From LOFAR to LOFAR2.0: advancing cutting-edge science in the next decade

René Vermeulen
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Jena

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What is LOFAR2.0?

• Anchor a state-of-the-art, unique, highly productive telescope from 2020-2030

• A staged expansion of the scientific and technical capabilities of LOFAR

• A path to SKA2-Low (like LOFAR was for SKA1-Low)
OFAR2.0: cutting-edge science for the next decade

• Leverage existing investments:
  - hardware (stations, networks, data centres)
  - algorithms, software, pipelines
  - community’s collected brainpower

• Remain *unique* and scientifically *impactful* (in SKA era):
  - lowest frequencies
  - highest resolution
  - versatility

• Evolution: continuous community support & productivity
• Financially, technically feasible on a 3-10 year timescale

LOFAR 2.0
Compared to SKA-Low Phase 1

LOFAR → LOFAR2.0
Reaches to 2x lower frequencies
>10x higher resolution

SKA-Low Phase 1
Reaches to 2x higher frequencies
>10x greater collecting area
OFAR2.0: cutting-edge science for the next decade

Augment station electronics
- Use all LBAs + all HBA tiles simultaneously
  Ionospheric calibration (with single clock)
  Sensitivity
  Broad-band transient science
- Improve RFI robustness/linearity
- Extend on-station data handling

New generation LBA dipoles
- Performance at <=30 MHz
- Flatter response function
OFAR2.0: cutting-edge science for the next decade

Additional antennas/stations
Science-driven (& costly):
- Sensitivity
- Imaging fidelity (1, 10, 100, 1000+ km baselines)
- Dedicated programmes (Space Weather)

Additional HBA beams
- Dedicated programmes (Space Weather)
- Transient science
- Efficiency multiplier

Integration of NenuFAR
- Ultimate LBA sensitivity at high resolution
LOFAR2.0 Stage 1: DUPLLO
Digital Upgrade for Premier LOFAR Low-band Observing
3.5 M€ funding obtained from NWO
design; upgrade NL stations
All ILT partners intending to join

Reveal what is invisible to
the high-band antennas
DUPLLO All-Sky Survey

All-sky map that is unique for the next 20 years.

Provides a monumental legacy data set for the astronomical community.
Parameter space
The challenge
The challenge
The challenge

Scientifically limited

No ionospheric correction

Breakthrough techniques

Rich in science

Ionosphere well modeled
The challenge

Scientifically limited
No ionospheric correction

Breakthrough techniques
DUPLLO

Rich in science
Ionosphere well modeled

The Goal
The challenge

Scientifically limited

No ionospheric correction

Breakthrough techniques

High-Band

Rich in science

Ionosphere well modeled

Low-Band

DUP LLO

The Goal

2x
The challenge

Scientifically limited
No ionospheric correction
Rich in science
Ionosphere well modeled

Breakthrough techniques

High-Band

Low-Band

2x

DUPLLO

Precision clock

The Goal
The challenge

Scientifically limited
No ionospheric correction

Breakthrough techniques
Transfer Information
DUPLLO
Precision clock

Rich in science
Ionosphere well modeled

The Goal

2x

Low-Band

High-Band
Proof of concept

- Shown that low-band and high-band ionosphere track each other
- Shown that we can derive an ionospheric phase screen from high-band data

Recent Breakthrough!
DUPLO Innovation

Scientifically limited

- =

Rich in science

The stage is set...
• When do the first stars start to shine?

• How do supermassive black holes and galaxy clusters shape the Universe?

• What is the habitability around low-mass stars and can we directly detect exoplanets?
Exoplanets, stars, and habitability

- Magnetically active stars (M-dwarfs) irradiating their nearby planets
- Directly detect exoplanets (cf. Io-Jupiter interaction)
- Non-synchrotron emission only visible at very low frequencies
Galactic science in our Milky Way

- Discover the 90% “missing” supernova remnants
- Pulsar wind nebulae as particle accelerators
- Probe interstellar medium using RRLs
Nearby galaxies

- Look at the global properties of galaxies in a spatially resolved way
- See how the interstellar gas absorbs energy
- Understand the cycles of star-formation
Active galactic nuclei

- Feedback of energy that regulates star formation
- Study the radio jets that probe the energetics
- “Fossil” emission gives the history of activity level
Galaxy clusters

- Cluster mergers are most energetic events since the Big Bang
- Radio haloes and relics trace energetics and history of merger
- Understand structure formation in Universe
High-redshift Universe

- Discover high-redshift (z > 2) radio galaxies
- Large sample to study galaxy formation and evolution
- Probe EOR with >100 high-redshift radio galaxies at z > 6
Transients

- Compare 2-epoch all-sky coverage
- Coherent emitters (compact objects)
- Gravitational wave counterparts
Pulsars

- Ultra-steep spectrum point sources in imaging surveys
- Find super-fast- or super-slow-spinning neutron stars
- Constrain neutron star equation of state
Cosmic rays

- Most energetic particles in the Universe, but their origin is still unclear
- What sources, and what acceleration mechanism(s)
- LOFAR can study the transition from Galactic to extragalactic sources
Earth lightning

- Buffer boards can also capture lightning strikes
- Lightning formation and propagation still not well understood
- Much higher precision imaging of where lightning is forming
Earth ionosphere

- Calibration will give insight into the structure and dynamics of the ionosphere
- Detect 2nd and 3rd order effects
- Model the scattering conditions giving rise to scintillation
Sun & space weather

- Solar flares and coronal mass ejections create space weather
- Early detection of these bursts in radio
- This space weather can disrupt artificial satellites and the Earth’s magnetosphere
LOFAR4SW: A Comprehensive Space Weather Observatory
LOFAR - Probing Space Weather: solar radio bursts, solar wind, magnetic field, ionosphere

Scintillation of compact radio sources used to probe solar wind velocity and density. Multiple stations enable more-accurate cross-correlation analysis.

Faraday rotation of polarised signal, from pulsars or Galactic foreground, offers prospect of interplanetary magnetic field measurement.
Serendipity

- Sky never before probed at such low frequencies, with such high sensitivity and angular resolution
- Other types of non-synchrotron emitters
Meteors
Supernovae
Solar System Planets
Supernovae
Solar System Planets
Ionosphere
Lightning
Meteors
Space weather
Cosmic magnetism
Pulsars
Cosmic rays
Interstellar medium
Gravitational wave events

“extraordinarily broad scientific program” Ref. 2
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