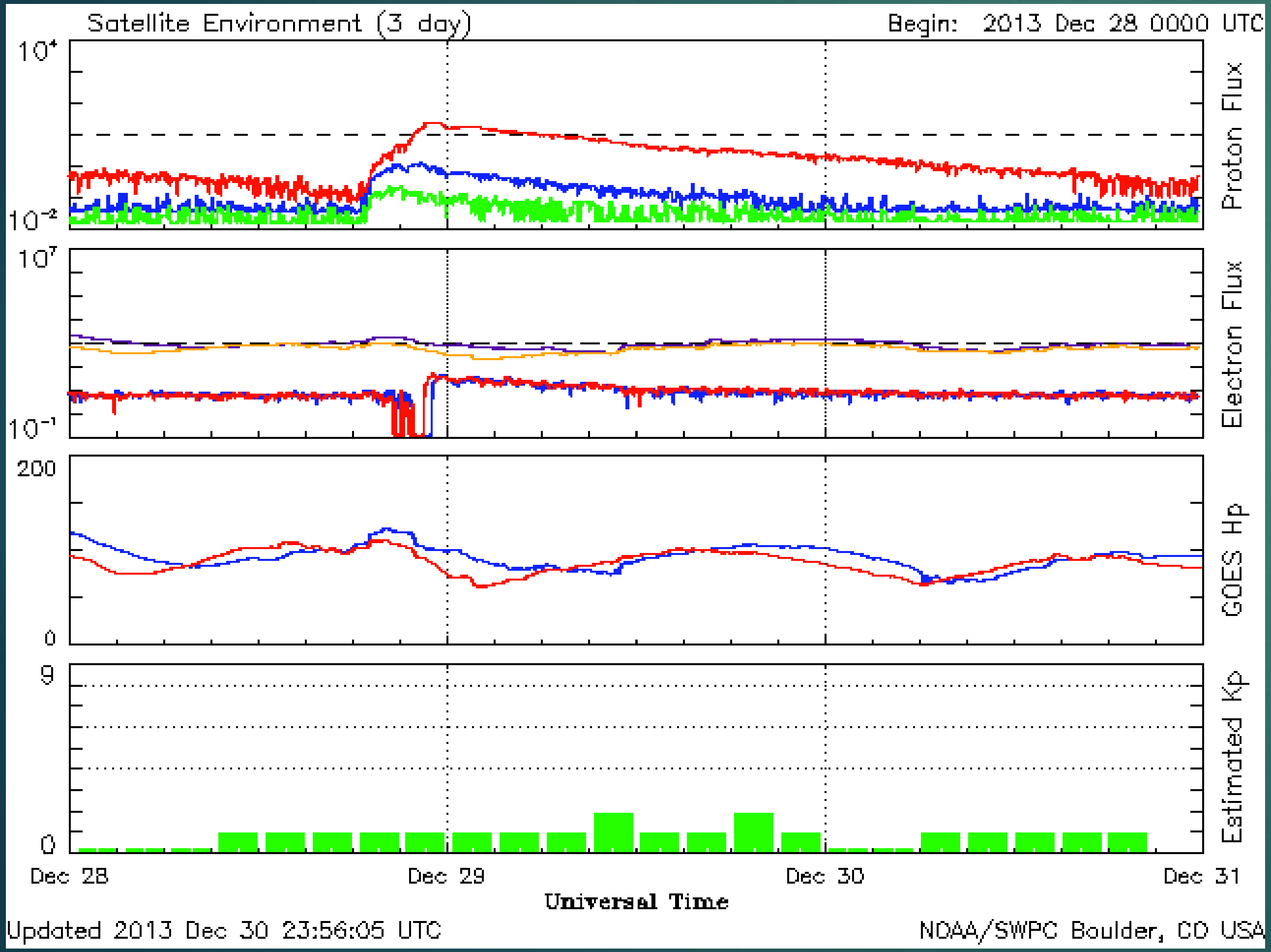


Measure offset from nominal position

All sources, measured with core only (3km)

Local TEC gradients : <0.01 TECU/km

Low frequency radio astronomy and the ionosphere



- No clear ionospheric activity measured
- Bad data is likely correlated with large TEC gradients (~ 1-2 TEC/100 km)
- Small scale TIDS
- But also small scale disturbances traveling on LSTIDS
- High drift velocities?

- Need to establish link between TID detection and LOFAR quality (~ 3000 observations since 2016 have quality assessment)


LOFAR

The Low Frequency Array

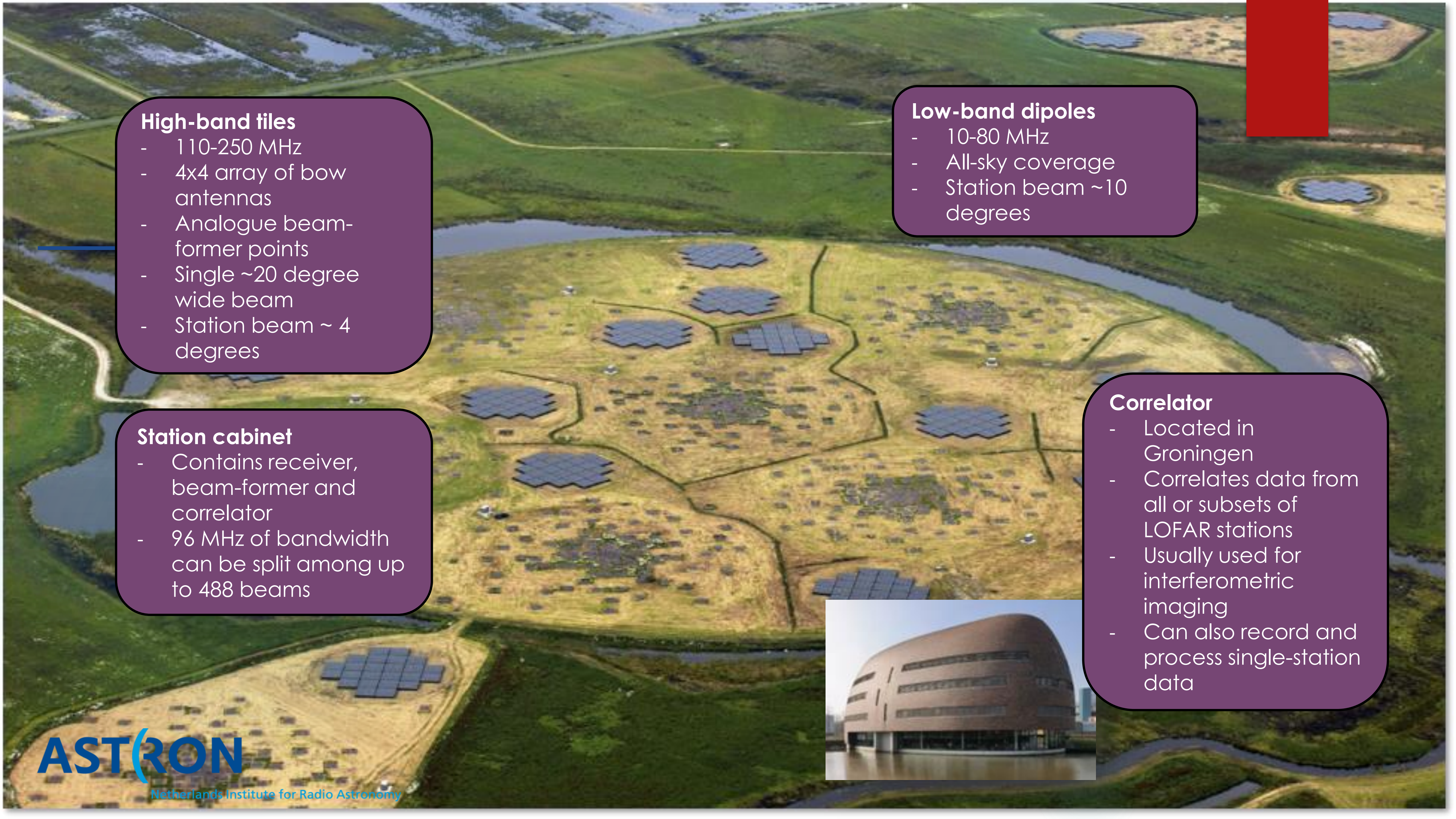
In NL:
A core of 24 stations in area within 4 km diameter and 14 remote stations scattered across the NE of NL

14 stations operational across EU:
- 6 in DE
- 3 in PL
- 1 each in FR, IE, LV, SE, UK

New stations in 2025: IT, BG

52 stations operational in Europe, 2 more will be added in 2025-2026

ASTRON
Netherlands Institute for Radio Astronomy



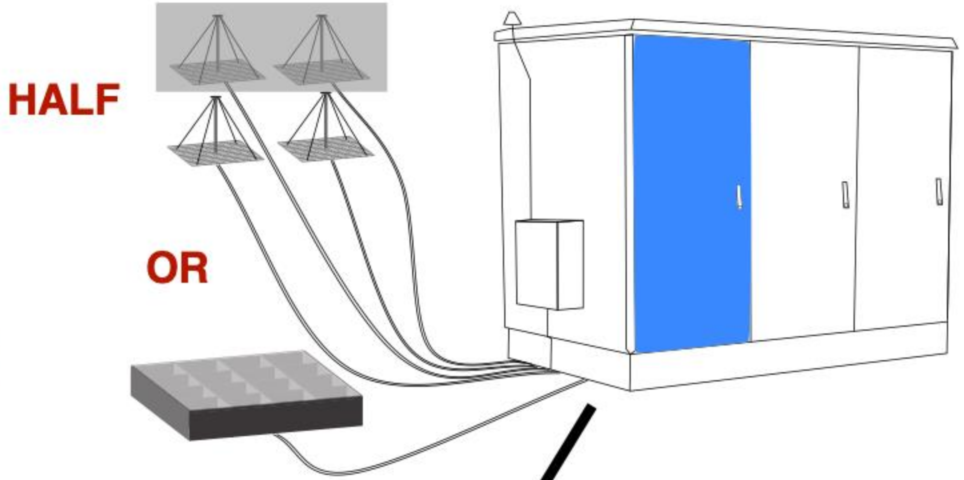
High-band tiles
- 110-250 MHz
- 4x4 array of bow antennas
- Analogue beam-former points
- Single ~20 degree wide beam
- Station beam ~ 4 degrees

Low-band dipoles
- 10-80 MHz
- All-sky coverage
- Station beam ~10 degrees

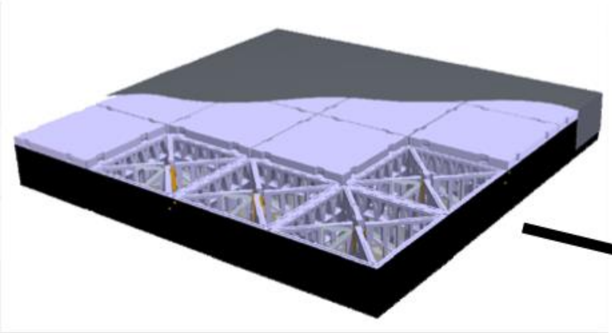
Station cabinet
- Contains receiver, beam-former and correlator
- 96 MHz of bandwidth can be split among up to 488 beams

Correlator
- Located in Groningen
- Correlates data from all or subsets of LOFAR stations
- Usually used for interferometric imaging
- Can also record and process single-station data

From LOFAR to LOFAR2.0



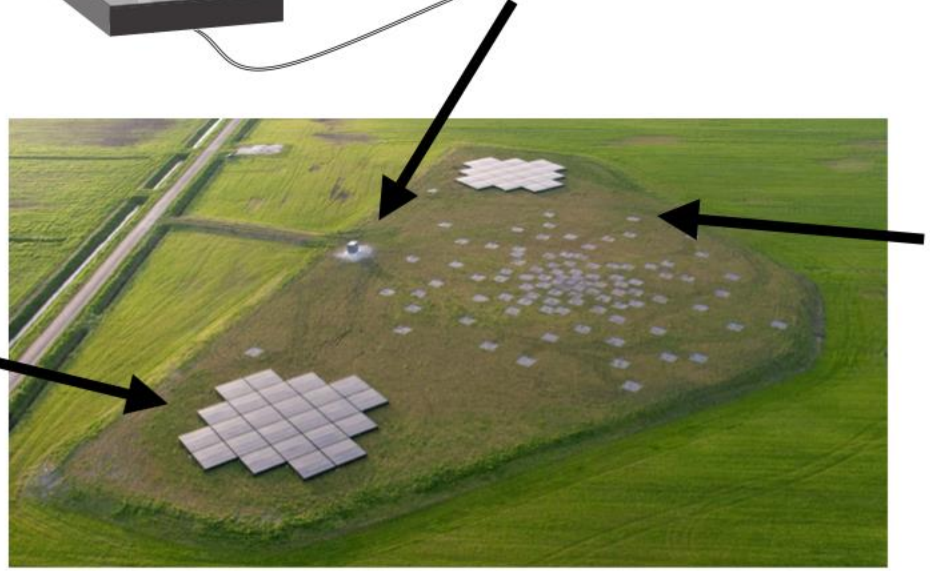
Robust, full-sensitivity imaging



High-Band Antennas

Frequency = 110-240 MHz

Wavelength = 1-3 metres



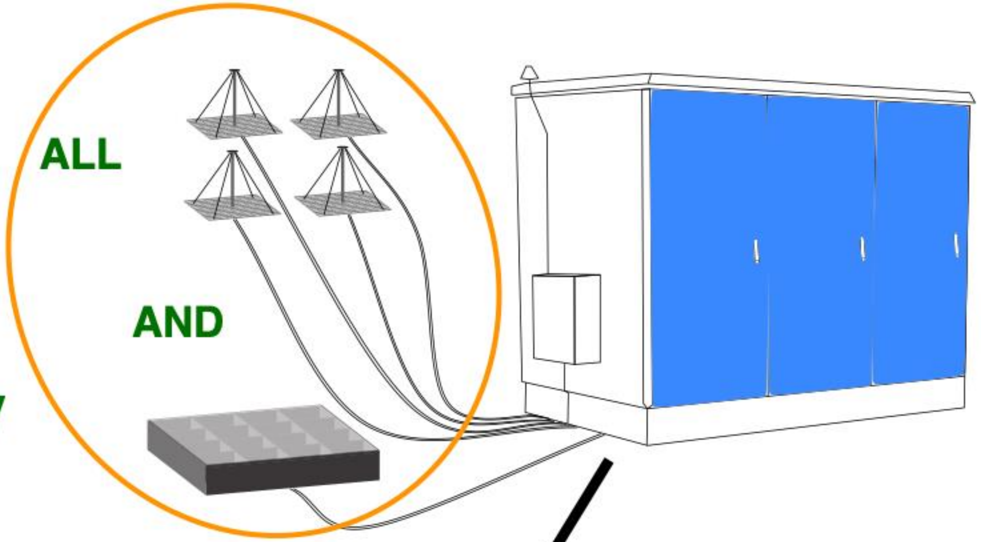
Sensitivity and accuracy limited by ionosphere

Low-Band Antennas

Frequency = 10-90 MHz

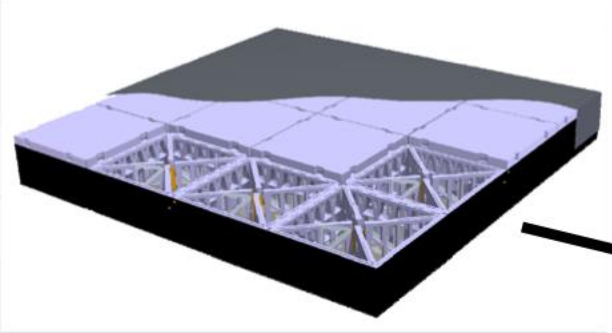
Wavelength = 3-30 metres

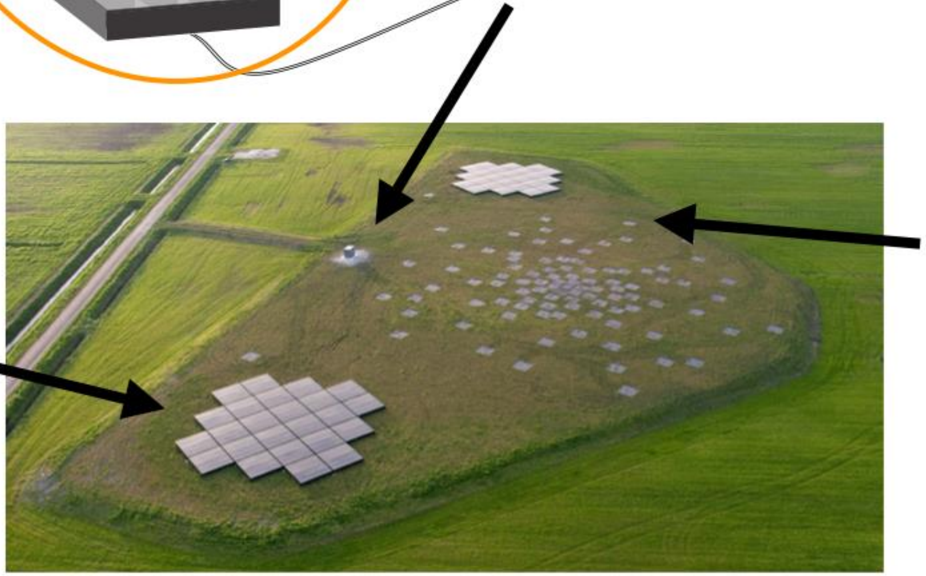
From LOFAR to LOFAR2.0



Robust, full-sensitivity imaging

Robust, full-sensitivity imaging





High-Band Antennas

Frequency = 110-240 MHz

Wavelength = 1-3 metres

Low-Band Antennas

Frequency = 10-90 MHz

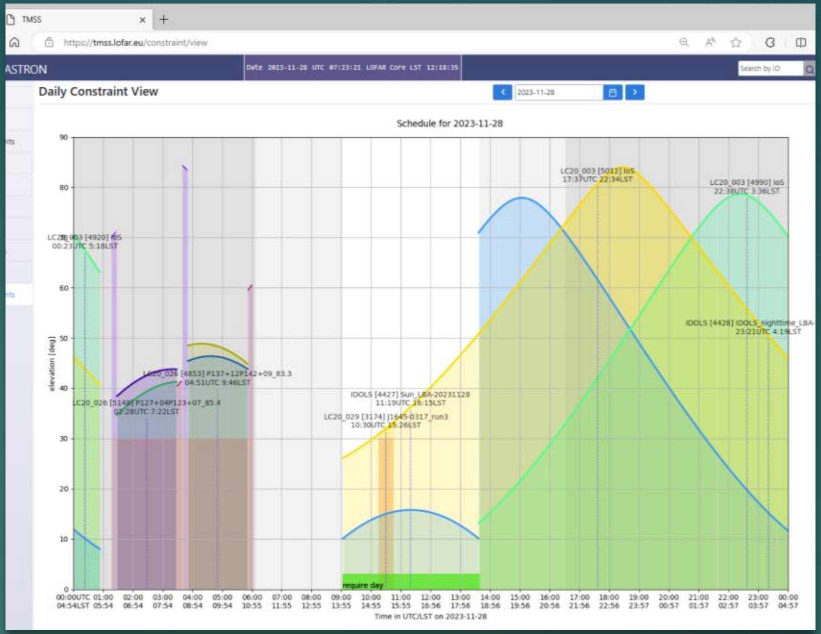
Wavelength = 3-30 metres

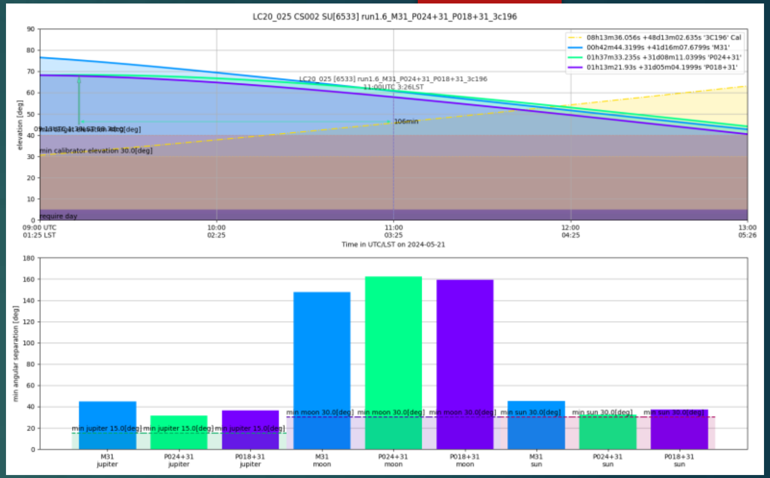
Operations, processing, data storage

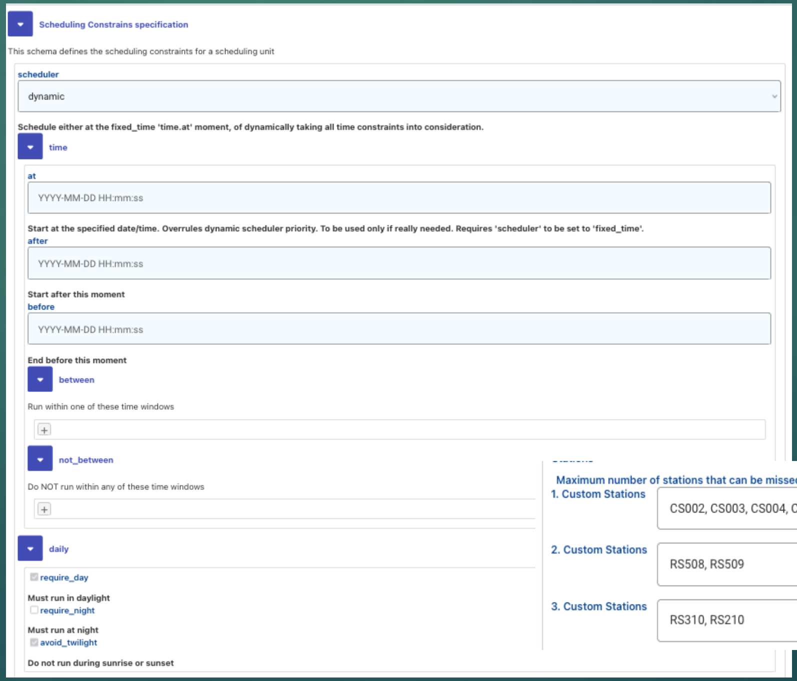
- From observation to storage:
  - Typical observation times:
    - 1 hour LBA (lucky imaging)
    - 2/4- 8 hours HBA
  - Directly after observation: Start preprocessing -> computational load
  - Data storage:
    - LOFAR1 -> 50 PetaByte
    - LOFAR2: ??

Scheduling LOFAR observation

- Dynamic scheduling based on sets of scheduling constraints, LST availability, and scientific rank.
- Array constraints: e.g. availability of a defined number of stations
- Scheduling constraints: e.g. time of the day, range of allowed time, distance from Sun, Moon, Jupiter and minimum elevation.






Scheduling Constrains specification

This schema defines the scheduling constraints for a scheduling unit

scheduler

dynamic

Schedule either at the fixed_time 'time.at' moment, of dynamically taking all time constraints into consideration.

time

at

YYYY-MM-DD HH:mm:ss

Start at the specified date/time. Overrules dynamic scheduler priority. To be used only if really needed. Requires 'scheduler' to be set to 'fixed_time'.

after

YYYY-MM-DD HH:mm:ss

Start after this moment

before

YYYY-MM-DD HH:mm:ss

End before this moment

between

Run within one of these time windows

not_between

Do NOT run within any of these time windows

daily

require_day

Must run in daylight

require_night

Must run at night

avoid_twilight

Do not run during sunrise or sunset


Maximum number of stations that can be missed in the selected groups

1. Custom Stations	CS002, CS003, CS004, CS005, CS006, CS007...	Maximum Number of missing stations	4
2. Custom Stations	RS508, RS509	Maximum Number of missing stations	1
3. Custom Stations	RS310, RS210	Maximum Number of missing stations	0

Goal: extend scheduling constraints to ionospheric conditions

*Topic of a dedicated working group

- Given a metric and figure of merit for the ionosphere* e.g. good, medium, poor;
- Apply it scheduling constrains for the following cases:
  - GOOD Any observation LBA, HBA and Solar observations can be schedule
  - MEDIUM Only HBA observations can be scheduled
  - POOR Only Solar observations can be performed

- To help defining the lever of predictability needed:
- DURATION of Single observing runs are:
- HBA observations ~ 8 hours declination>+26deg, 4 hours +25deg <declination<16deg , 2 hours +15deg <declination< +10 deg
- LBA 1 hrs

Observation modes

Main disturbances from changes in space or time or both

Mode	Band	Length scale	Absolute TEC	TEC gradients			
Single	LBA/HBA	100 m	Faraday rotation	Amplitude Scintillation			
Tied array	LBA/HBA	3 km	Faraday rotation	Amplitude Scintillation	decorrelation		
Dutch	HBA	100 km		Phase gradients	Field of view variations		
EU	HBA	1000 km		Phase gradients	decorrelation	Faraday rotation	
Dutch	LBA	100 km		Phase gradients	Field of view variations	Faraday rotation	
Dutch	LBA<40MHz	100 km		Phase gradients	Field of view variations	Faraday rotation	Third order
EU	LBA	1000 km		Phase gradients	decorrelation	Faraday rotation	

increasing complexity

LOFAR2: a responsive telescope

Scenarios:

- Historical data: add ionospheric quality flag to existing data, decide on reprocessing/ saving data
- Hindcasting: stop preprocessing/data storage
- Short time forecast/nowcasting: stop observation -> reschedule other observation
  (~10 minutes)
- 2-hour forecast: schedule observations based on expected quality

Rescheduling based on severity of effects:

frequency of observation: <40MHz/40-80MHz/110+ MHz

baselines: European/Dutch/Core

Type of observation: imaging/beamformed/pulsar(Faraday rotation)/...

Duration of the observation

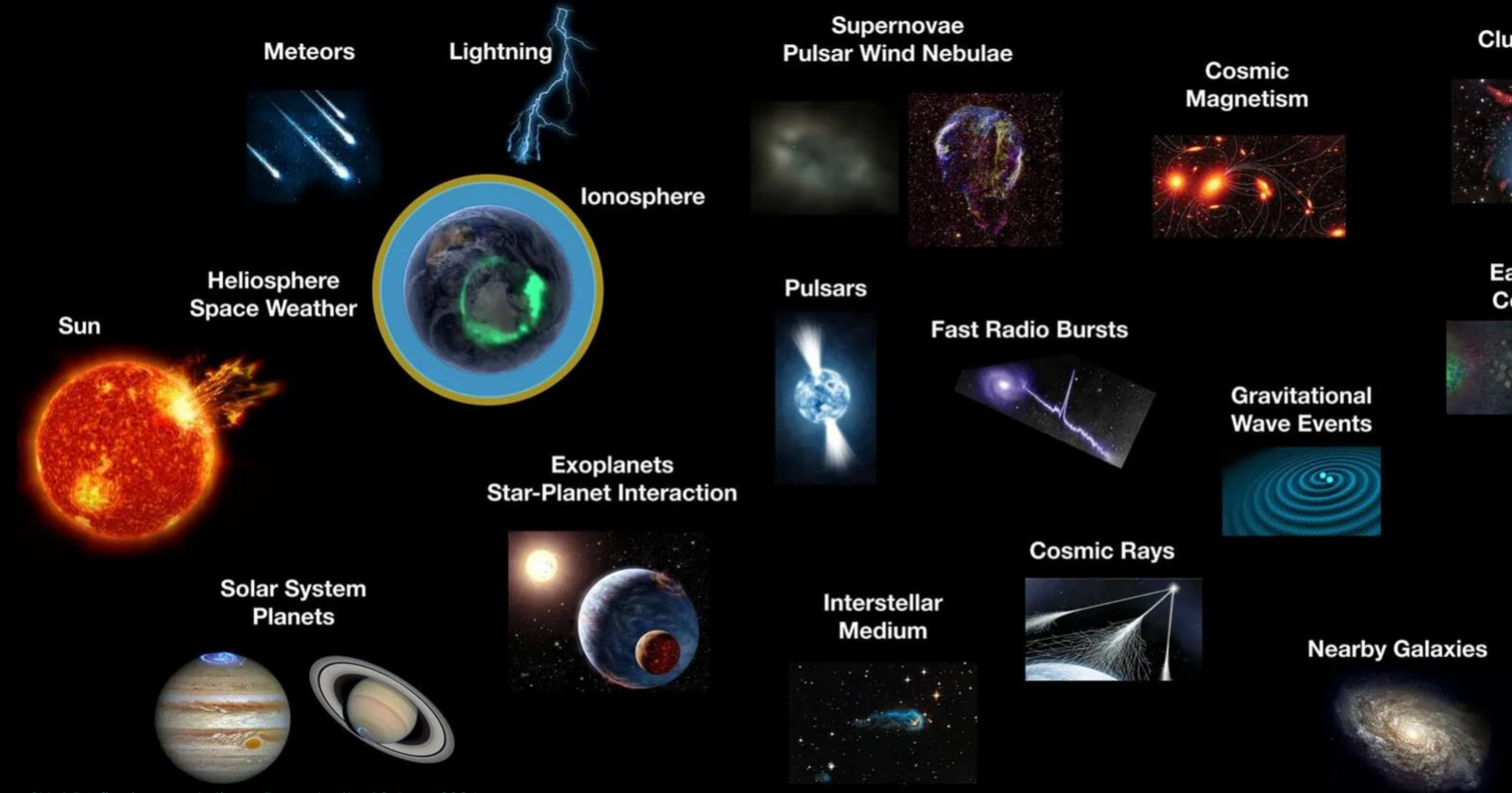
Declination (elevation angle)

Location of the expected disturbance (point to different object in the sky)

Conclusion

- Data storage and processing cost will become major showstopper in the future
- Dynamic scheduling: LOFAR2 can respond and flexible reschedule based on conditions:
- Response time: 10 min-2 hours, but even nowcast is beneficial
- Low frequency arrays suffer from local/ small scale ionospheric disturbances
- Not all disturbances related to LSTID/MSTID
- However:
  - smaller scale disturbances likely to travel with LSTID
  - MSTID will disturb radio astronomical observations
  - Knowing the location of the disturbances can provide an extra asset
- Need to establish a good figure of merit -> correlate ~ 3000 hours of historical LOFAR data with ionospheric indices
- Goal of special LOFAR2 working group

Backup slides


Meteors
Lightning
Supernovae
Pulsar Wind Nebulae
Cosmic
Magnetism
Ionosphere
Heliosphere
Space Weather
Sun
Pulsars
Fast Radio Bursts
Gravitational
Wave Events
Exoplanets
Star-Planet Interaction
Cosmic Rays
Solar System
Planets
Interstellar
Medium
Nearby Galaxies

LOFAR SW Observing modes