



Delft University of Technology

Document Version

Final published version

Citation (APA)

Bentum, M. J., Verma, M. K., Rajan, R. T., Boonstra, A. J., Verhoeven, C. J. M., Gill, E. K. A., van der Veen, A. J., Falcke, H., Gurvits, L. I., & More Authors (2020). A roadmap towards a space-based radio telescope for ultra-low frequency radio astronomy. *Advances in Space Research*, 65(2), 856-867. <https://doi.org/10.1016/j.asr.2019.09.007>

Important note

To cite this publication, please use the final published version (if applicable). Please check the document version above.

Copyright

In case the licence states "Dutch Copyright Act (Article 25fa)", this publication was made available Green Open Access via the TU Delft Institutional Repository pursuant to Dutch Copyright Act (Article 25fa, the Taverne amendment). This provision does not affect copyright ownership.

Unless copyright is transferred by contract or statute, it remains with the copyright holder.

Sharing and reuse

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights. We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.

Green Open Access added to TU Delft Institutional Repository

'You share, we take care!' – Taverne project

<https://www.openaccess.nl/en/you-share-we-take-care>

Otherwise as indicated in the copyright section: the publisher is the copyright holder of this work and the author uses the Dutch legislation to make this work public.



A roadmap towards a space-based radio telescope for ultra-low frequency radio astronomy

M.J. Bentum^{a,d,*}, M.K. Verma^b, R.T. Rajan^b, A.J. Boonstra^d, C.J.M. Verhoeven^b
E.K.A. Gill^c, A.J. van der Veen^b, H. Falcke^{e,d}, M. Klein Wolt^e, B. Monna^g,
S. Engelen^g, J. Rotteveel^h, L.I. Gurvits^{f,c}

^a Eindhoven University of Technology, Faculty of Electrical Engineering, 5600 MB Eindhoven, the Netherlands

^b Delft University of Technology, Faculty EEMCS, Mekelweg 4, 2628 CD Delft, the Netherlands

^c Delft University of Technology, Faculty of Aerospace Engineering, Kluyverweg 1, 2629 HS Delft, the Netherlands

^d ASTRON, Netherlands Institute for Radio Astronomy, Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, the Netherlands

^e Radboud University Nijmegen, P.O. Box 9010, 6500 GL Nijmegen, the Netherlands

^f Joint Institute for VLBI ERIC, Oude Hoogeveensedijk 4, 7991 PD Dwingeloo, the Netherlands

^g Hyperion Technologies, Vlinderweg 2, 2623 AX Delft, the Netherlands

^h Innovative Solutions in Space, Motorenweg 23, 2623 CR Delft, the Netherlands

Received 25 December 2018; received in revised form 2 September 2019; accepted 3 September 2019

Available online 23 September 2019

Abstract

The past two decades have witnessed a renewed interest in low frequency radio astronomy, with a particular focus on frequencies above 30 MHz e.g., LOFAR (LOW Frequency ARray) in the Netherlands and its European extension ILT, the International LOFAR Telescope. However, at frequencies below 30 MHz, Earth-based observations are limited due to a combination of severe ionospheric distortions, almost full reflection of radio waves below 10 MHz, solar eruptions and the radio frequency interference (RFI) of human-made signals. Moreover, there are interesting scientific processes which naturally occur at these low frequencies. A space or Lunar-based ultra-low-frequency (also referred to as ultra-long-wavelength, ULW) radio array would suffer significantly less from these limitations and hence would open up the last, virtually unexplored frequency domain in the electromagnetic spectrum.

A roadmap has been initiated by astronomers and researchers in the Netherlands to explore the opportunity of building a swarm of satellites to observe at the frequency band below 30 MHz. This roadmap dubbed Orbiting Low Frequency Antennas for Radio Astronomy (OLFAR), a space-based ultra-low frequency radio telescope that will explore the Universe's so-called dark ages, map the interstellar medium, and study planetary and solar bursts in the solar system and search them in other planetary systems. Such a radio astronomy system will comprise of a swarm of hundreds to thousands of satellites, working together as a single aperture synthesis instrument deployed sufficiently far away from Earth to avoid terrestrial RFI. The OLFAR telescope is a novel and complex system, requiring yet to be proven engineering solutions. Therefore, a number of key technologies are still required to be developed and proven. The first step in this roadmap is the NCLE (Netherlands China Low Frequency Explorer) experiment, which was launched in May 2018 on the Chinese Chang'e 4 mission. The NCLE payload consists of a three monopole antenna system for low frequency observations, from which the first data stream is expected in the second half of 2019, which will provide important feedback for future science and technology opportunities.

* Corresponding author.

E-mail addresses: m.j.bentum@tue.nl (M.J. Bentum), m.k.verma@student.tudelft.nl (M.K. Verma), r.t.rajan@tudelft.nl (R.T. Rajan), boonstra@astron.nl (A.J. Boonstra), C.J.M.Verhoeven@tudelft.nl (C.J.M. Verhoeven), e.k.a.gill@tudelft.nl (E.K.A. Gill), a.j.vanderveen@tudelft.nl (A.J. van der Veen), h.falcke@astro.ru.nl (H. Falcke), m.kleinwolt@astro.ru.nl (M.K. Wolt), b.monna@hyperiontechnologies.nl (B. Monna), s.engelen@hyperiontechnologies.nl (S. Engelen), j.rotteveel@isispace.nl (J. Rotteveel), lgurvits@jive.eu (L.I. Gurvits).

In this paper, the roadmap towards OLFAR, a brief overview of the science opportunities, and the technological and programmatic challenges of the mission are presented.

© 2019 COSPAR. Published by Elsevier Ltd. All rights reserved.

Keywords: OLFAR; Nanosatellite; Satellite swarms; Ultra-long wavelength astronomy; Ultra-low frequency radio astronomy

1. Introduction

One of the last unexplored domains of the electromagnetic spectrum unexplored by astronomers is the ultra-low frequency band. This frequency domain, which covers frequencies from 0.1 to 30 MHz, contains footprints of the early Universe (between 0.38 and 400 million years after the Big Bang) (Jester and Falcke, 2009; Rajan et al., 2016), magnetospheric radio emissions from planets in the Solar System and perhaps from exoplanets (Zarka, 1998, 2007; Bentum, 2017, 2018), and imprints of a broad variety of astrophysical processes (Jester and Falcke, 2009).

For a variety of reasons, astronomical observations in this frequency domain have been rare. One of the key reasons is a major impact of ionosphere on radio propagation. The ionosphere reflects and refracts radio waves at low frequencies, and completely blocks signals from space below the ionospheric cut-off frequency. The cutoff frequency depends on the time of the day and the activity of the Sun, but can be as high as 10 MHz. In addition, human-made long range radio communications use this reflection property to broadcast signals across continents, as it keeps the radio waves inside the atmosphere (so called ‘ducting effect’). This makes the situation with RFI for radio astronomy problematic, as it is almost impossible to find or create a radio quiet zone. Both these two factors make it impossible to make observations at the surface of the Earth in the ultra-low frequency domain.

A space or Lunar-based radio telescope will overcome these problems and enable observations in the ultra-low frequency domain. There have been four space missions dedicated to low-frequency radio astronomical observations. The first radio astronomy explorer RAE-1 was deployed in an Earth orbit and made the first measurements of the Galaxy’s spectrum, between 0.4 and 6.5 MHz (Alexander et al., 1969). In 1971, the Interplanetary Monitoring Platform (IMP-6) conducted measurements of the Galactic radiation at 22 frequencies between 130 and 2600 kHz (Brown, 1973). The third mission was the radio astronomy explorer RAE-2 placed in a lunar orbit and observed between 25 kHz and 13 MHz (Alexander et al., 1975). The fourth, and the most recent experiment on long-wavelength observations is the Netherlands Chinese Low Frequency Explorer (NCLE), which was launched as a part of the Chinese Chang’E 4 Lunar mission on May 21, 2018. Another synergistic development of the past decades is the implementation of the first generation Space Very Long Baseline Missions, the Japan-led

VSOP/HALCA and Russia-led RadioAstron (Gurvits (2020) and references therein).

The NCLE consists of three monopole antennas of 5 m each, low noise amplifiers, a receiver system and a calibration unit, for monitoring the sky at low frequencies between 80 kHz and 80 MHz (Prinsloo et al., 2018). In addition to these four implemented missions, there have been numerous concept studies for space-based radio arrays in the past (French et al., 1967; Weiler et al., 1988; Basart et al., 1997; Jones et al., 2000). The more recent initiatives will be discussed in the next section.

In order to match in angular resolution and sensitivity modern Earth-based low-frequency radio astronomy systems as LOFAR-ILT at ultra-low frequencies, a system with a synthesized aperture of at least ~ 100 km is needed. Such a system can be composed of multiple satellites forming an interferometer, similar in principle to Earth-based low-frequency instruments e.g., LOFAR (van Haarlem et al., 2013). A space-based radio instrument as OLFAR will use small (nano-cube) satellites instead of conventional micro to large satellites. Several small satellites can be built with off-the-shelf components, making them affordable and simple to assembly. Hundreds to thousands of satellites can be deployed in a swarm formation, offering a good aperture (u, v) coverage and also baseline redundancy.

Satellite swarms in Earth orbits can in principle be formed while meeting the required aperture (u, v)-geometry and sufficient orbit stability. However, such a system will not be protected against human-made RFI. In addition, the Auroral Kilometre Radiation (AKR) (Mutel et al., 2003) which is the strongest near-Earth source between a few tens of kHz and approximately 700 kHz, will contribute to the interference sustained by OLFAR. On Lunar orbits a swarm formation could be shielded from the terrestrial RFI (Bentum and Boonstra, 2016). However, recent studies have shown that on the Lunar orbits suitable for effective shielding, the relative motion of the satellites are unacceptably fast (Bentum et al., 2019).

A solution for reducing RFI might be deploying OLFAR at larger distances from Earth where the intensity of terrestrial RFI is lower. Lower RFI allows for a smaller dynamic range of receiver systems on the satellites and therefore requires smaller data storage capacity. However, a larger distance over which the data need to be transmitted back to Earth increases the data transport challenge – a clear subject of a trade-off consideration. Deploying OLFAR closer to Earth requires more data to achieve

the same measurement fidelity compared with a higher altitude. On the other hand, the shorter distance to Earth makes it possible to transfer the data a higher speed.

In this article the roadmap for implementing OLFAR is presented. Several intermediate steps are envisioned. The article is organized as follows. In Section 2, a brief overview of recent initiatives for an ultra-low frequency space-borne radio astronomy telescope is given. In Section 3, the OLFAR science cases and high level requirements are presented after which, in Section 4, the roadmap towards a full OLFAR is discussed. Conclusions are presented in Section 5.

2. Overview of recent initiatives

During the last decade, several concept studies and projects have been drafted with the aim of building an ultra-low-frequency radio interferometer in space, and thus allows sky imaging down to a few kHz. This has long been impossible to implement due to the required aperture size. But it should be possible with current technology. The space-based studies have significantly improved the technology readiness levels (TRLs) of various subsystems, such as navigation, communications, small-spacecraft technology and swarm analysis. At this moment several teams in the world are working towards an implementation of such a radio telescope, including:

- In the Netherlands, a team consisting of several universities (Eindhoven University of Technology, Radboud University, Delft University of Technology), institutes (ASTRON, Joint Institute for VLBI ERIC, SRON), and companies (of which: Innovative Solutions in Space, Hyperion, NLR, TNO) started several initiatives: the ESA-funded DARIS (Distributed Aperture Array for Radio Astronomy In Space) project, (Saks et al., 2010; Rajan et al., 2016), the Dutch-funded OLFAR project (Bentum et al., 2009; Rajan et al., 2011, 2016), the ESA-proposed projects SURO (Space-based Ultra-long wavelength Radio Observatory) (Blott et al., 2013) and DSL (Discovering the Sky at the Longest Wavelengths, together with a Chinese team) (Boonstra et al., 2016) and the ESA-funded CLE (CubeSat Low Frequency Explorer) study (Bentum et al., 2018). These studies made the foundation for the Dutch-Chinese NCLE (Netherlands-China Low Frequency Explorer) space-mission, which is a single-antenna satellite launched in 2018, located in the Moon-Earth L2 point, and which observes at low frequencies.
- In France, a NOIRE concept (Nanosatellites pour un Observatoire Interferometrique Radio dans l'Espace/Nanosatellites for a Radio Interferometer Observatory in Space) was proposed by a team of several institutes led by the LESIA group (Cecconi et al., 2018). The concept focused on the feasibility study of a swarm of nanosatellites equipped with ultra-low frequency radio astronomy instruments.
- A combined Swedish and UK team proposed the FIRST explorer (Bergman et al., 2009), a constellation including six daughter spacecraft with radio astronomy antennas, and a mother spacecraft for science and metrology data processing and communications.
- A number of initiatives and design studies of various concepts of ultra-low frequency missions have been presented over the past several decades in the USA. A comprehensive review of early studies is given by Alexander et al. (1975) and Basart et al. (1997) and references therein. The most recent USA initiative, RELIC (Belov et al., 2018) aims to deploy a multi-spacecraft constellation forming a decametric wavelength synthesized telescope on a selenocentric orbit. The science case of RELIC is presented extensively in about ten papers cited by Belov et al. (2018). The authors conclude that the proposed concept is viable for implementation on a rather short timescale of about five years. Another recent initiative in the USA, SunRISE (Kasper et al., 2019) aims at studies of particle acceleration and transport in the inner heliosphere by means of radio interferometric imaging at frequencies from 100 kHz to 25 MHz. The concept assumes a formation of six satellites on a geosynchronous orbit with a typical baseline length between the satellites of about 10 km. The key technological idea behind the SunRISE concept is in utilizing commercial access to space, including a launch of all six spacecraft to their target orbit as a piggyback payload in conjunction with a larger spacecraft intended for GEO positioning.
- Several design studies of a broad range of prospective Space VLBI missions have been addressed in China over the past decade, including those aiming to operate in the ultra-low frequency domain (An et al., 2020). The NCLE experiment on the Chang'E-4 mission (Prinsloo et al., 2018) provided a new momentum for the ultra-low frequency studies which are envisioned in the framework of the DSL (Discovering the Sky at Longest wavelengths) initiative (Boonstra et al., 2016; Chen et al., 2019).

In Table 1, an overview of the initiatives is given, including the frequency range, maximum length of the baselines, the number of spacecrafts and the deployment location. All the initiatives, except NCLE, are project studies that have not proceeded to implementation stages. NCLE as well as OLFAR are discussed in more details in the following sections.

3. OLFAR – Orbiting Low Frequency Antennas for Radio Astronomy

Opening up the low frequency regime of 0.1–30 MHz for radio astronomy requires a space-borne, in particular, Moon-based or Moon-orbiting, instrument as mentioned in the previous section. The objective of the OLFAR project is to design and build scalable autonomous satellite

Table 1
History of space-based low frequency radio observatory studies.

Name	Freq. range [MHz]	Baseline [km]	No. S/C	deploy. location	Ref.
DARIS	1 – 30	≤ 100	6–8	Dyn. Solar Orbit	Saks et al. (2010)
FIRST	0.5 – 50	≤ 30	7	Sun-Earth L2	Bergman et al. (2009)
SURO	0.1 – 30	≤ 30	8+	Sun-Earth L2	Blott et al. (2013)
DSL	0.1 – 50	≤ 100	8	Lunar Orbit	Boonstra et al. (2016)
NOIRE	0.001 – 100	≤ 100	various	Lunar Orbit	Cecconi et al. (2018)
RELIC	0.1–30	≤ 100	33	Lunar orbit	Belov et al. (2018)
NCLE	0.08 – 80	0	1	Earth-Moon L2	Prinsloo et al. (2018)
OLFAR	0.1 – 30	100	≥ 50	TBD	Rajan et al. (2016)

units to be used as an astronomical instrument at the ultra-low frequencies. In this frequency range, the sky brightness temperature can be as high at 10^7 K at around 1 MHz. The OLFAR instrument should be able to measure weak astronomical signals, orders of magnitude less bright than the sky itself, and will therefore need a very high dynamic range. In Section 3.2 the requirements of the OLFAR instrument are presented.

3.1. Science case

A number of science case studies or ultra-low frequency astronomy have been published over the past decades, e.g. Gorgolewski (1966), Griebmeier et al. (2007), Jester and Falcke (2009), Mimoun et al. (2012), Boonstra et al. (2016), Rajan et al. (2016), Saks et al. (2010), Cecconi et al. (2018), Zarka et al. (2012) and references therein. We briefly summarize major topics of these cases, not attempting a comprehensive review of the above mentioned publications.

3.1.1. Cosmology

The most popular high-profile science case for low frequency radio astronomy is the study of cosmology, especially mapping the so called Dark Ages, Jester and Falcke (2009) and references therein. It addresses the observation of the highly redshifted HI line, originated at the cosmological epoch before the formation of the first stars. Mapping and tomography of the HI distribution with adequate angular resolution, would require baselines of the order of tens of kilometers and a large number of antennas (Jester and Falcke, 2009).

3.1.2. Planetary radio emission

The magnetized planets in Solar System (Earth, Jupiter, Saturn, Uranus and Neptune) are emitting intense radio signals resulting from particle accelerations in various places of their magnetospheres. The auroral radio emission is emitted from above the magnetic poles of the planet through a cyclotron instability. The radiation belts (in the case of Jupiter and possibly the Earth) are emitting synchrotron radiation. The auroral radio emission, including AKR, carries imprints of the geophysical processes

important for understanding the genesis and evolution of planets and their electromagnetic properties. Yet, comprehensive studies of AKR cannot be conducted from the Earth's surface due to the opaque ionosphere (Mutel et al., 2003) thus requiring a space-borne facility.

The planetary atmospheric discharges can also be the source of radio pulses, which are associated with lightning. With an ultra-low-frequency space-based array, observations of lightning from planets in Solar system will become possible, including the Earth-originated lightning emission too. In addition, signals from magnetized exoplanets could also be detected. Given the prominence of the exoplanetary studies in the modern astronomy agenda, a contribution from ultra-low-frequency astronomy should be seen as strong science driver (Griebmeier et al., 2007; Zarka et al., 2012).

3.1.3. Galactic and stellar astrophysics

The low frequency sky mapping and monitoring of the galactic and extragalactic sky address a multitude of science topics on radio galaxies, active galactic nuclei, large scale structures like clusters with radio halos. As demonstrated by, e.g., a number of studies of galactic and extragalactic targets at decameter wavelengths reviewed by Konovalenko et al. (2016) and the ongoing LOFAR Two-Metre Sky Survey (LoTTS, Shimwell et al. (2017)), the decameter to meter wavelength domain offers a very rich scientific harvest. There are no reasons to believe that pushing the frequency domain to even lower frequencies will be less productive. Of special interest for studies at ultra-low frequencies are extremely redshifted galaxies as beacons in the early cosmological epochs. While a number of ground-based radio observatories have produced sky maps at frequencies close but still above the ionosphere cut-off at about 10 MHz, only very cursory sky mapping at frequencies below 10 MHz is currently available. The latter observations were provided by the Interplanetary Monitoring Platform (IMP-6) presented by Brown (1973), the Radio Astronomy Explorers RAE-1 described by Alexander and Novaco (1974) and RAE-2 Alexander et al. (1975), Novaco and Brown (1978). The need for deeper sky mapping at ultra-low frequencies, especially in polarised emission is discussed by Rajan et al. (2016) and references therein.

3.1.4. Space weather

An important gap in the current space weather research capabilities can be filled by a space-based array. A terrestrial low-frequency array such as LOFAR can observe in the frequencies as low as 30 MHz. However, at lower frequencies a space-based instrument is needed, which will enable a wide range of solar and space weather research topics. These include for example, tracing the initial launch of a CME (coronal mass ejections), detailed tracking of the solar wind and CMEs through interplanetary space and in-depth studies of micro-structure in the Earth's ionosphere (Oberoi and Kasper, 2004).

3.1.5. Ultra-high energy particles

Ultra-high energy particles are likely composed of atomic nuclei, protons and potentially photons or neutrinos, which are extremely hard to detect due to their small flux of less than 1 particle per square kilometer per century, requiring large detectors such as the LOFAR. However, if a large array of low-frequency antennas are placed on the Lunar surface, then an increased sensitivity to cosmic rays and neutrinos can be exploited, as compared to the LOFAR (Nelles et al., 2015). In addition, the radio quietness at the Lunar surface would greatly benefit such measurements (Scholten et al., 2006).

3.2. OLFAR high level system requirements

Table 2 lists the high level system requirements of OLFAR derived from the science cases (see (Rajan et al., 2016)). The minimum distances between the satellites must be more than 10 km and due to interstellar scattering the maximum baseline is limited to 100 km, giving a resolution of 1 arc-minute at 10 MHz. OLFAR will comprise of more than 50 satellites, each containing three linearly polarized antennas, observing the sky from 0.1 to 30 MHz. Extrapolation to higher frequencies will increase data bandwidth and processing overload. On the other hand, the number of satellites could vary from 50 to larger than 10000, and meet a diverse set of aforementioned science cases, as discussed in Jester and Falcke (2009). The satellites will employ passive formation flying and yet maintain sufficient position stability for a given integration time. In the presence of a stable orbit and thus stable baseline, position estimates can be more precisely known and thus the

Table 2
OLFAR system requirements.

Number of satellites	≥ 50 (scalable)
Number of antennas	2 or 3
Observation frequency range	0.1–30 MHz
Instantaneous bandwidth	≥ 1 MHz
Spectral resolution	1kHz
Snapshot integration time	1–1000 s
Maximum baseline between satellites	100 km
Deployment location	Moon orbit, Earth trailing, L2

integration time can be extended up to 1000 s and thereby reducing the down-link data rate (Rajan et al., 2016).

4. Roadmap

A roadmap towards realizing the OLFAR mission is illustrated in Fig. 1, which provides a wide range of technology candidates and a development pathway for the oncoming decade. The long term goal is to enable the deployment of OLFAR satellites in a Lunar orbit by 2030. Furthermore, the roadmap outlines the high-level requirements of each phase, and the necessary technological developments, which will be incorporated into the mission along the road to realizing OLFAR.

The roadmap is divided into 4 distinct phases, as illustrated in Fig. 1, to gradually build up on operation experience, validate newly developed technologies, and address diverse science cases. Furthermore, the proposed roadmap is in alignment with the long term planning of other major space agencies, which allows for gradual build up of the swarm in the final location of OLFAR.

In this section, we will outline all the four phases and provide a description, high level requirements, and the technologies that need to be developed to successfully realize the phase. We also mention the strategic importance of each phase in the context of the overall OLFAR mission. To this end, each phase description is divided into key subsections, as follows.

- Mission description
- Technology challenges
- High level requirements
- Time to launch.

4.1. Phase 1: Netherlands Chinese Low Frequency Explorer (NCLE)

4.1.1. Mission description

The NCLE is a low-frequency payload which is currently on-board the Chang'e 4 satellite (see Fig. 2), which was launched on May 21st, 2018, and is located in a Lissajous orbit around the Earth-Moon L2 point (Boonstra et al., 2017). The NCLE design concept involves 3 co-located, orthogonal, monopole antenna elements, each of 5 m in length. These 3 active antennas are mounted perpendicular to the upper side of the satellite body. The voltages between the monopoles and the spacecraft body are measured, digitized and send to Earth for further processing. The frequency range of NCLE is 80 kHz to 80 MHz, and overlaps with the Earth-based LOFAR LBA spectrum (van Haarlem et al., 2013), which could be useful for validation.

The NCLE is a pathfinder for a future space-based low-frequency radio interferometer, and thus one of the key objectives of NCLE is to characterize the lunar radio environment and to understand the RFI at ultra-low frequen-

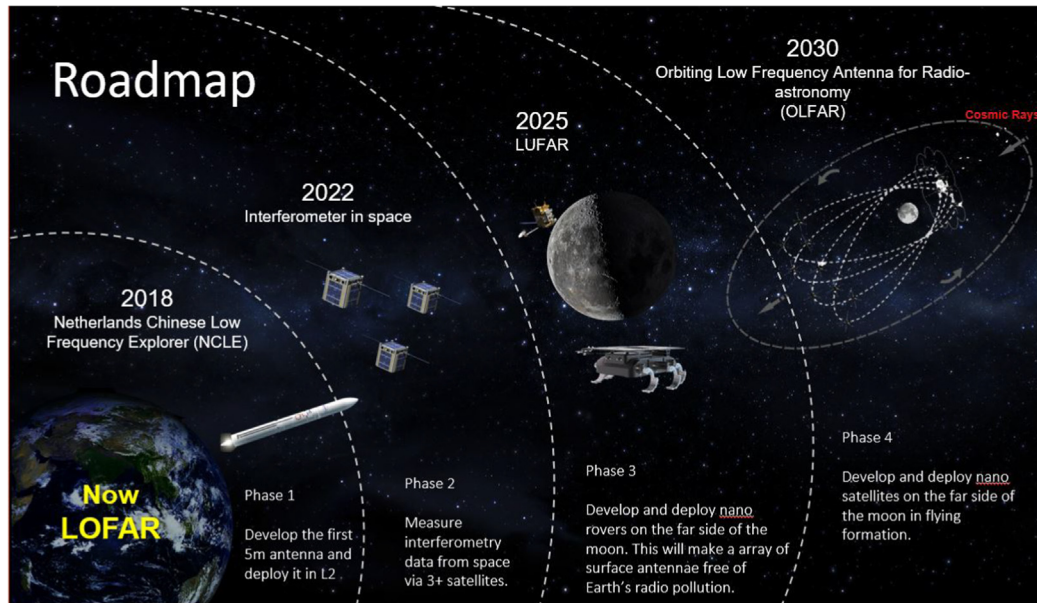


Fig. 1. OLFAR roadmap.

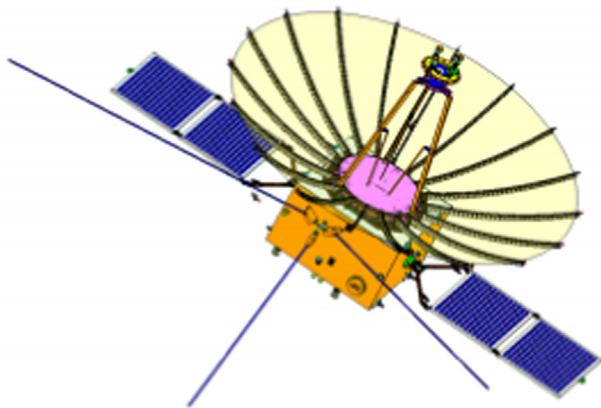


Fig. 2. An illustration of the Chang'e 4 satellite with three monopole antennas mounted on the body of the satellite (Boonstra et al., 2017).

cies. In addition, NCLE will also enable the study of solar activity, space weather, and possibly a detection of bright pulsars and other radio transient phenomena at ultra-long wavelengths, although the latter is not warranted due to the sensitivity limitations.

4.1.2. Technological challenges

One of the fundamental challenge in the NCLE payload is the design and development of the wideband science antenna and the following low-noise amplifier (LNA) (Prinsloo et al., 2018). The EMI modelling, system integration and calibration of the science front-end is a critical challenge in the NCLE mission. The analogue signals are digitized in a DSP system on which dedicated science modes are implemented in a flexible software-defined radio system, which is part of the NCLE payload. These modes for instance perform fast Fourier transforms to create

average radio spectra, allow triggering on transient radio events, or allow to retrieve direction of arrival information using beam-forming or goniopolarimetry techniques (Boonstra et al., 2017). Finally, the data is relayed back Earth-based ground stations, by the Chang'e 4 satellite. The high level requirements of the NCLE Science instrument are listed in Table 3 (Prinsloo et al., 2018).

4.2. Phase 2: LEO CubeSat Low Frequency Explorer (LCLE)

4.2.1. Mission description

The LCLE will be the first standalone mission to allow key *interferometry technologies* to be tested for OLFAR. The mission will consist of 3 cubesatellites in a low Earth orbit (LEO), each equipped with 3 dipoles. The low frequency measurements will take place every time the satellites are at the apogee point of orbit, which is followed by correlation and integration of the measured data. The processed data is sent to the ground station for further analysis, when the satellites are nearest to Earth.

4.2.2. Technological challenges

There are several technical advancements that are needed, to make this mission feasible. The LCLE is by no means the first mission to have cubesats flying as a group of three but it will be the first to deploy a radio sensitive payload in LEO and fly in a very tight formation. The high accuracy needed to maintain flight within small position error means that the mission will heavily rely on an active attitude determination and control subsystem (ADCS) system. In the ADCS system, having a propulsion system which can provide enough delta V constantly maintaining the attitude and last for more than 3–4 years is one

Table 3
High level requirements of the NCLE payload.

Req. ID	Requirement
NCLE1	The NCLE antennas operates in the frequency range of 80 kHz to 80 MHz
NCLE2	Each of the three antennas is 5 m in length
NCLE3	NCLE instrument is adhere to electromagnetic interference specifications of MIL-STD-461
NCLE4	The location of the NCLE antennas on the spacecraft is not influencing the radiation performance of the antennas

the biggest challenges to overcome for this mission. This also means a very accurate and reliable pointing algorithm is needed to make sure each satellite can independently locate its position and in relation to each other by sharing their own location details in the orbit. For inter-satellite communication, not only position data will be shared but also the raw measurements will be sent to each one of them to do distributed correlations. As each measurements will produce several Gigabits of data, a very high data inter-satellite communication is necessary which can be laser or RF based. The science front-end comprising of the antenna, antenna deployment mechanism, LNA and the digital signal processing system, will be miniaturized to enable power and mass efficiency. The high level requirements for the LCLE payload is listed in Table 4.

4.2.3. Estimated time to launch

The mission is expected to be ready for launch in 2022/2023.

4.3. Phase 3: LUNar low Frequency Antennas for Radio Astronomy (LUFAR)

4.3.1. Mission description

LUFAR stands apart from the previously planned single-rover missions (see (Mimoun et al., 2012)), as it makes use of several individual nodes, like LOFAR (van Haarlem et al., 2013), to make a large array of antennas. Where all other concepts deploy large static stretched out antennas from a central node, a group of nanorovers (swarm) will carry one antenna each for LUFAR. State-of-the-art rovers will enable a flexible spatial sampling of the UVW plane for radio astronomy observations. As the array is made up of mobile platforms, formation is dynamic in nature and can adjust in shape and size to test a number of configurations.

The rovers will be deployed on the far side of the Moon onboard a lander which will land on the edge of the far side. This way, the lander can be in the field of view of

the swarm on the far side and ground stations on Earth. This will allow the lander to act as a communication hub and relay data between the ground station, if a in-orbit relay spacecraft is not available. The rovers will take measurements and transfer raw data within the swarm for correlation via fibre optic cables. The processed data can be sent by the rovers to the relay system to be communicated to Earth. In the initial study, the number of rovers needed to make LUFAR successful for a wide range of science cases, is similar to OLFAR (50+ antenna systems). Therefore, the swarm will build itself gradually by adding 5–10 rovers each time a mission is flown to the Moon, if the ideal case of a dedicated mission is not feasible.

Given results from the LCLE, the initial formation algorithm and on-board correlation, LUFAR will be implementing the same technology but at a much larger scale which will be a much closer representation of the OLFAR mission. One of the biggest advantages of testing high accuracy navigation subsystems and techniques on LUFAR is that the change in attitude is very low and the nodes are in much more stable and predictable relative position. This allows for much less risk factor and focus every aspect of the mission to optimize for the large number of nodes and mass production. Besides testing systems for lunar environment, an autonomous self-organization ('swarm-intelligence') algorithm will be implemented for the first time on a large scale and provide vital experience for the next phase of OLFAR. LUFAR will also validate the science cases possible that can be carried out on the far side of the Moon as rovers can maintain continuous observations for a long period of time, which is vital to know if OLFAR satellites are optimized for the science cases described in Section 3.1.

LUFAR can be extended to allow the rovers to be used as a navigation reference for OLFAR satellites on lunar ground and provide auxiliary data for validation of observations made in orbit. In case of emergency, LUFAR may also provide a communications relay for flying nanosatellites and a data backup location.

Table 4
High level requirements of LCLE.

Req. ID	Requirement
LCLE1	The science instrument shall operate in the radio frequency range of 1–30 MHz
LCLE2	Inter satellite distance shall be 100 km at maximum
LCLE3	Observations shall take place at least for a year
LCLE4	Minimum inter-satellite communication data rate shall be 6 Mbps

4.3.2. Technological challenges

LUFAR rovers will be deployed in harsh lunar environment, and carry out very sensitive measurements over a long period of time, in full autonomy. This mission therefore brings a relatively new list of technical challenges compared to the last two phases but is also critical to the next and final phase.

For housekeeping and nominal operations of the rover, an autonomous swarming algorithm shall be developed which not only ensures the survival of the rover and swarm in very cold conditions but also navigates and maintains relative positioning. Antenna and its deployment system will also need to be developed to survive the abrasive and electrostatic nature of the dust particles. An ‘intelligent’ inter-rover communications will also be a demanding task to develop in order to prevent data congestion because a large amount of raw data will flow through this system. During night time, the rover should house a miniaturized very efficient power and active thermal system which will ensure critical system survive -180°C and have minimal electromagnetic interference with the measurements. One major bottleneck that is unique to LUFAR mission is the communication relay system. Although the lander and in-orbit satellite provide a means to do so, the data communications systems on board the rover needs to handle a very high data rate while also being miniaturized enough for a shoe-box sized rover, which is currently not available off-the-shelf. In addition, the LUFAR will establish inter-rover communication links for exchanging raw data, and enable distributed processing for correlation in the swarm and navigation. Furthermore, the processed data must be downlinked to Earth via an rover on the near-side or using a relay satellite. The high level requirements for the LUFAR mission are listed in [Table 5](#).

4.3.3. Estimated time to launch

Delft university of technology and various Dutch partners are currently working on a concept of a Lunar Rover which will be a stepping stone for LUFAR. Given that NASA, ESA and other major agencies have similar plans and are up-scaling lunar missions in the coming decade, LUFAR has a good chance to be ready for flight by 2025, with full capability of swarm reached by 2030.

4.4. Phase 4: Orbiting low Frequency Antennas for Radio Astronomy (OLFAR)

4.4.1. Mission description

Our dot on the horizon, OLFAR, aims to develop a space-based antenna array for radio astronomy comprising of 100’s to 1000’s of nano-satellites for radio astronomy observations at 0.1–100 MHz. The satellites will be spatially co-located within a maximum of 100 km, which will result in sky-maps of sub arc-minute resolutions at these wavelengths. This means that OLFAR will be 1–3 orders of magnitude more capable than its ground-based or space-borne predecessors in terms of sensitivity, dynamic range, and both angular and spectral resolution. The exact location of OLFAR is still under investigation. It could either be an orbit around the Moon or a location far away from Earth to overcome the RFI from Earth.

4.4.2. Technological challenges

To be able to launch OLFAR, a few technology breakthroughs will be needed. Many of the collaborators in aforementioned projects, including the NCLE, are part of our current consortium, offering a blend of expertise from radio astronomy, telecommunications, aerospace systems, embedded systems and navigation. A few of the fundamental science and technology challenges, which are listed in 5 distinct domains:

- *Array calibration and 3-D imaging* Antenna calibration is one of the biggest challenges for any low-frequency phased arrays, and for terrestrial arrays, calibrating ionospheric phase fluctuations tops the list ([van Haarlem et al., 2013](#)). The instrumental beam shape, and the frequency dependent gains of the antennas must be calibrated on the fly with minimal Earth-assistance. For low frequency observations, the requirements on positional stability and clock accuracies are in the order of sub-meters and sub-nanoseconds respectively, which drive the navigation requirements of OLFAR. Secondly, unlike terrestrial low-frequency arrays which are quasi-planar and have (at best) a hemispheric view, OLFAR will enable an instantaneous 3D view of the sky with a field-of-view of the full celestial sphere. 3D Imaging on

Table 5
High level requirements of LUFAR.

Req. ID	Requirement
LUFAR1	The science instrument shall be able to operate in the radio frequency range of 0.1–30 MHz
LUFAR2	The distance between rovers shall be 10 km at maximum
LUFAR3	Each rover shall have an internal operating temperature range of -40°C to 50°C
LUFAR4	Each rover shall have the ability to be commanded from ground station individually
LUFAR5	The science instrument’s antenna shall be 10 m long
LUFAR6	Each rover shall not have a mass of more than 8 kg
LUFAR7	The swarm shall be able to navigate and operate autonomously

a sphere with an interferometric array has been addressed by Carozzi (2015)) as well as by Vugt et al. (2017).

- *Navigation* The knowledge of position, time and orientation of individual satellites is vital for radio-science interferometry and for communication. However, due to the distant deployment and the sheer number of satellites, current dependence on GPS-satellites and Earth-based ground segment are either not scalable or too expensive. In particular, when OLFAR is orbiting the far side of the Moon, the satellite swarm is completely disconnected from Earth for few hours (Rajan et al., 2011). This drawback calls for self-navigation or relative navigation of OLFAR, which suffices the needs of radio science, intra-satellite communication and collision avoidance. The desired synchronization accuracy is related to the accuracy of the onboard clocks and the observation frequencies of the OLFAR network (Rajan et al., 2013). Despite satellite mobility, clock synchronization can be achieved by employing generalized two-way ranging between mobile satellites (Rajan and van der Veen, 2015). Recent studies show that joint relative localization and synchronization is feasible for such GPS-denied or reference-free networks (Rajan et al., 2015; Rajan et al., 2019), however numerous questions still remain unanswered. For example, how can the relative time-varying position-time-orientation be estimated sufficiently accurate by a satellite swarm by only communicating with the neighbouring satellites? Can data fusion be applied to combine the satellite orbital dynamics and kinematics? Answering these questions will not only enable space-missions such as OLFAR, it would also contribute to breakthroughs in terrestrial navigation.
- *Communications and Antenna Design* In the swarm of satellites there is a need for high-data-rate inter-satellite communication, both for localization and navigation purposes as well as for the exchange of data for the interferometric data processing. Multi satellite systems, operating as interferometers will generate so much data, that it needs to be processed to reduce the data volume to the essential information before it will be possible to relay the information onto the end user via a ground station. Apart from the need for high speed inter satellite communication, the need for high speed satellite-to-ground station communication is also rapidly growing. The total antenna system for the intended applications can be distinguished in three parts: the antenna system for the payload (the reception of astronomical signals), the antenna system for communication in the distributed space system and the antenna system for the data downlink to Earth.
- *Space systems engineering and miniaturization* To establish a swarm of satellites of perhaps hundreds of elements, miniaturization of the elements is required. This holds technology challenges on the level of individual elements, but also requires systems engineering

breakthroughs in order to guarantee their efficient development, and a robust and efficient operations of the entire swarm and other mission elements. Miniaturization may result in the design of small antennas. However, with smaller antennas, communication on lower frequencies is not possible. Higher frequencies are power hungry which might be a problem given that small harvesters provide limited energy. In the coming years, we want to address such problems both in terms of hardware and communication. Attitude control is necessary for antenna pointing and orientation and energy harvesters towards the energy source. To this end, we want to explore the ways to miniaturize attitude control systems such as momentum wheels, magneto-torquers, and our existing micro-propulsion system.

- *Distributed processing* The OLFAR swarm will employ distributed architectures for navigation, communication and processing science data, to avoid single point of failure, optimize efficiency and to abide by power constraints imposed by nano-satellites (Rajan et al., 2013). While distributed computing in these individual domains are common in terrestrial applications, OLFAR will juggle between these tasks while adhering to the strict science requirements levied on the mission. OLFAR will employ on-board distributed correlations to process streaming payload data, in order to reduce the data-downlink back to Earth.

5. Conclusion

Space-based ultra-low-frequency radio astronomy will present a new milestone in our understanding of the Universe. It will open the frequency range below 30 MHz, which will enable unique science. For that purpose, missions such as OLFAR are essential to get access to this low-frequency part of the spectrum. The road to OLFAR, however, includes both scientific opportunities, and challenges concerning technological development and programmatic. In this article, we briefly summarized the previous missions, and presented a roadmap to tackle the technological challenges for the dot on the horizon, a fully operational OLFAR.

Acknowledgements

We are grateful to the anonymous referees for very useful critique and constructive suggestions on the present paper.

References

- Alexander, J., Kaiser, M., Novaco, J., Grena, F., Weber, R., 1975. Scientific instrumentation of the Radio-Astronomy-Explorer-2 satellite. *Astron. Astrophys. J.* 40 (4), 365–371.
- Alexander, J.K., Brown, L.W., Clark, T.A., Stone, R.G., Weber, R.R., 1969. The spectrum of the cosmic radio background between 0.4 and 6.5 MHz. *Astrophys. J.* 157, L163.

- Alexander, J.K., Novaco, J.C., 1974. Survey of the galactic background radiation at 3.93 and 6.55 MHz. *Astron. J.* 79, 777–785.
- An, T., Hong, X., Zheng, W., Ye, S., Qian, Z., Fu, L., Guo, Q., Jaiswal, S., Kong, D., Lao, B., Liu, L., Liu, Q., Lü, W., Mohan, P., Shen, Z., Wang, G., Wu, F., Wu, X., Zhang, J., Zhang, Z., Zheng, Z., Zhong, W., 2020. Space very long baseline interferometry in China. *Adv. Space Res.* 65 (2), 850–855.
- Basart, J.P., Burns, J.O., Dennison, B.K., Weiler, K.W., Kassim, N.E., Castillo, S.P., McCune, B.M., 1997. Directions for space-based low frequency radio astronomy: 1. System considerations. *Radio Sci.* 32 (1), 251–263.
- Belov, K., Branch, A., Broschart, S., Castillo-Rogez, J., Chien, S., Clare, L., Dengler, R., Gao, J., Garza, D., Hegedus, A., Hernandez, S., Herzig, S., Imken, T., Kim, H., Mandutianu, S., Romero-Wolf, A., Schaffer, S., Troesch, M., Wyatt, E.J., Lazio, J., 2018. A space-based decametric wavelength radio telescope concept. *Exp. Astron.* 46 (2), 241–284.
- Bentum, M., Alpay Koc, N., Fuster, S., Ravi Kumar, R., Prinsloo, D., Klein Wolt, M., Brinkerink, C., Boonstra, A., Verhoeven, C., Verma, M., 2018. The cubesat low frequency explorer (cle) in lunar orbit. Presentation at the 42nd COSPAR Scientific Assembly, Pasadena, California, USA, July 2018.
- Bentum, M., Verhoeven, C., Boonstra, A.J., znd Gill, E., van der Veen, A., 2009. A novel astronomical application for formation flying small satellites. In: Proceedings of the 60th International Astronautical Congress, Daejeon, South Korea, October 2009, Daejeon, South Korea, IAC-09.A3.4.3.
- Bentum, M.J., 2017. The search for exoplanets using ultra-long wavelength radio astronomy. In: Proceedings of the IEEE Aerospace Conference, Big Sky, Montana, USA, March 2017. IEEE, inspec: 16932672.
- Bentum, M.J., 2018. Algorithms for direct radio detections of exoplanets in the neighbourhood of radiating host stars. In: Proceedings of the IEEE Aerospace Conference, Big Sky, Montana, USA, March 2018. IEEE, inspec: 17877993.
- Bentum, M.J., Boonstra, A., 2016. The RFI situation for a space-based low-frequency radio astronomy instrument. In: Proceedings of the 2016 RFI conference, Socorro, New Mexixo, USA, October 2016. IEEE, inspec: 16620879.
- Bentum, M.J., van Vugt, P., Horlings, W., Boonstra, A., 2019. The radio environment for a space-based low-frequency radio astronomy instrument. In: Proceedings of the IEEE Aerospace Conference, Big Sky, Montana, USA, March 2019. IEEE, <https://doi.org/10.1109/AERO.2019.8741975>.
- Bergman, J.E.S., Blott, R.J., Forbes, A.B., Humphreys, D.A., Robinson, D.W., Stavrinidis, C., 2009. First explorer – an innovative low-cost passive formation-flying system. In: Proceedings of CEAS 2009 – European Air & Space Conference, Manchester, UK, Royal Aeronautical Society, October 2009, pp. 1–14.
- Blott, R., Baan, W., Boonstra, A., Bergman, J., Robinson, D., Liddle, D., Navarathinam, N., Eves, S., Bridges, C., Gao, S., Bentum, M., Forbes, A. ad Humphreys, D., Harroch, C., 2013. Space-based ultra-long wavelength radio observatory (low cost) – suro-lc. Presentation at the European Planetary Science Congress, London, UK, September 2013.
- Boonstra, A., Wise, M., van der Marel, J., Ruiter, M., Arts, M., Prinsloo, D., Bast, J., Kruithof, G., Falcke, H., Klein-Wolt, M., et al., 2017. The Netherlands-China Low Frequency Explorer. Presentation at the 32nd International Union of Radio Science (URSI) General Assembly Scientific Symposium (GASS), Montreal, Canada, August 2017.
- Boonstra, A.-J., Garrett, M., Kruithof, G., Wise, M., van Ardenne, A., Yan, J., Wu, J., Zheng, J., Gill, E.K.A., Guo, J., Bentum, M., Girard, J.N., Hong, X., An, T., Falcke, H., Klein-Wolt, M., Wu, S., Chen, W., Koopmans, L., Rothkaehl, H., Chen, X., Huang, M., Chen, L., Gurvits, L., Zarka, P., Cecconi, B., de Haan, H., 2016. Discovering the Sky at the Longest Wavelengths (DSL). In: Proceedings of the IEEE Aerospace Conference, Big Sky, Montana, US, March 2016. IEEE, inspec: 16121612.
- Brown, L.W., 1973. The galactic radio spectrum between 130 and 2600 kHz. *ApJ* 180, 359–370.
- Carozzi, T.D., 2015. Imaging on a sphere with interferometers: the spherical wave harmonic transform. *Month. Notices Roy. Astronom. Soc.: Lett.* 451 (1), L6–L10.
- Cecconi, B., Dekkali, M., Briand, C., Segret, B., Girard, J.N., Laurens, A., Lamy, A., Valat, D., Delpech, M., Bruno, M., Gelard, P., Bucher, M., Nenon, Q., Griesmeier, J.-M., Boonstra, A.-J., Bentum, M. (2018). NOIRE study report: Towards a low frequency radio interferometer in space. In: Proceedings of the IEEE Aerospace Conference, Big Sky, Montana, US, March 2018. IEEE, inspec: 17878057.
- Chen, X., Wu, J., Burns, J., Silk, J., Koopmans, L., Rothkael, H., Falanga, M., Bale, S., Boonstra, A.-J., Cecconi, B., Chang, C., Chen, L., Deng, L., Falcke, H., Fan, Q., Fang, G., Fialkov, A., Gurvits, L., Ji, Y., Kasper, J., Li, K., Mao, Y., Mckinley, B., Monsalve, R., Pen, U.-L., Peterson, J., Ping, J., Subrahmanyam, R., Vedantham, H., Wang, C., Klein Wolt, M., Wu, F., Yan, Y.X.J., Yue, B., 2019. Discover the Sky by Longest Wavelengths with small satellite constellation, volume 14 of Taikong. International Space Science Institute-Beijing.
- French, F., Huguenin, G., Rodman, A., Rodman, A., 1967. A synthetic aperture approach to space-based radio telescopes. *J. Spacecr. Rock.* 4 (12), 1649–1656.
- Gorgolewski, S., 1966. Lunar radio astronomy observatory. In: Malina, F., (Ed.), Proceedings of the First Lunar International Laboratory (LIL) Symposium Research in Geosciences and Astronomy, Athens, Greece, September 1965, Springer, Berlin, Heidelberg, pp. 78–84.
- Grießmeier, J.-M., Zarka, P., Spreeuw, H., 2007. Predicting low-frequency radio fluxes of known extrasolar planets. *Astron. Astrophys.* 475 (1), 359–368.
- Gurvits, L.I., 2020. Space VLBI: from first ideas to operational missions. *Adv. Space Res.* 65 (2), 868–876.
- Jester, S., Falcke, H., 2009. Science with a lunar low-frequency array: from the dark ages of the universe to nearby exoplanets. *New Astron. Rev.* 53 (1–2), 1–26.
- Jones, D., Allen, R., Basart, J., Bastian, T., Blume, W., Bougeret, J.-L., Dennison, B., Desch, M., Dwarakanath, K., Erickson, W., Farrell, W., Finley, D., Gopalswamy, N., Howard, R., Kaiser, M., Kassim, N., Kuiper, T., MacDowall, R., Mahoney, M., Perley, R., Preston, R., Reiner, M., Rodriguez, P., Stone, R., Unwin, S., Weiler, K., Woan, G., Woo, R., 2000. The ALFA medium explorer mission. *Adv. Space Res.* 26 (4), 743–746.
- Kasper, J., Lazio, J., Romero-Wolf, A., Lux, J., Neilsen, T., 2019. The sun radio interferometer space experiment (sunrise) mission concept. In: Proceedings of the IEEE Aerospace Conference, Big Sky, Montana, March 2019. IEEE, inspec: 18759562.
- Alexander, J., Kaiser, M., Novaco, J., Grena, F., Weber, R., 1975. Scientific instrumentation of the Radio-Astronomy-Explorer-2 satellite. *Astron. Astrophys. J.* 40 (4), 365–371.
- Konovalenko, A., Sodin, L., Zakharenko, V., Zarka, P., Ulyanov, O., Sidorchuk, M., Stepkin, S., Tokarsky, P., Melnik, V., Kalinichenko, N., Stanislavsky, A., Koliadin, V., Shepelev, V., Dorovskyy, V., Ryabov, V., Koval, A., Bubnov, I., Yerin, S., Gridin, A., Kulishenko, V., Reznichenko, A., Bortsov, V., Lisachenko, V., Reznik, A., Kvasov, G., Mukha, D., Litvinenko, G., Khristenko, A., Shevchenko, V.V., Shevchenko, V.A., Belov, A., Rudavin, E., Vasylieva, I., Miroshnichenko, A., Vasilenko, N., Olyak, M., Mylostna, K., Skoryk, A., Shevtsova, A., Plakhov, M., Kravtsov, I., Volvach, Y., Lytvinenko, O., Shevchuk, N., Zhouk, I., Bovkun, V., Antonov, A., Vavriv, D., Vinogradov, V., Kozhin, R., Kravtsov, A., Bulakh, E., Kuzin, A., Vasilyev, A., Brazhenko, A., Vashchishin, R., Pylaev, O., Koshovyy, V., Lozinsky, A., Ivantyshein, O., Rucker, H.O., Panchenko, M., Fischer, G., Lecacheux, A., Denis, L., Coffre, A., Grießmeier, J.M., Tagger, M., Girard, J., Charrier, D., Briand, C., Mann, G., 2016. The modern radio astronomy network in Ukraine: UTR-2, URAN and GURT. *Exp. Astron.* 42 (1), 11–48.
- Mimoun, D., Wiczorek, M.A., Alkalai, L., Banerdt, W.B., Baratoux, D., Bougeret, J.-L., Bouley, S., Cecconi, B., Falcke, H., Flohrer, J.,

- Garcia, R.F., Grimm, R., Grott, M., Gurvits, L., Jaumann, R., Johnson, C.L., Knapmeyer, M., Kobayashi, N., Konvalenko, A., Lawrence, D., Feuvre, M.L., Lognonné, P., Neal, C., Oberst, J., Olsen, N., Röttgering, H., Spohn, T., Vennerstrom, S., Woan, G., Zarka, P., 2012. Farside explorer: unique science from a mission to the farside of the moon. *Exp. Astron.* 33 (2–3), 529–585.
- Mutel, R., Gurnett, D.A., Christopher, I.W., J.S. Pickett, a.M.S., 2003. Locations of auroral kilometric radiation bursts inferred from multi-spacecraft wideband cluster vbi observations: 1. Description of technique and initial results. *J. Geophys. Res.: Space Phys.* 108 (A11), 1398.
- Nelles, A., Hörandel, J.R., Karskens, T., Krause, M., Buitink, S., Corstanje, A., Enriquez, J.E., Erdmann, M., Falcke, H., Haungs, A., Hiller, R., Huege, T., Krause, R., Link, K., Norden, M.J., Rachen, J. P., Rossetto, L., Schellart, P., Scholten, O., Schröder, F.G., ter Veen, S., Thoudam, S., Trinh, T.N.G., Weidenhaupt, K., Wijnholds, S.J., Anderson, J., Bähren, L., Bell, M.E., Bentum, M.J., Best, P., Bonafede, A., Bregman, J., Brouw, W.N., Brügggen, M., Butcher, H. R., Carbone, D., Ciardi, B., de Gasperin, F., Duscha, S., Eislöffel, J., Fallows, R.A., Frieswijk, W., Garrett, M.A., van Haarlem, M.P., Heald, G., Hoeft, M., Horneffer, A., Iacobelli, M., Juette, E., Karastergiou, A., Kohler, J., Kondratiev, V.I., Kuniyoshi, M., Kuper, G., van Leeuwen, J., Maat, P., McFadden, R., McKay-Bukowski, D., Orru, E., Paas, H., Pandey-Pommier, M., Pandey, V.N., Pizzo, R., Polatidis, A.G., Reich, W., Röttgering, H., Schwarz, D., Serylak, M., Sluman, J., Smirnov, O., Tasse, C., Toribio, M.C., Vermeulen, R., van Weeren, R.J., Wijers, R.A.M.J., Wucknitz, O., Zarka, P., 2015. Calibrating the absolute amplitude scale for air showers measured at LOFAR. *J. Instrum.* 10 (11), P11005.
- Novaco, J.C., Brown, L.W., 1978. Nonthermal galactic emission below 10 megahertz. *Astrophys. J.* 221, 114–123.
- Oberoi, D., Kasper, J., 2004. Lofar: the potential for solar and space weather studies. *Planet. Space Sci.* 52 (15), 1415–1421.
- Prinsloo, D., Ruiter, M., Arts, M., Marel, J., Boonstra, A., Kruithof, G., Wise, M., Falcke, H., KleinWolt, M., Rothkaehl, H., Cecconi, B., Dekkali, M., Ping, J., 2018. EMI modelling of an 80 kHz to 80 MHz wideband antenna and low-noise amplifier for radio astronomy in space. In: *Proceedings of the 12th European Conference on Antennas and Propagation (EuCAP 2018)*, London UK, April 2018. Institution of Engineering and Technology. <https://doi.org/10.1049/cp.2018.0820>.
- Rajan, R.T., Bentum, M., Boonstra, A.-J., 2013. Synchronization for space based ultra low frequency interferometry. In: *Proceedings of the IEEE Aerospace Conference, Big Sky, Montana, USA, March 2013*. IEEE, inspec: 13502805.
- Rajan, R.T., Bentum, M., Gunst, A., Boonstra, A., 2013. Distributed correlators for interferometry in space. In: *Proceedings of the IEEE Aerospace Conference, Big Sky, Montana, USA, March 2013*. IEEE, inspec: 13502806.
- Rajan, R.T., Boonstra, A.-J., Bentum, M., Klein-Wolt, M., Belien, F., Arts, M., Saks, N., van der Veen, A.-J., 2016. Space-based aperture array for ultra-long wavelength radio astronomy. *Exp. Astron.* 41 (1–2), 271–306.
- Rajan, R.T., Engelen, S., Bentum, M., Verhoeven, C., 2011. Orbiting low frequency array for radio astronomy. In: *Proceedings of the IEEE Aerospace Conference, Big Sky, Montana, USA, March 2011*. IEEE, inspec: 11943731.
- Rajan, R.T., Leus, G., van der Veen, A.-J., 2015. Joint relative position and velocity estimation for an anchorless network of mobile nodes. *Signal Process.* 115, 66–78.
- Rajan, R.T., Leus, G., van der Veen, A.-J., 2019. Relative kinematics of an anchorless network. *Signal Process.* 157, 266–279.
- Rajan, R.T., van der Veen, A.-J., 2015. Joint ranging and synchronization for an anchorless network of mobile nodes. *IEEE Trans. Signal Process.* 63 (8), 1925–1940.
- Saks, N., Boonstra, A., Rajan, R.T., Bentum, M., Belien, F., van 't Klooster, K., 2010. Daris, a fleet of passive formation flying small satellites for low frequency radio astronomy. In: *Proceedings of the Small Satellite Systems and Services - The 4S Symposium*, Madeira, Portugal, June 2010, pages 1–15, Funchal, Madeira, Portugal.
- Scholten, O., Bacelar, J., Braun, R., De Bruyn, A., Falcke, H., Stappers, B., Strom, R., 2006. Optimal radio window for the detection of ultra-high energy cosmic rays and neutrinos off the moon. *Astropart. Phys.* 26 (3), 219–229.
- Shimwell, T.W., Röttgering, H.J.A., Best, P.N., Williams, W.L., Dijkema, T.J., de Gasperin, F., Hardcastle, M.J., Heald, G.H., Hoang, D.N., Horneffer, A., Intema, H., Mahony, E.K., Mandal, S., Mechev, A.P., Morabito, L., Oonk, J.B.R., Rafferty, D., Retana-Montenegro, E., Sabater, J., Tasse, C., van Weeren, R.J., Brügggen, M., Brunetti, G., Chyży, K.T., Conway, J.E., Haverkorn, M., Jackson, N., Jarvis, M.J., McKean, J.P., Miley, G.K., Morganti, R., White, G.J., Wise, M.W., van Bemmel, I.M., Beck, R., Brienza, M., Bonafede, A., Calistro Rivera, G., Cassano, R., Clarke, A.O., Cseh, D., Deller, A., Drabant, A., van Driel, W., Engels, D., Falcke, H., Ferrari, C., Fröhlich, S., Garrett, M.A., Harwood, J.J., Heesen, V., Hoeft, M., Horellou, C., Israel, F.P., Kapińska, A.D., Kunert-Bajraszewska, M., McKay, D.J., Mohan, N.R., Orrú, E., Pizzo, R.F., Prandoni, I., Schwarz, D.J., Shulevski, A., Sipior, M., Smith, D.J.B., Sridhar, S.S., Steinmetz, M., Stroe, A., Varenus, E., van der Werf, P.P., Zensus, J.A., Zwart, J.T.L., 2017. The LOFAR Two-metre Sky Survey. I. Survey description and preliminary data release. *Astron. Astrophys.*, 598:A104.
- van Haarlem, M.P., Wise, M.W., Gunst, A.W., Heald, G., McKean, J.P., Hessels, J.W.T., de Bruyn, A.G., Nijboer, R., Swinbank, J., Fallows, R., Brentjens, M., Nelles, A., Beck, R., Falcke, H., Fender, R., Hörandel, J., Koopmans, L.V.E., Mann, G., Miley, G., Röttgering, H., Stappers, B.W., Wijers, R.A.M.J., Zaroubi, S., van den Akker, M., Alexov, A., Anderson, J., Anderson, K., van Ardenne, A., Arts, M., Asgekar, A., Avruch, I.M., Batejat, F., Bähren, L., Bell, M.E., Bell, M. R., van Bemmel, I., Bennema, P., Bentum, M.J., Bernardi, G., Best, P., Birzan, L., Bonafede, A., Boonstra, A., Braun, R., Bregman, J., Breitling, F., van de Brink, R.H., Broderick, J., Broekema, P.C., Brouw, W.N., Brügggen, M., Butcher, H.R., van Cappellen, W., Ciardi, B., Coenen, T., Conway, J., Coolen, A., Corstanje, A., Damstra, S., Davies, O., Deller, A.T., Dettmar, R., van Diepen, G., Dijkstra, K., Donker, P., Doorduyn, A., Dromer, J., Drost, M., van Duin, A., Eislöffel, J., van Enst, J., Ferrari, C., Frieswijk, W., Gankema, H., Garrett, M.A., de Gasperin, F., Gerbers, M., de Geus, E., Griebmeier, J., Grit, T., Gruppen, P., Hamaker, J.P., Hassall, T., Hoeft, M., Holties, H., Horneffer, A., van der Horst, A., van Houwelingen, A., Huijgen, A., Iacobelli, M., Intema, H., Jackson, N., Jelic, V., de Jong, A., Juette, E., Kant, D., Karastergiou, A., Koers, A., Kollen, H., Kondratiev, V.I., Kooistra, E., Koopman, Y., Koster, A., Kuniyoshi, M., Kramer, M., Kuper, G., Lambropoulos, P., Law, C., van Leeuwen, J., Lemaitre, J., Loose, M., Maat, P., Macario, G., Markoff, S., Masters, J., McKay-Bukowski, D., Meijering, H., Meulman, H., Mevius, M., Middelberg, E., Millenaar, R., Miller-Jones, J.C.A., Mohan, R.N., Mol, J.D., Morawietz, J., Morganti, R., Mulcahy, D. D., Mulder, E., Munk, H., Nieuwenhuis, L., van Nieuwpoort, R., Noordam, J.E., Norden, M., Noutsos, A., Offringa, A.R., Olofsson, H., Omar, A., Orrú, E., Overeem, R., Paas, H., Pandey-Pommier, M., Pandey, V.N., Pizzo, R., Polatidis, A., Rafferty, D., Rawlings, S., Reich, W., de Reijer, J., Reitsma, J., Renting, A., Riemers, P., Rol, E., Romein, J.W., Roosjen, J., Ruiter, M., Scaife, A., van der Schaaf, K., Scheers, B., Schellart, P., Schoenmakers, A., Schoonderbeek, G., Serylak, M., Shulevski, A., Sluman, J., Smirnov, O., Sobey, C., Spreeuw, H., Steinmetz, M., Sterks, C.G.M., Stiepel, H., Stuurwold, K., Tagger, M., Tang, Y., Tasse, C., Thomas, I., Thoudam, S., Toribio, M.C., van der Tol, B., Usov, O., van Veelen, M., van der Veen, A., ter Veen, S., Verbiest, J.P.W., Vermeulen, R., Vermaas, N., Vocks, C., Vogt, C., de Vos, M., van der Wal, E., van Weeren, R., Weggemans, H., Weltevrede, P., White, S., Wijnholds, S.J., Wilhelmsson, T., Wucknitz, O., Yatawatta, S., Zarka, P., Zensus, A., van Zwieten, J., 2013. LOFAR: the LOW-frequency ARray. *Astron. Astrophys.* 556, A2.
- van Vugt, P., Wijnholds, S., Meijerink, A., Bentum, M.J., 2017. Frequency smearing in full 3d interferometry. In: *Proceedings of the*

- IEEE Aerospace Conference, Big Sky, Montana, USA, March 2017. IEEE, inspec: 16946319.
- Weiler, K., Johnston, K., Simon, R., Dennison, B., Erickson, W., Kaiser, M., Cane, H., Desch, M., 1988. A low frequency radio array for space. *Astron. Astrophys.* 372, 372–379.
- Zarka, P., 1998. Auroral radio emissions at the outer planets: observations and theories. *J. Geophys. Res.: Planets* 103 (E9), 20159–20194.
- Zarka, P., 2007. Plasma interactions of exoplanets with their parent star and associated radio emissions. *Planet. Space Sci.* 55 (5), 598–617.
- Zarka, P., Bougeret, J.-L., Briand, C., Cecconi, B., Falcke, H., Girard, J., Griebmeier, J.-M., Hess, S., Klein-Wolt, M., Konovalenko, A., Lamy, L., Mimoun, D., Aminaei, A., 2012. Planetary and exoplanetary low frequency radio observations from the Moon. *Planet. Space Sci.* 74, 156–166.