
Unintended electromagnetic radiation from LEO satellites

A call to action to the LOFAR community

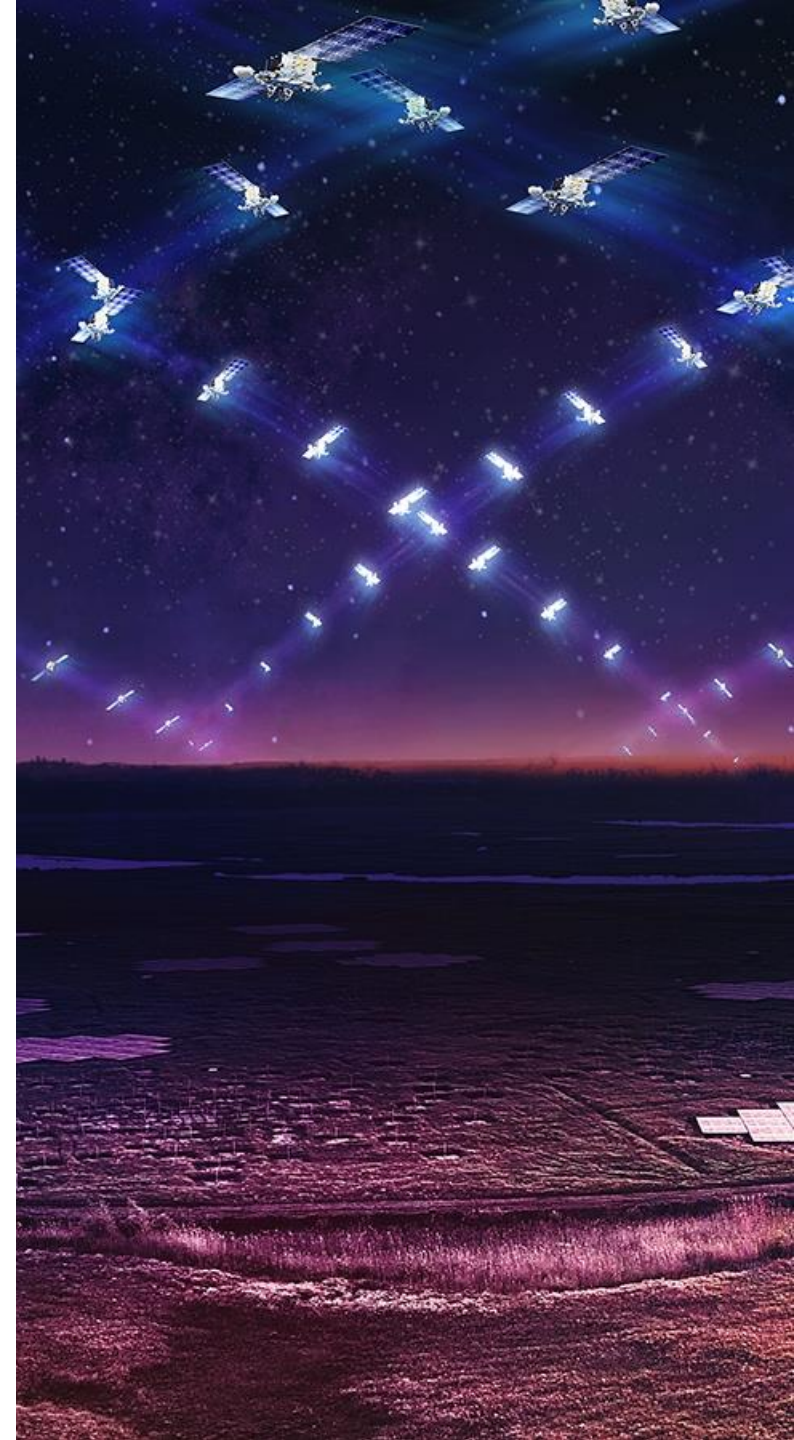
Dr. Emma van der Wateren

wateren@astron.nl

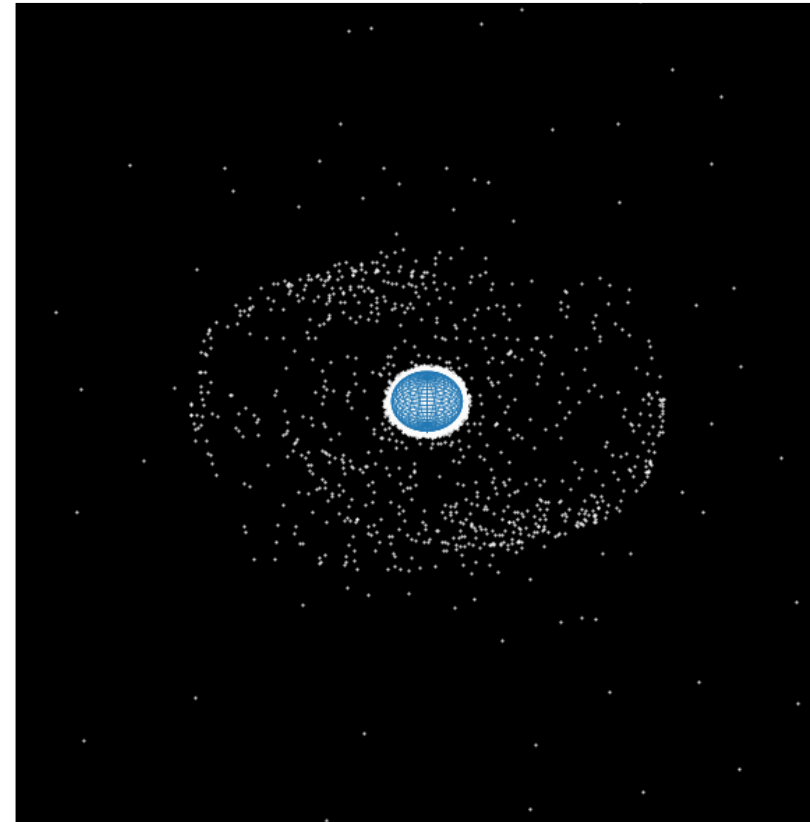
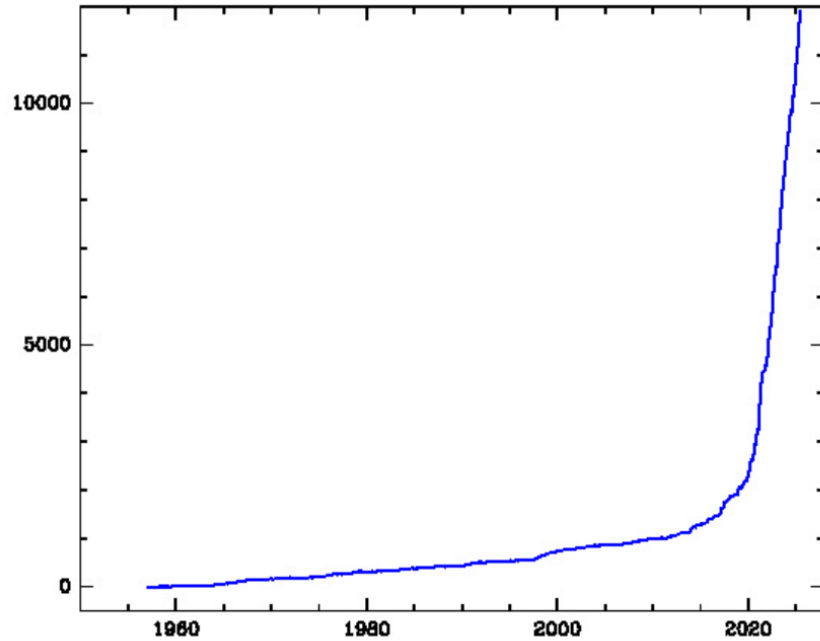
Based on work with collaborators: Cees Bassa, Lindsay DeMarchi, Federico Di Vruno, Fabio Giovanardi, Greg Hellbourg, Balthasar Indermuehle, Gyula Josza, Michael Lindqvist, Ivan Thomas, Benjamin Winkel

ASTRON

Netherlands Institute for Radio Astronomy

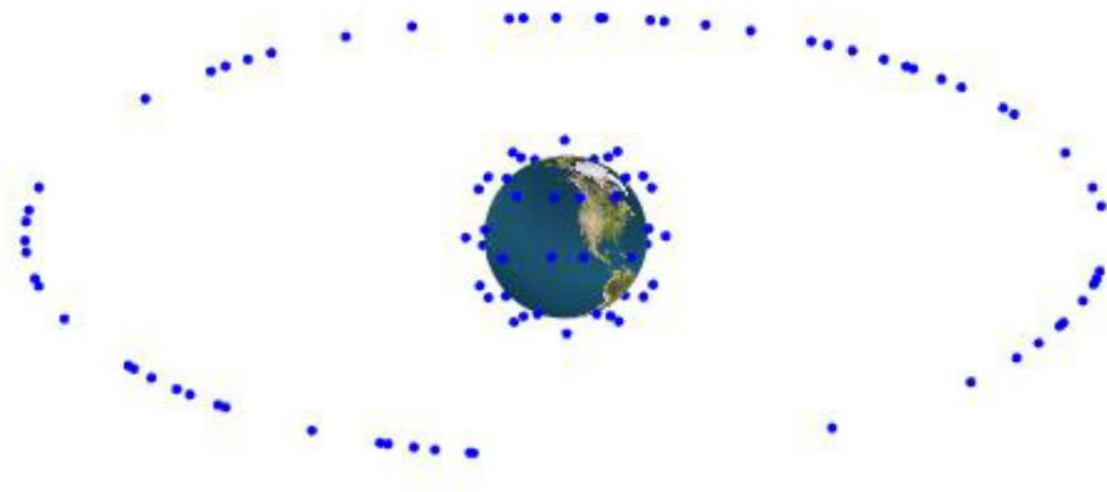


Large LEO constellations



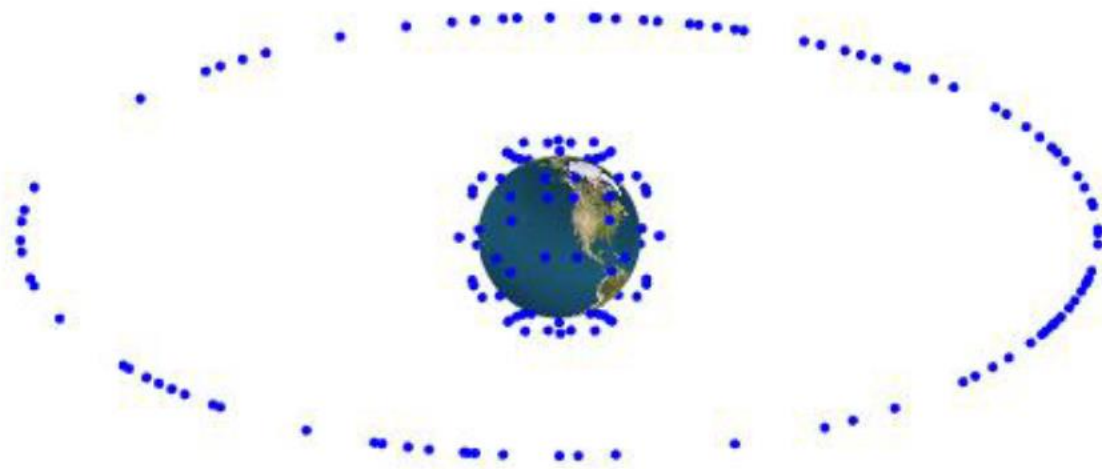
(Left) Number of satellites in LEO, source: J. McDowell. Snapshot of satellites in space around Earth, data source: Celestrak.

Large LEO constellations



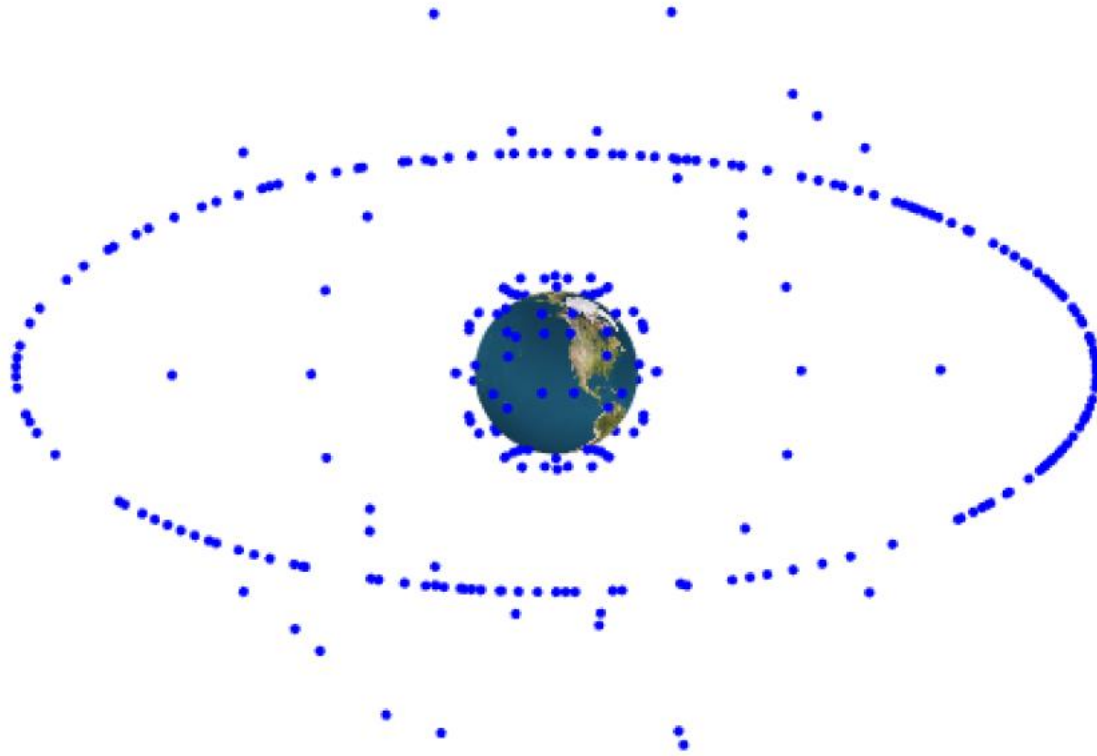
2000

Large LEO constellations



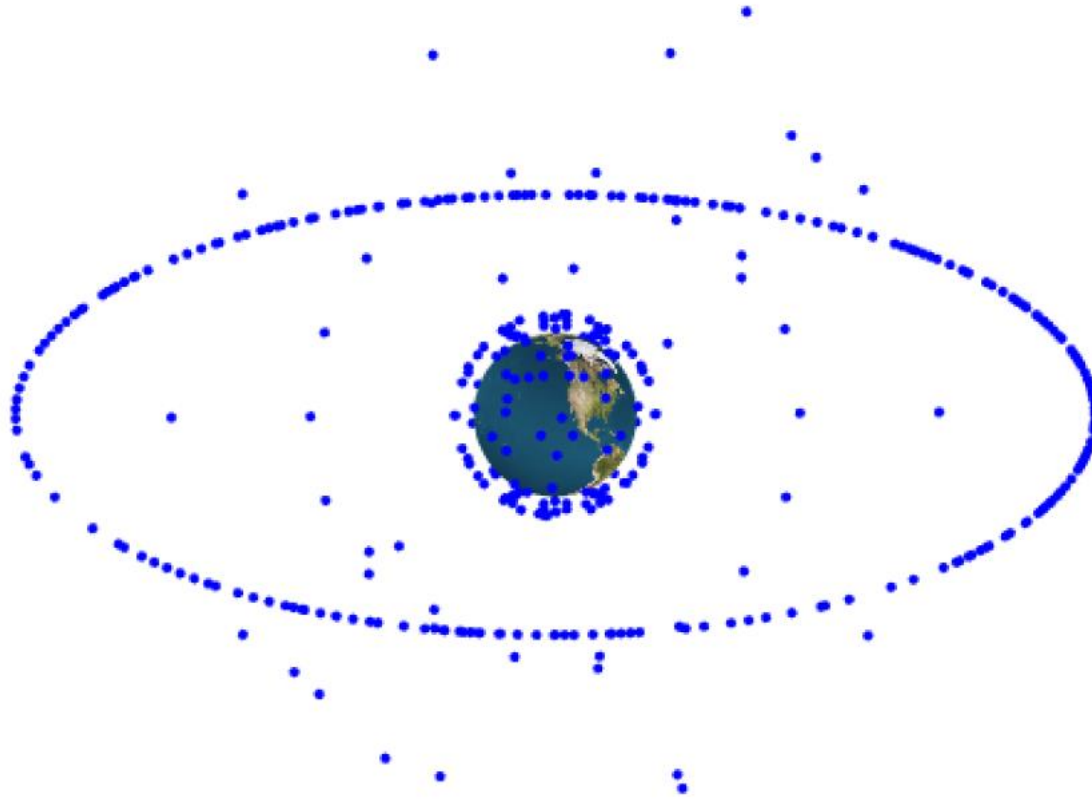
2003

Large LEO constellations



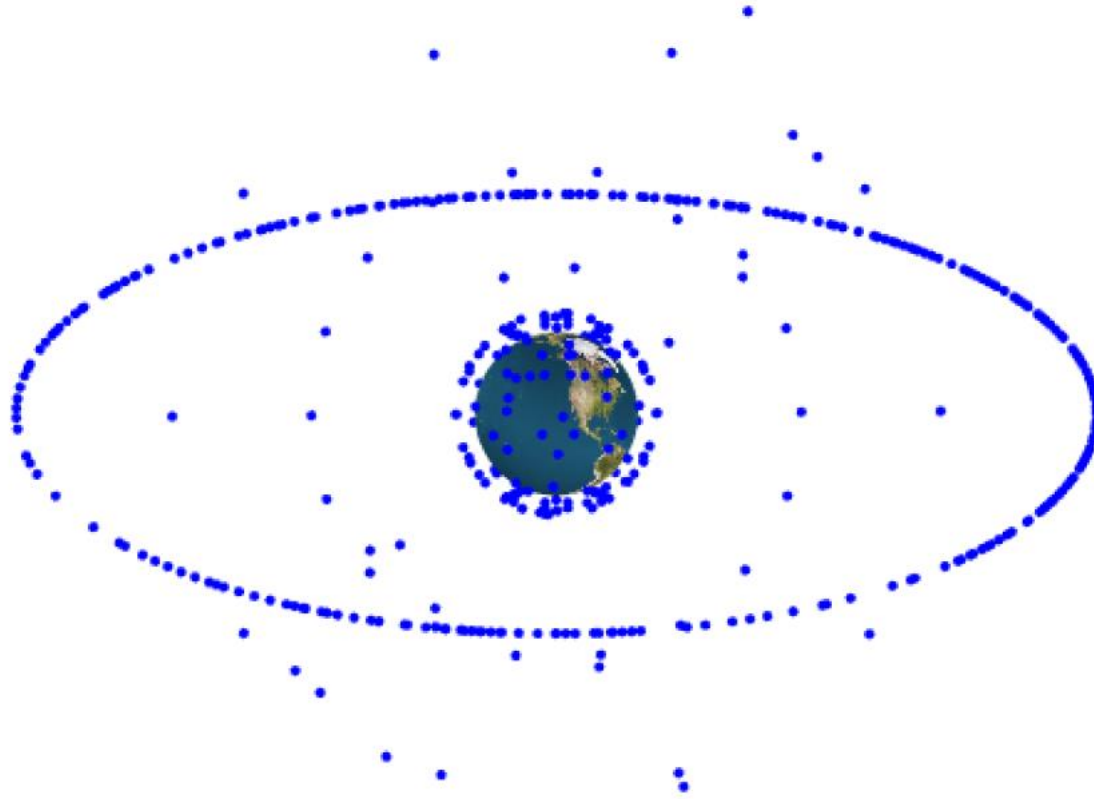
2007

Large LEO constellations



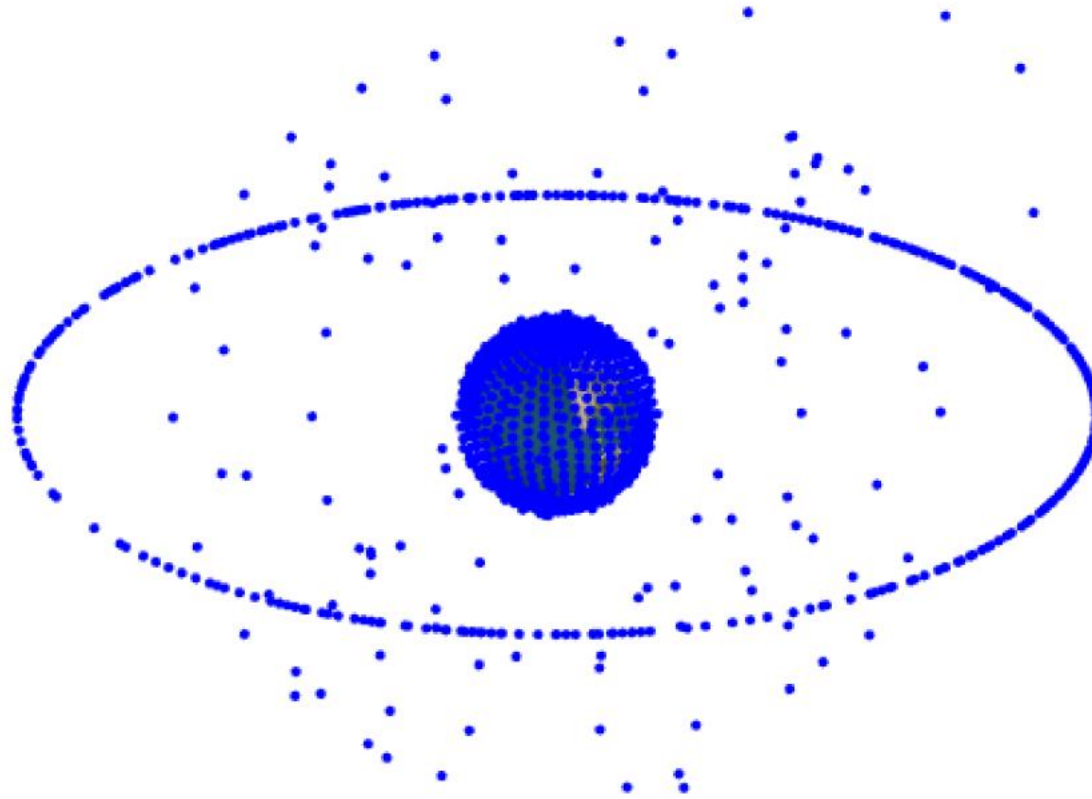
2012

Large LEO constellations



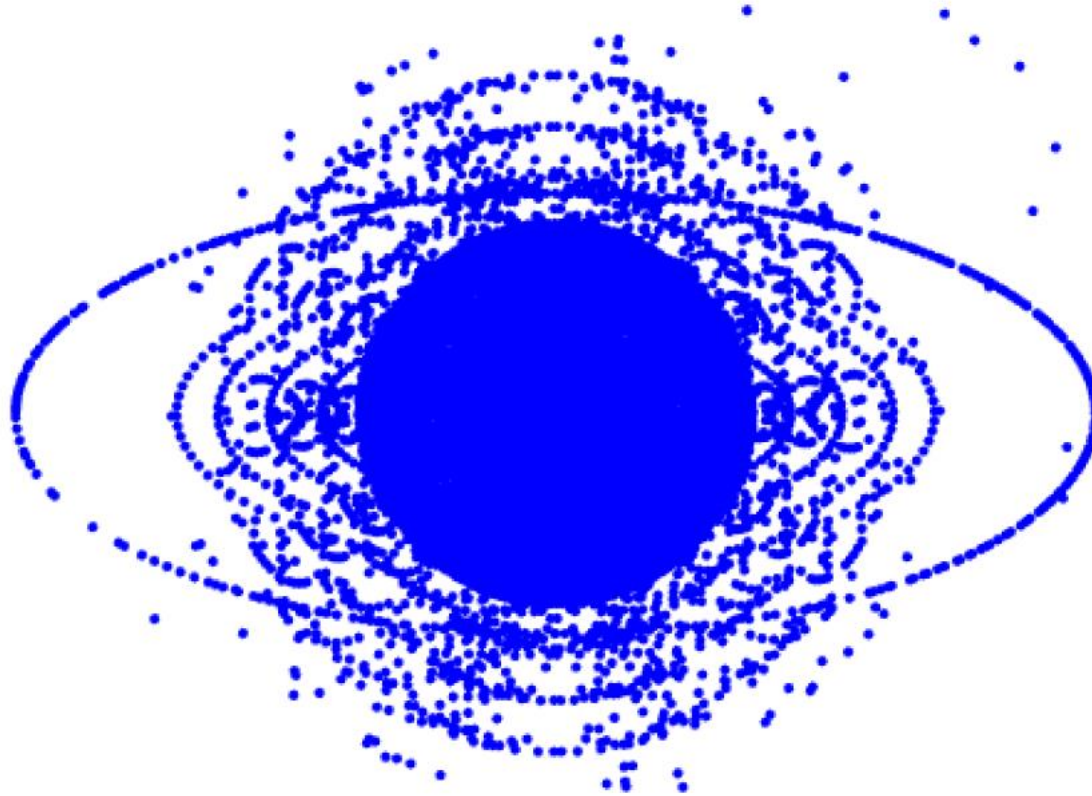
2015

Large LEO constellations



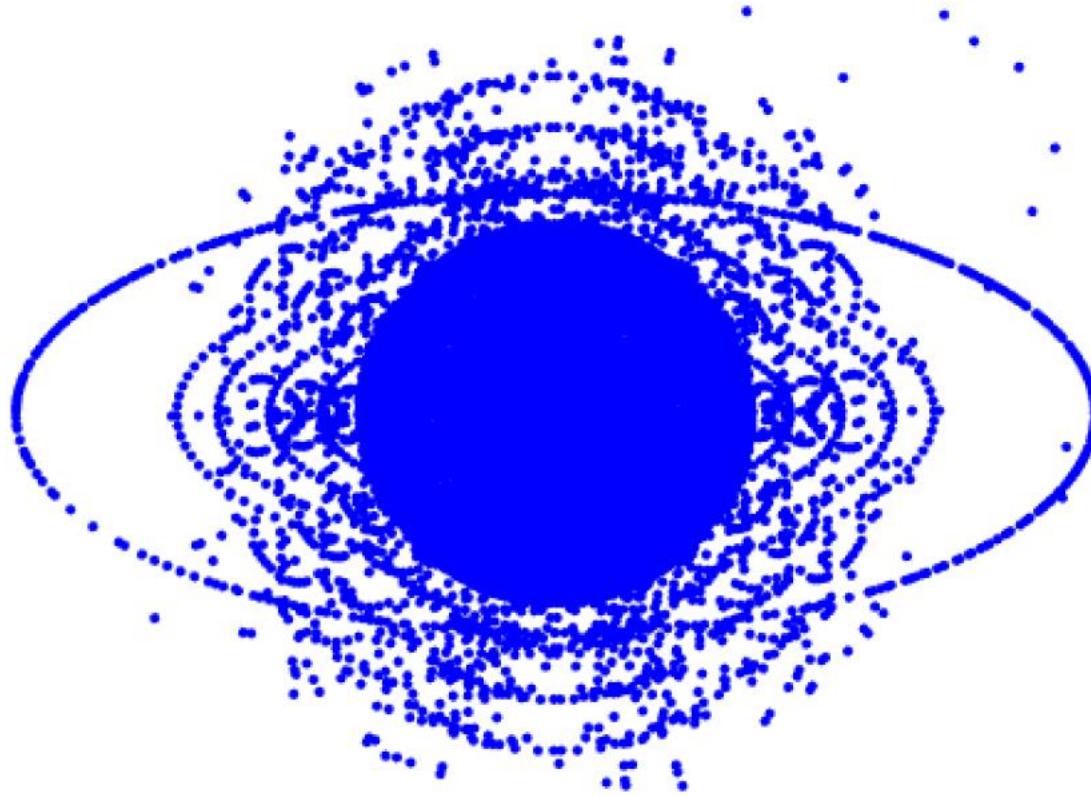
2019: first launch of Starlink

Large LEO constellations



2023

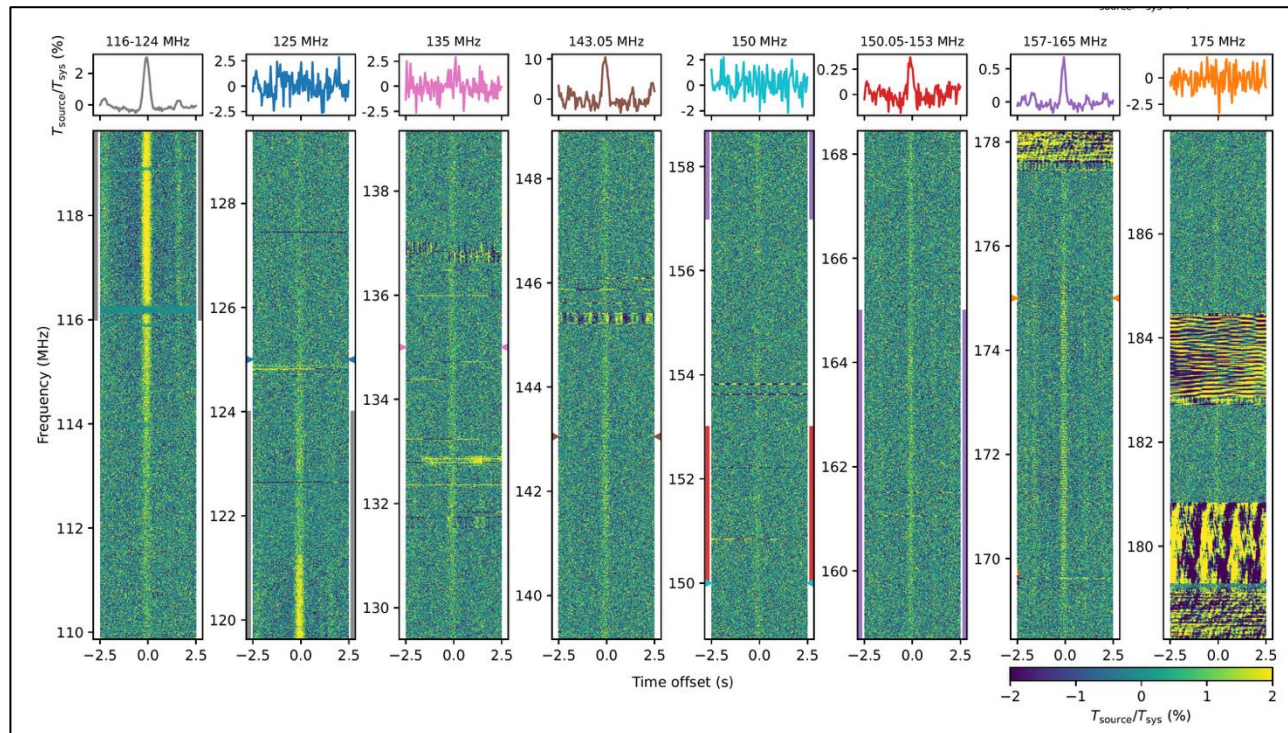
Large LEO constellations



Now

First measurements of UEMR with LOFAR

- Broadband signals far away from Tx frequencies
- Relatively strong narrowband signals
- Signals detected in RAS primary band (150MHz) in ~90% of cases where satellite is present

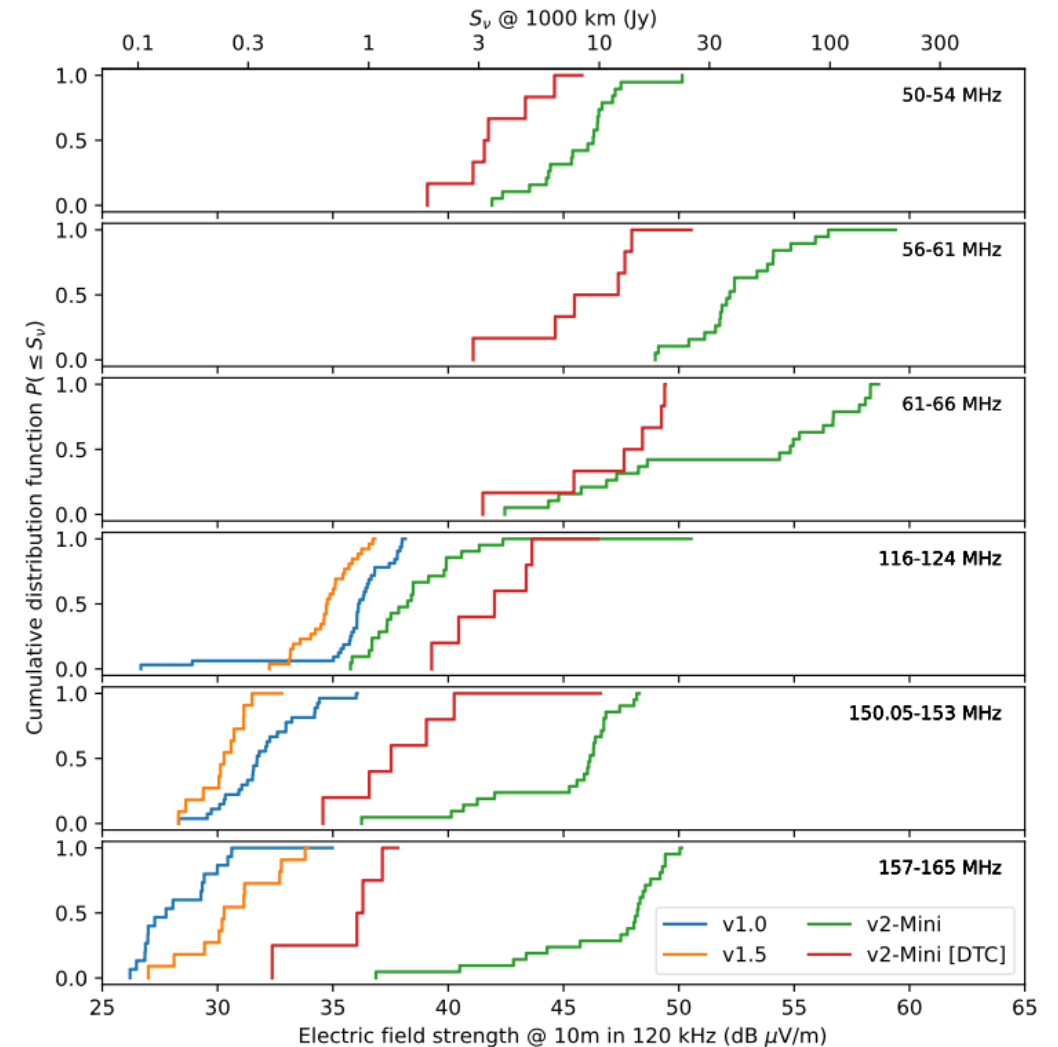
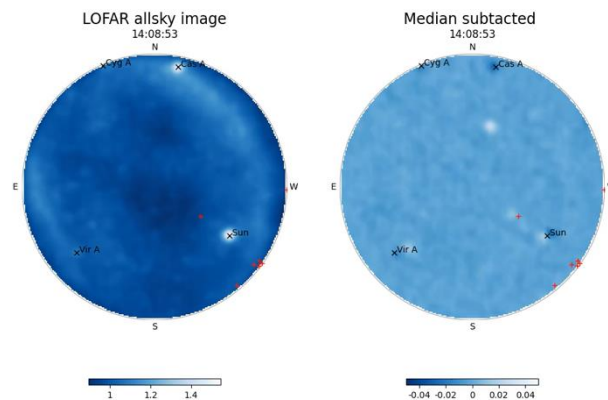


Artist's impression of a large satellite constellation in low Earth orbit circling above the LOFAR telescope. Credit: Daniëlle Futselaar.

Source: Di Vruno et al 2023.

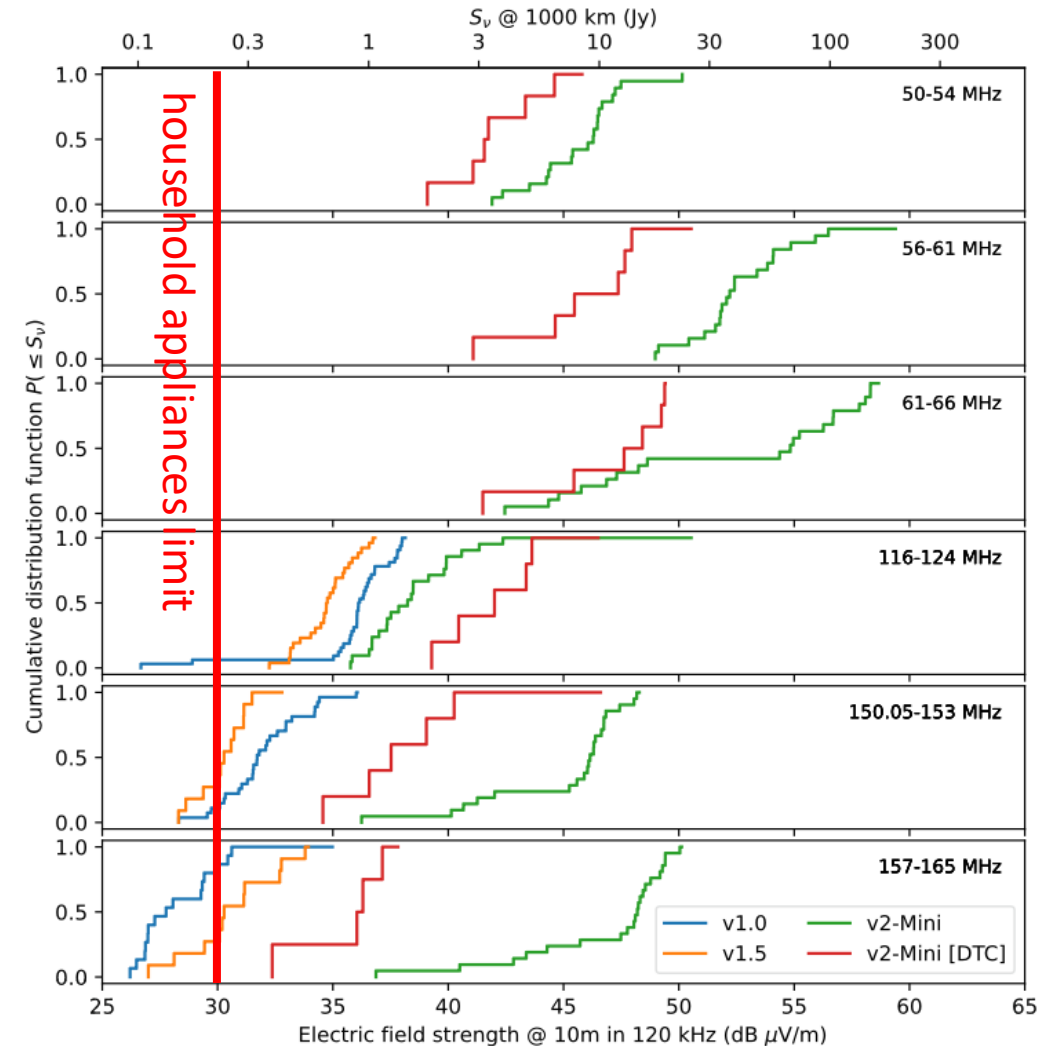
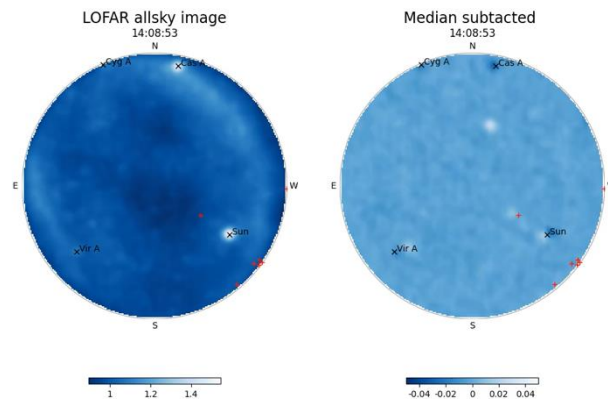
Second measurement of UEMR with LOFAR

- Cumulative distribution function of detections per frequency band
- Calculated E-field for Starlink is greater than 25 dB[$\mu\text{V}/\text{m}$] for all versions
- Most exceed CISPR-32 limit for household appliances by orders of magnitude
- Loss of data and observing time



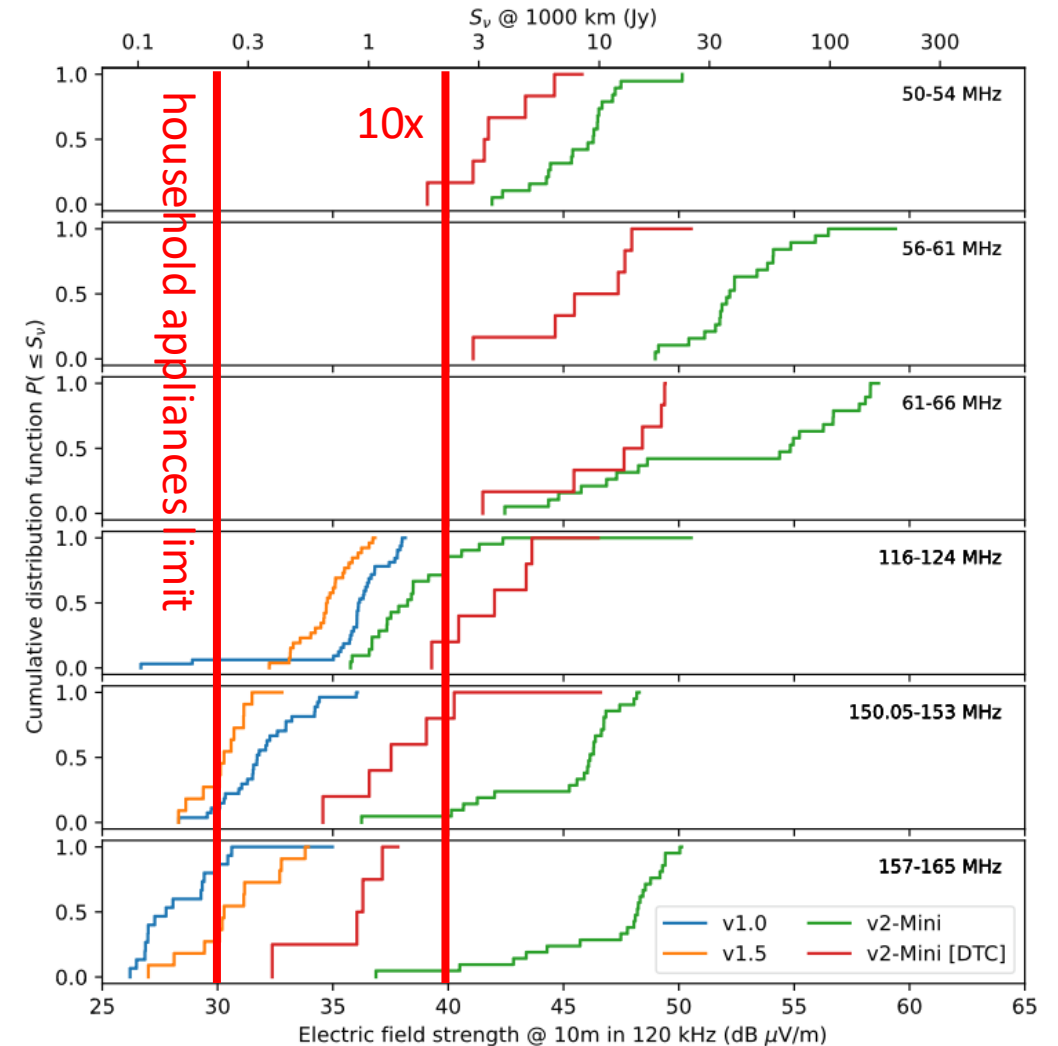
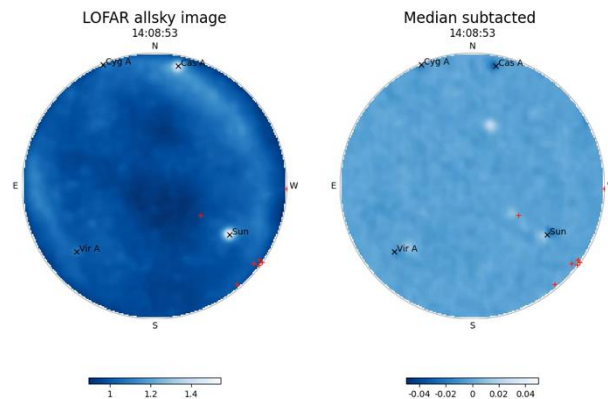
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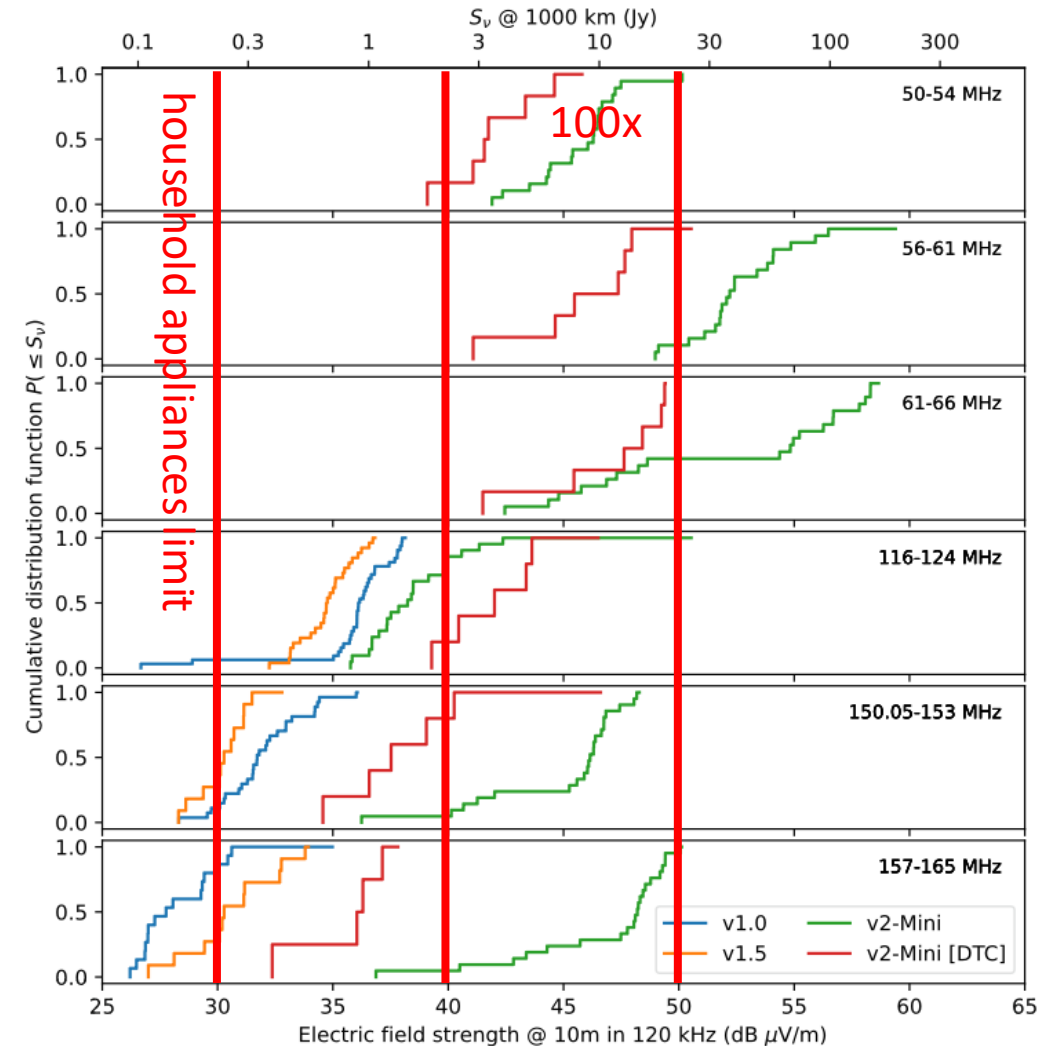
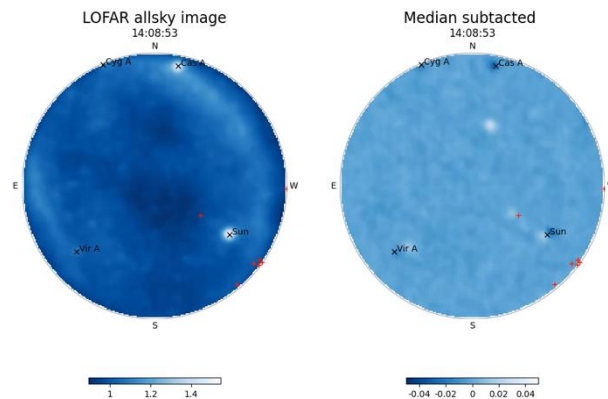
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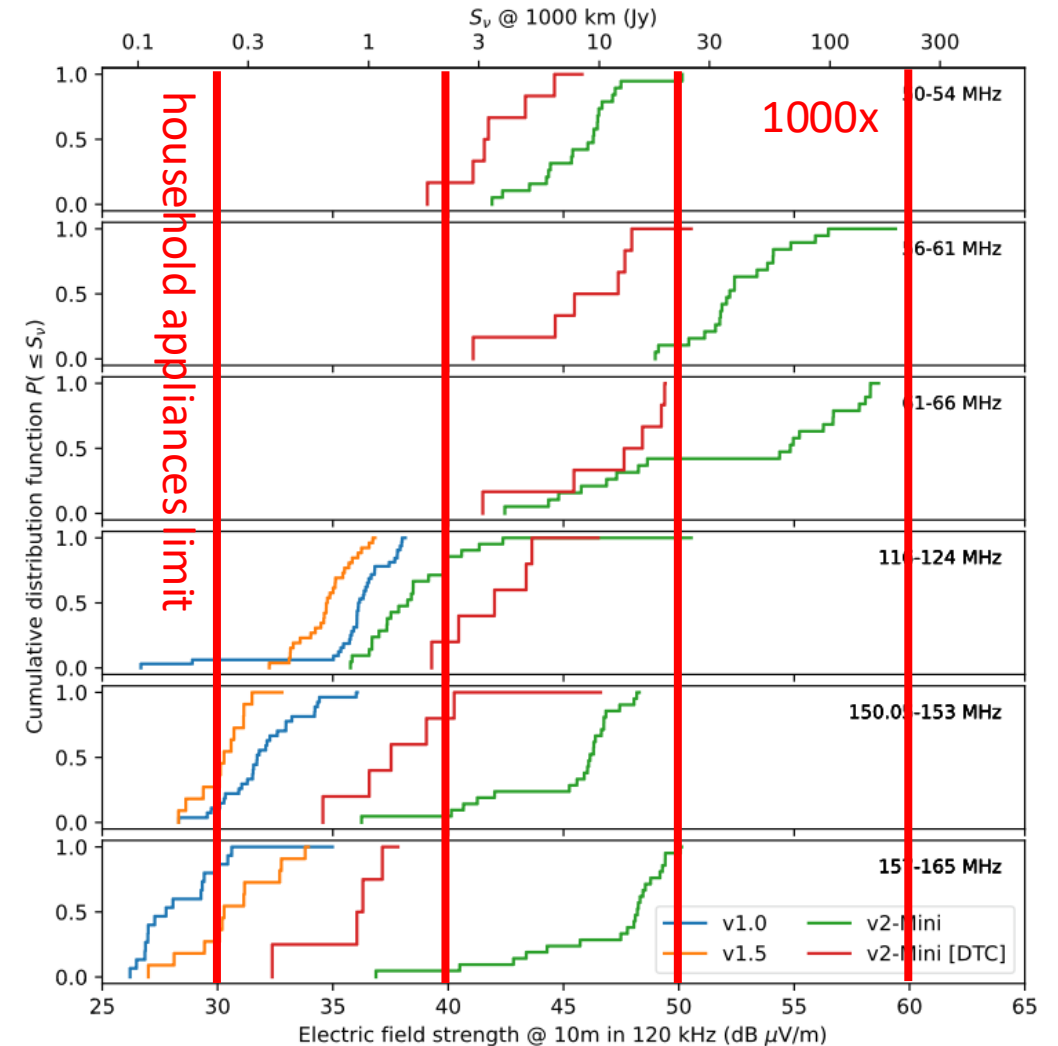
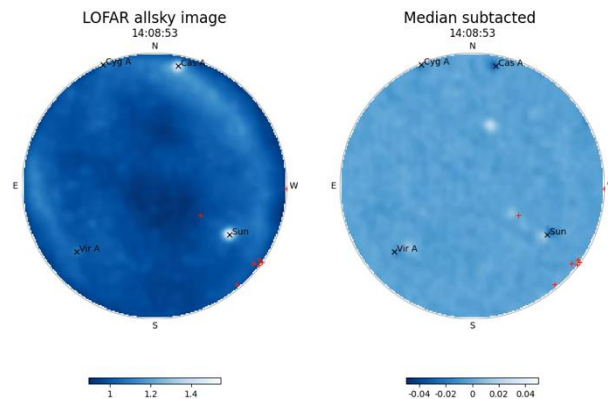
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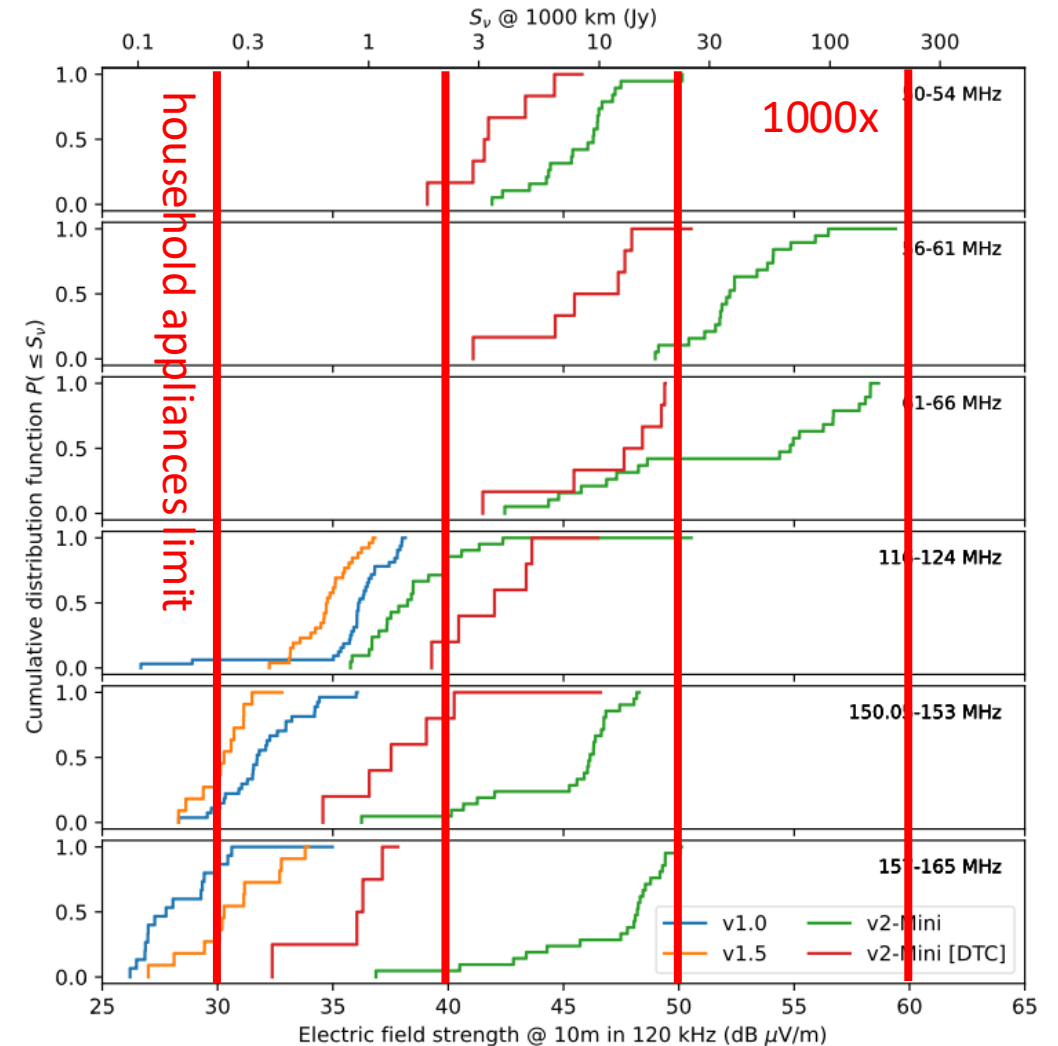
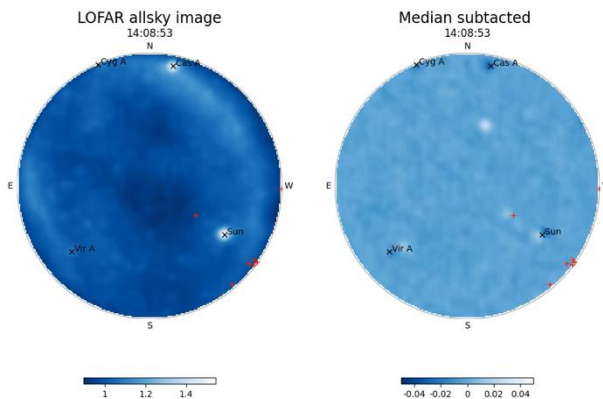


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**UEMR now seen
in X-band (9 GHz)!**

**LOFAR, NenuFAR,
MWA, MOPRA,
ATCA**



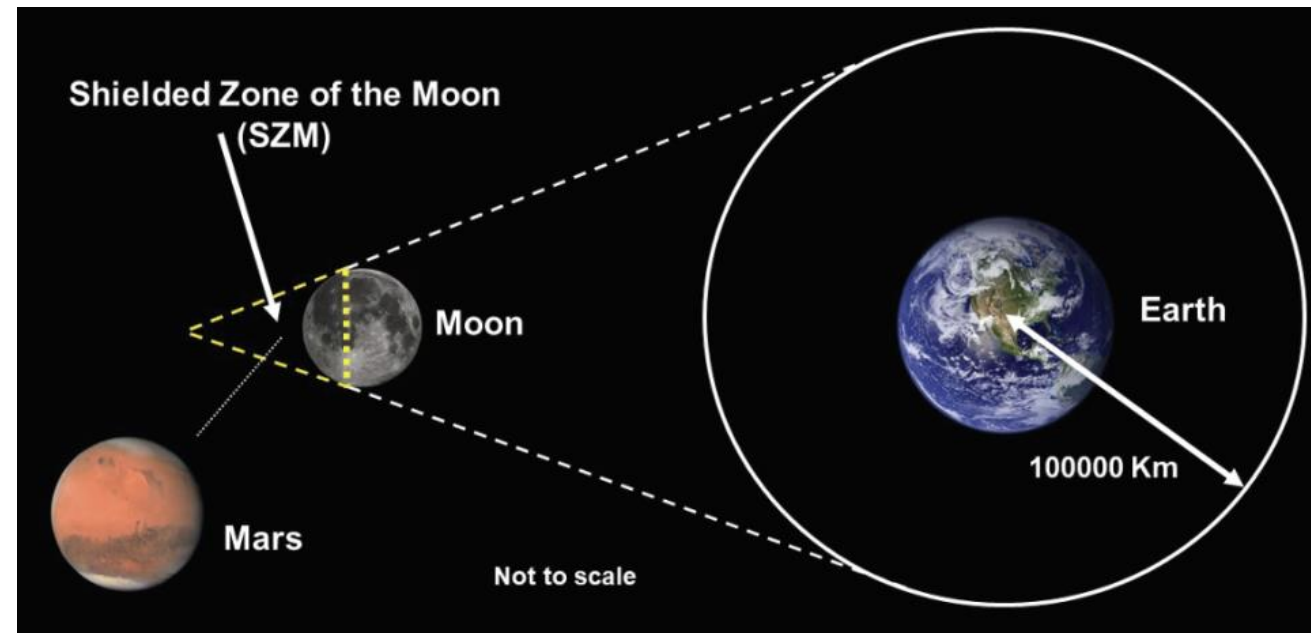
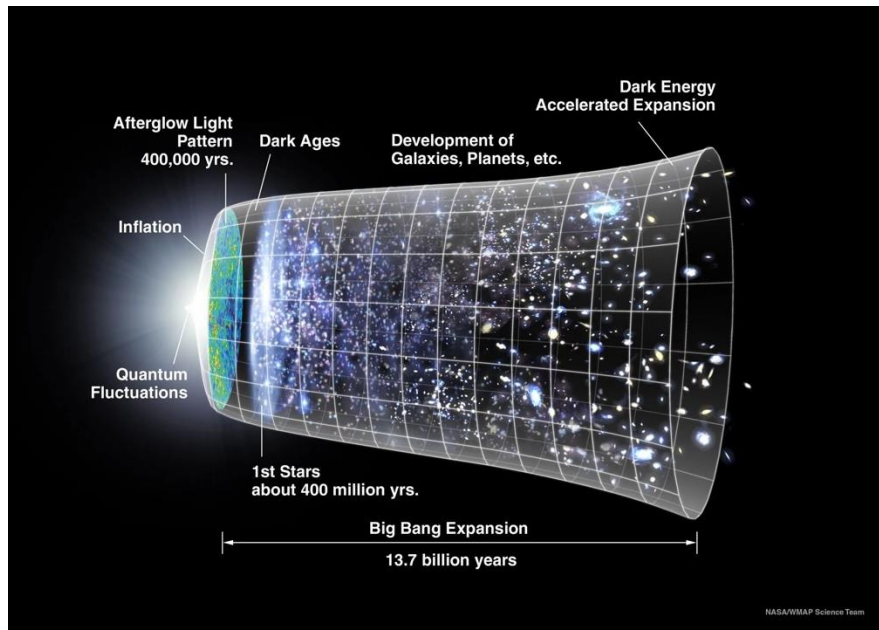
EoR observations and the moon

Early universe

- LOFAR & SKA search for the first stars and galaxies
- Satellite interference could erase the signal completely

Shielded zone of the moon

- Last 'easily' accessible RFI free zone
- Currently, status of UEMR protection in SZM unclear



The regulatory gap

Not illegal but unregulated

- Emissions exceed ITU-R protection thresholds
- May be covered by the Radio Regulations, but views differ
- No specific regulation in the Radio Regulations

What ITU covers

- Generic interference thresholds exist and are applied to emissions from transmitters
- UEMR comes from onboard electronics, not transmitters
- Radio Regulations imply that interference from "electrical apparatus" is prohibited
- UEMR not explicitly covered

The gap

- We are pushing the ITU to address this, progress remains slow
- No international EMC/EMI standards exist for satellites in orbit



Work on international regulations

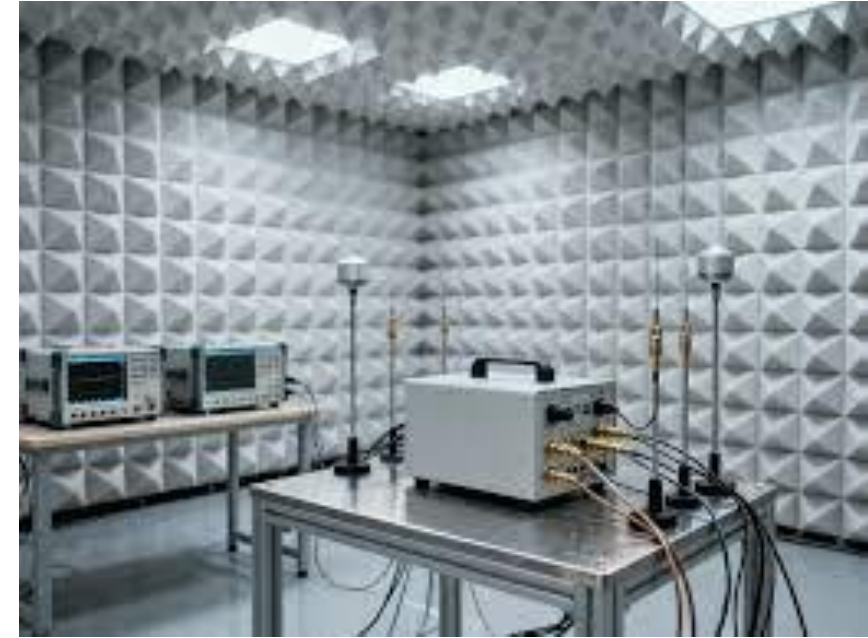


- Working through the ITU-R to get formal recognition of UEMR
- Draft technical report but no regulatory discussions yet
- Decisions require international consensus
- Difficult with US and SpaceX in the room

15.12 § 8 Administrations shall take all practicable and necessary steps to ensure that the operation of electrical apparatus or installations of any kind, including power and telecommunication distribution networks, but excluding equipment used for industrial, scientific and medical applications, does not cause harmful interference to a radiocommunication service and, in particular, to a radionavigation or any other safety service operating in accordance with the provisions of these Regulations¹.

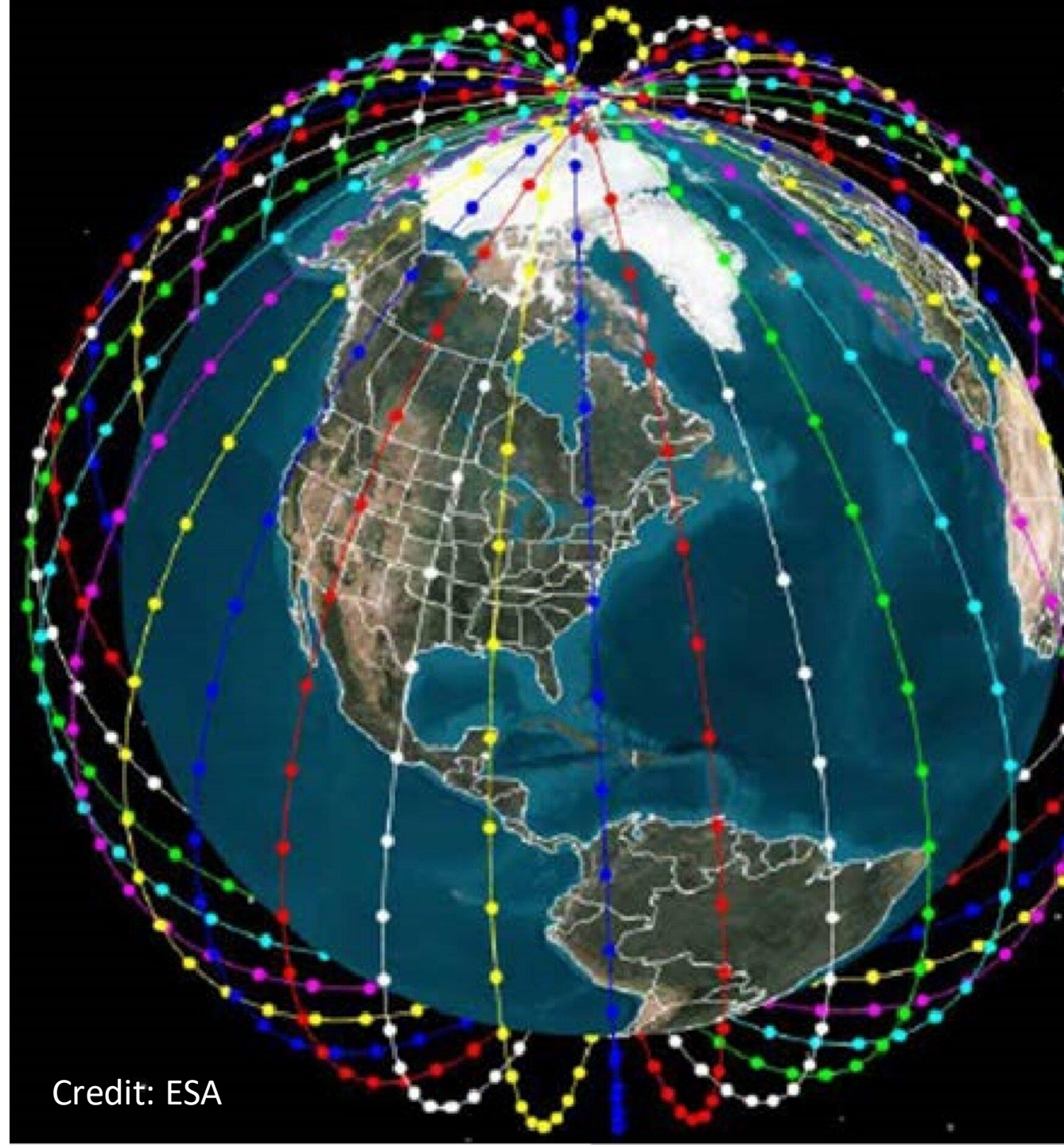
Electromagnetic compatibility standardisation

- UEMR is sometimes framed as an electromagnetic compatibility (EMC) issue
- EMC standards limit unintended radiation from electrical equipment
- Standards define requirements, measurement methods and compliance tests
- Standards are not laws, but are frequently incorporated into regulations and contracts
- No internationally recognised EMC standard for satellites considering radio astronomy
- Goal: develop EMC standards for satellites that protect radio astronomy



EPFD simulations

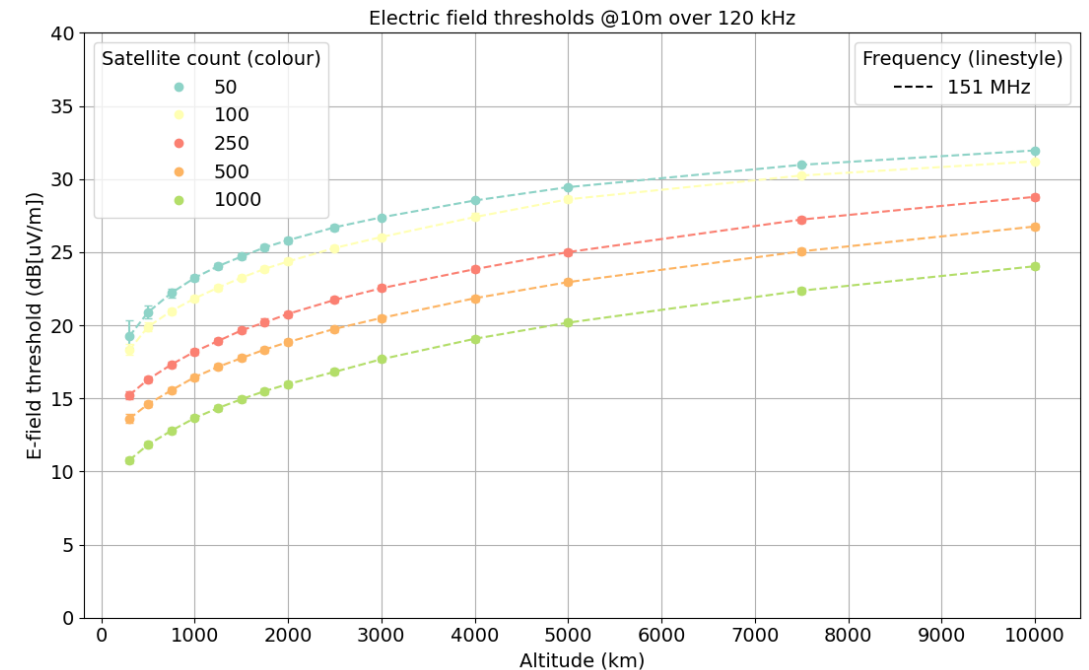
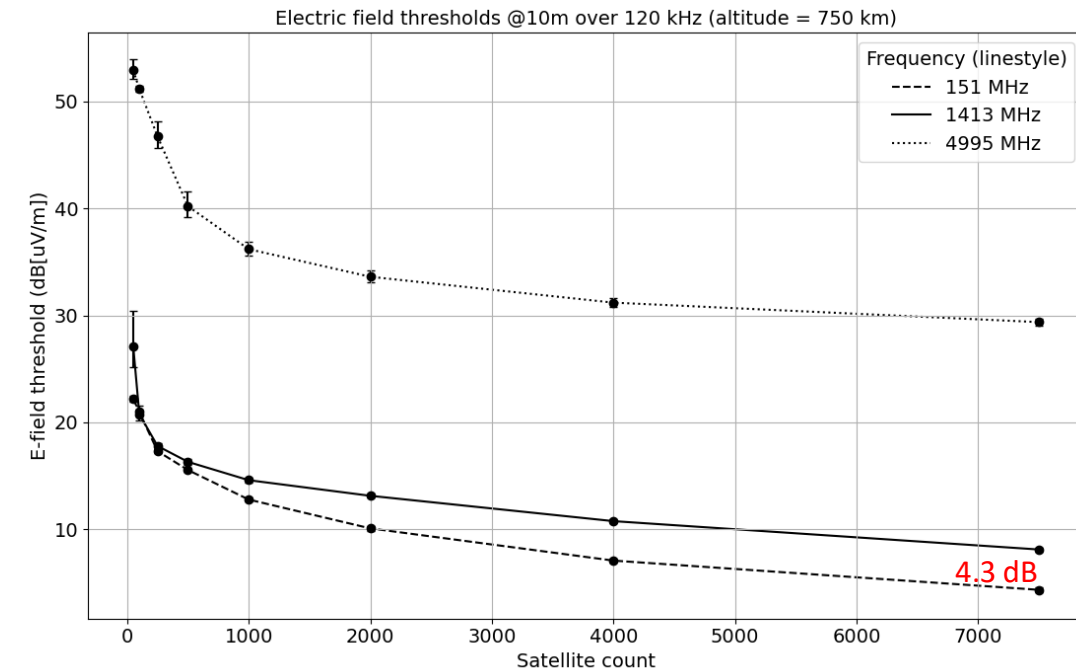
- Simulated satellite positions at 1-second resolution
- All possible telescope pointings
- 2000-second iterations
- Built statistical map of average received power
- Mapped results onto local sky
- Derived maximum allowed emission per satellite for a given protection criterion



Credit: ESA

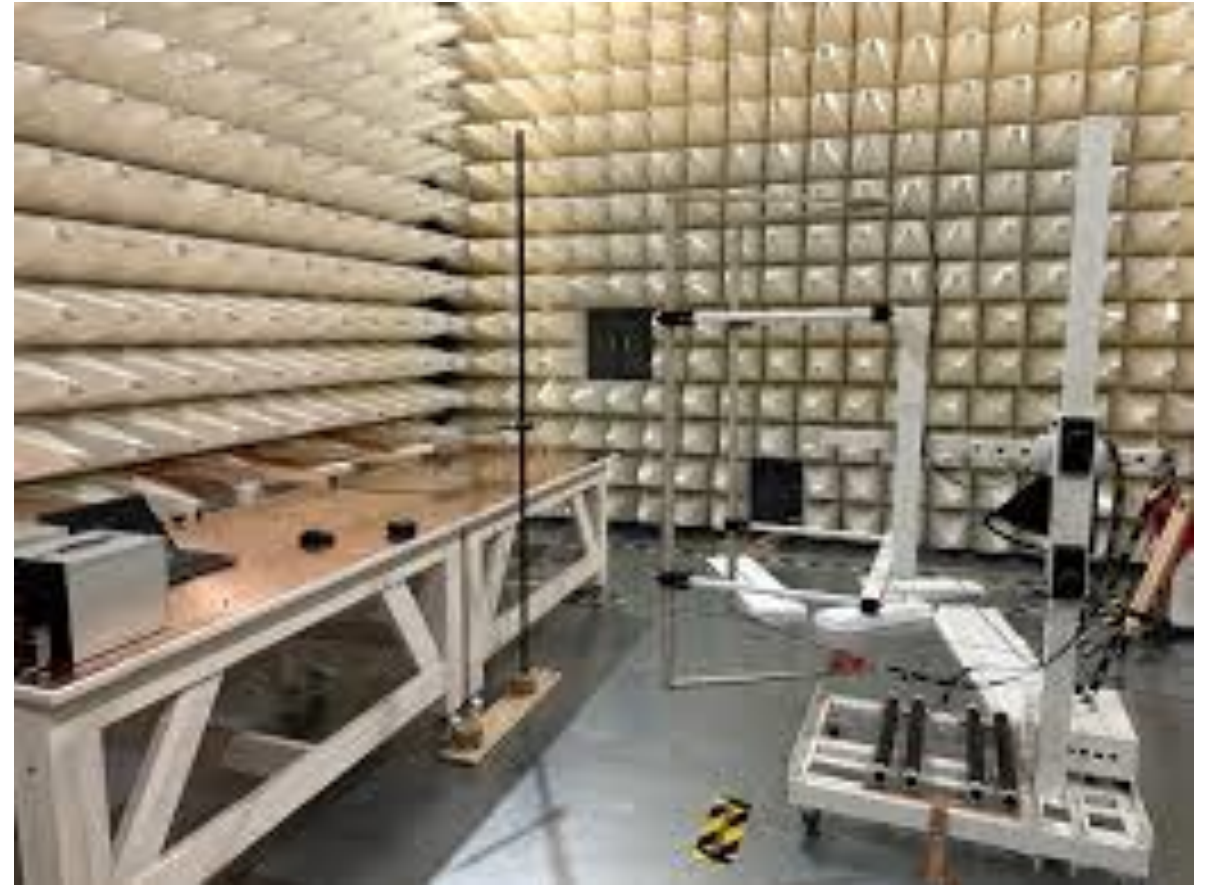
Electric field limits

- E field strength limits
- Assuming isotropic radiation
- Strong dependence on number of satellites and frequency
- Dependence on altitude weaker
- Approximation of limit for 100,000 satellites compared to 7500 sats: $10 \cdot \log(7500/100,000) = -11$ dB, going below 0 dB[uV/m]



Considerations for an EMC standard

- Frequencies: 10 MHz – 10 GHz?
- Lower frequencies for lunar observations?
- Broad band or narrow band?
- Up to which altitude?
- How many satellites?
- Protection thresholds from ITU-R regulations or something else?
- What limits?
- Measurable?
- Where to implement, how to enforce



Scientific impact

The impact is currently not known – detailed studies have not yet been performed

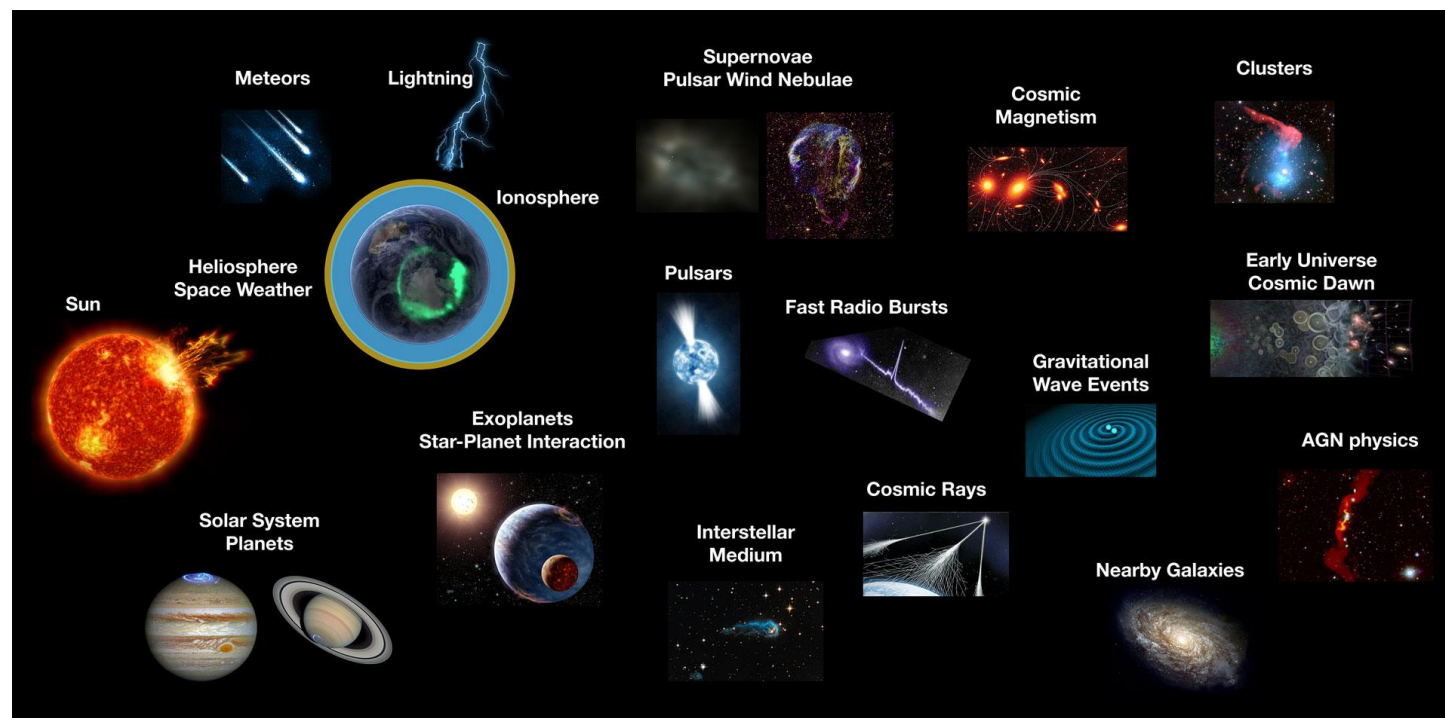
Expectations:

- Impact depends on science case; some science cases may cope, others may not
- Increased noise in all observations
- Temporal variations due to satellite motion; may impact transient searches
- No decorrelation on short baselines; may make large scale structures invisible
- Spectral structure due to combs; may impact spectral line studies



Example:

Studies by Wilensky et al. (2020) and Gehlot et al. (2024) show that the Epoch-of-Re-ionization science case can currently handle the radio frequency interference situation, but will rely on future improved mitigation methods.



Call to action to the LOFAR community

- Scientific impact still largely unknown
- Need science-case-specific assessment
- Simulate LOFAR data with UEMR
- Explore different satellite scenarios
- Realistic observing and processing setups
- Run through existing science pipelines
- Can the science still be done?
- Looking for community participation
- Contact: Cees Bassa (bassa@astron.nl) or Emma van der Wateren (wateren@astron.nl)

