KNAW-Agenda Grootschalige Onderzoeksfaciliteiten

I. VOORSTEL ALGEMEEN

Acroniem	LOFAR2.0
Naam van de infrastructuur	Low-Frequency Array 2.0
Hoofdindiener	Rene Vermeulen
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Samenvatting *Geeft korte samenvatting van deze faciliteit in termen van werking, wetenschappelijke voordelen etc. (max 350 woorden).*

We present LOFAR2.0, a major radio astronomy infrastructure for the Netherlands on the timescale leading up to 2025, and beyond. Astronomical radio sources are found as nearby as the Solar System, and reach back out as far as the first stars and galaxies formed in the Universe. Radio telescopes observe astronomical radio waves, which give unique information about the physics of planets, stars, galaxies, and the material between them. For example, astronomical radio signals allow us to probe elementary particle acceleration, magnetic fields, and the motion of interstellar material in ways that are impossible with other instruments.

On the timescale of 2025, LOFAR2.0, primarily located in the Netherlands, will be a major international radio telescope driving Dutch astronomy; this facility will leverage the current infrastructure of the Dutch-led Low-Frequency Array (LOFAR), which is constructed and operated by ASTRON – the Netherlands Institute for Radio Astronomy. LOFAR2.0 will be a unique telescope that will complement Phase I of the Square Kilometre Array (SKA), which is already planned for construction between 2018-2023. LOFAR2.0's unique strengths lie in its ability to make the sharpest possible images of the sky using the longest-wavelength radio waves we can see from Earth. It will detect the birth of the first generation of stars, map the evolution of galaxies, and elucidate the pivotal role of magnetic fields in shaping the Universe.

LOFAR2.0 will leverage ongoing research and development initiatives at ASTRON, as well as an ASTRON-hosted Science Data Centre that will serve the data to astronomical users. LOFAR2.0 presents "Big Data" as well as "Complex Data" challenges that are matched in scale by few other scientific projects (e.g., the SKA), and which will also drive ICT and High-Performance Computing advances in collaboration with well-established partners in industry and at academic institutes.

Kernwoorden *Geef maximaal 8 kernwoorden die de faciliteit typeren.*
Radio Astronomy, Astrophysics, Cosmology, Interferometry, Big Data, Complex Data, Science Data Centre

II. VOORSTEL INHOUDELIJKE UITWERKING

A. SCIENCE AND TECHNICAL CASE

Volledig nieuwe faciliteit of verbetering van reeds bestaande - *Beschrijf in hoeverre het hier een geheel nieuw idee betreft of een verbetering of opvolging van een reeds bestaande faciliteit.*

A.1 - The current landscape of major Dutch radio astronomy facilities

The Netherlands has a proud tradition of radio astronomy started by Oort and van de Hulst (see A.5); in this KNAW "Grootschalige Infrastructuur" proposal, we chart a roadmap for major Dutch radio astronomy infrastructure on the timescale leading up to and beyond 2025. ASTRON, the Netherlands Institute for Radio Astronomy, operates two major radio telescopes: the pan-European Low-Frequency Array (LOFAR) and the Westerbork Synthesis Radio Telescope (WSRT). These two existing telescopes observe at radically different wavelengths/frequencies: WSRT images the sky predominantly at radio wavelengths around 21cm (equivalently a frequency of 1420MHz), whereas LOFAR observes from 1.2-30m (i.e. from 240 MHz down to 10 MHz). These different radio frequencies probe different physical conditions and provide complementary astronomical information. Furthermore, JIVE, the Joint Institute for VLBI (Very-Long-Baseline interferometry) ERIC (European Research Infrastructure Consortium), is co-located with ASTRON in Dwingeloo. JIVE operates the European VLBI Network (EVN), which is a network of single-dish telescopes spread across Europe whose signals are brought to a central super-computer (a "correlator"), which combines the signals in such a way that it becomes possible to make radio images of the sky. The large geographical distances between the telescopes provide very high angular resolution, which allows the EVN to address different astronomical questions than LOFAR and WSRT. Lastly, the Netherlands is also heavily engaged in designing and building the largest radio telescope the world has ever seen, the Square Kilometre Array (SKA). In the first phase, SKA1, facilities will be located in South Africa and Australia. A significant fraction of the SKA science data will be hosted via an ASTRON-led Science Data Centre in the Netherlands. As background and context to the new LOFAR2.0 facility discussed in this proposal, we first provide more details on LOFAR and the SKA.

A.2 - LOFAR and its science

The Dutch-led LOFAR (Fig. 1) is designed, built and operated by ASTRON. LOFAR has given astronomers their best-ever tool to study the Universe using the longest wavelength radio waves visible from Earth. LOFAR employs a network of tens-of-thousands of mechanically simple dipole antennas, which are sensitive to wavelengths of 1.2-30m (or equivalently radio frequencies of 240 MHz down to 10 MHz). The LOFAR low-band antennas (LBAs) are sensitive between 10-90MHz, whereas the high-band antennas (HBAs) are sensitive from 110 - 240MHz. The commercial FM radio band from 90-110MHz is filtered out. These radio antennas are clustered into "stations", and linked to a central supercomputer via a dedicated high-bandwidth fibre network. LOFAR is essentially a geographically distributed sensor network, a "next-generation" radio telescope pushing the huge communications advances of the Internet Age. LOFAR antennas are concentrated in the Netherlands, but also spread across Europe, gathering information about radio waves from space at a variety of locations and times. With LOFAR, the Netherlands is in the driver's seat of a pan-European consortium, the International LOFAR Telescope (ILT), which unites host institute ASTRON and the Dutch astronomical community with LOFAR station owners and associated astronomical institutes in Germany (6 stations), Poland (3 stations), France (1 station), the United Kingdom (1 station), Sweden (1 station) and Ireland (1 station planned). This gives the Dutch radio astronomy community a very prominent position on the European and international stage.

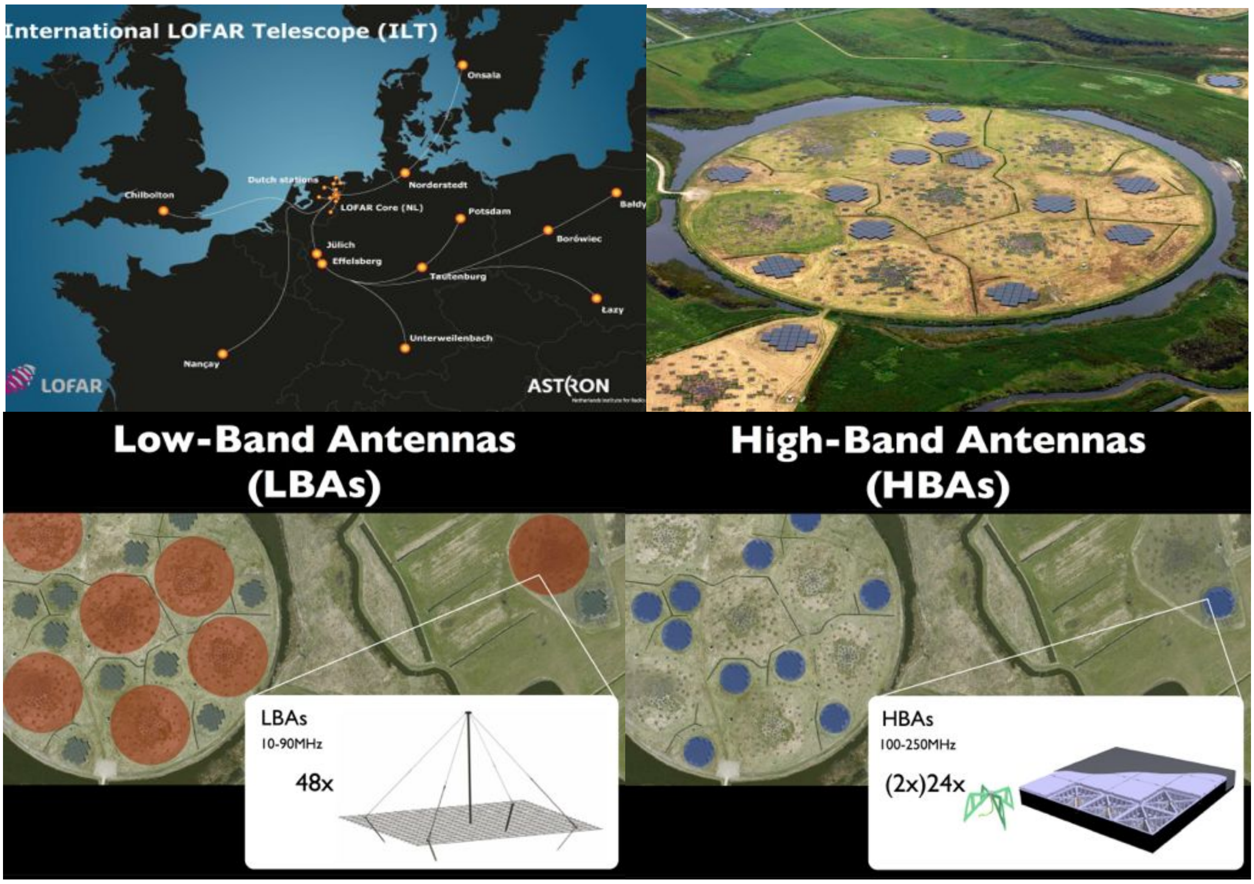

Figure 1: *Top Left*: LOFAR antenna stations across Europe, showing the 38 Dutch stations, 6 German stations, 3 Polish stations, and one station in each of Sweden, France and the United Kingdom. A new station in Ireland is also planned for construction in the coming year. *Top Right*: The LOFAR "Superterp", which is the central and most densely filled part of the telescope array, located in Exloo, Drenthe. *Bottom Left*: Each Dutch LOFAR station features 48 simultaneously operating low-band antennas (LBAs) sensitive from 10-90MHz radio frequencies. *Bottom Right*: Each Dutch LOFAR station also features 48 high-band antennas (HBAs) operating from 110-240MHz.

LOFAR is the largest continuously operating radio astronomical infrastructure in Europe, and was highlighted as one of the scientific cornerstones of European radio astronomy in the recent report of the European Radio Telescope Review Committee (ERTRC[1]). This report was commissioned by the FP7-funded ASTRONET[2] consortium in order to identify what major European radio telescopes are important for addressing the key questions of the Science Vision[3] strategic roadmap for astronomy in Europe. LOFAR featured very prominently in the ERTRC report; it scored very highly in terms of its ability to address the key ASTRONET Science Vision questions, in several cases in a unique way.

For example, LOFAR-enabled science includes: statistically detecting the "Epoch of Reionization" (EOR; i.e. the birth of the Universe's first generation of stars; see, e.g., Yattawatta et al. 2013, A&A, 550, 146); probing the composition of the mysterious cosmic rays (Buitink et al. 2016, Nature, 531, 70); unraveling the physics of neutron stars (e.g. Hermsen et al. 2013, Science, 338 436); and measuring the energetics involved in galaxy mergers (e.g. van Weeren et al. 2012, A&A, 543, 43). An updated list of LOFAR publications is available here: https://www.astron.nl/general/lofar/lofar-papers/lofar-papers, and Figure 2 shows a sample of recent LOFAR results.

LOFAR science is encapsulated by, but not restricted to, six Key Science Projects (KSPs)[4], four of which are based at the Dutch University astronomy institutes in Leiden (Deep Extragalactic Surveys), Amsterdam (Transient Sources), Nijmegen (Ultra-High Energy Cosmic Rays), and Groningen (Epoch of Reionization). The other two LOFAR KSPs, i.e. Solar Science & Space Weather and Cosmic Magnetism, are led by German astronomers but with

1 http://www.astronet-eu.org/IMG/pdf/Binder5-10revs-parSaskiaM-2.pdf
2 http://www.astronet-eu.org/, a consortium of European national funding agencies
3 http://www.eso.org/public/archives/oldpdfs/Astronet_ScienceVision.pdf
4 http://www.lofar.org/astronomy/key-science/lofar-key-science-projects

very significant Dutch participation. Thus, Dutch astronomers are heavily involved in the science exploitation of LOFAR, and their work spans the full gamut of its capabilities. Many of these science teams and projects are funded by a large number of NWO and ERC grants to Dutch astronomers, and young LOFAR astronomers have recently been awarded NWO VENI, VIDI, and European ERC Starting Grants (see B.3) – thus ensuring that the next generation of Dutch radio astronomy is secure.

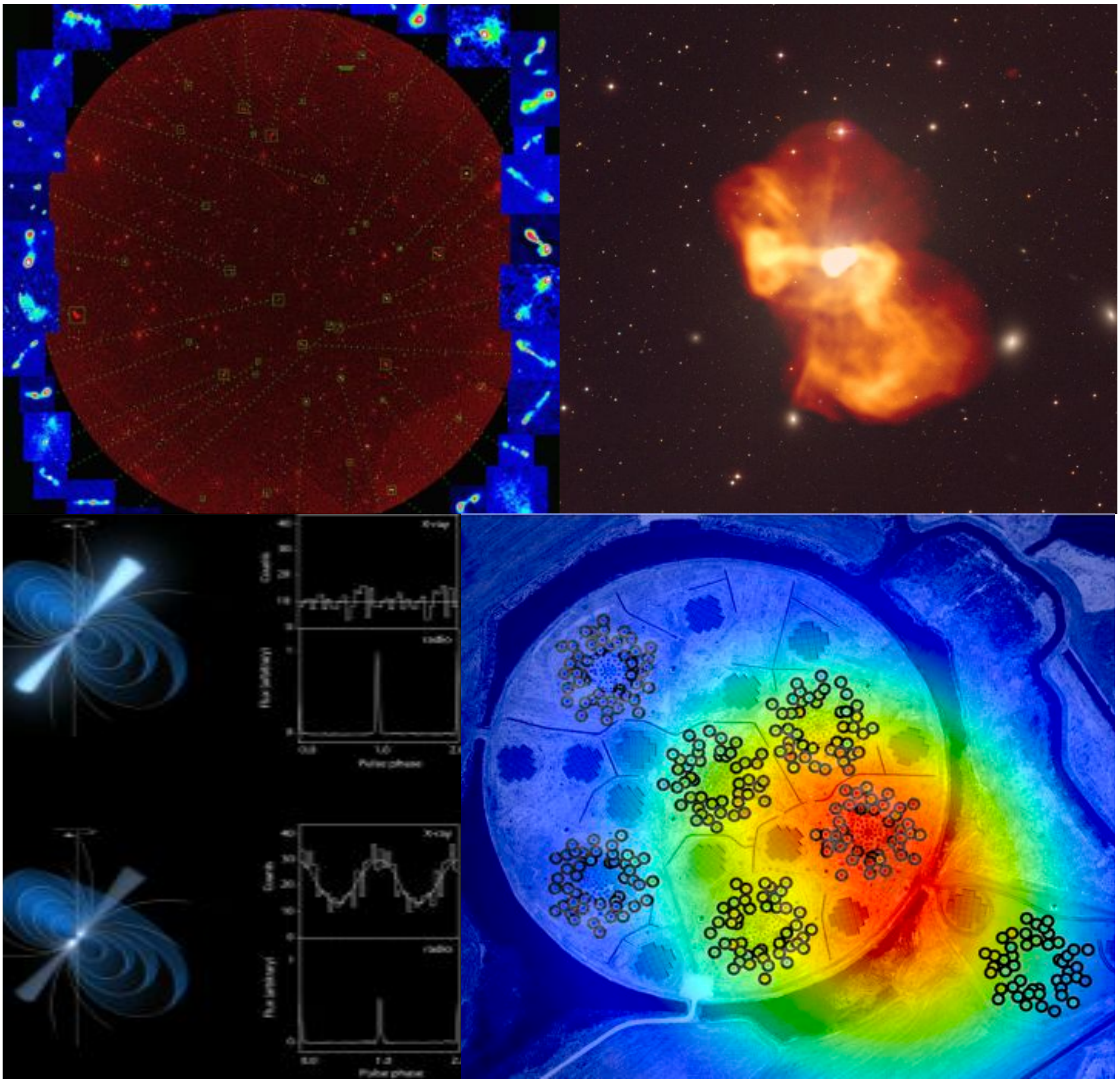

Figure 2: *Top Left*: LOFAR image of the Boötes field, which is a region of the sky observed with instruments across the electromagnetic spectrum. LOFAR's huge field-of-view is ideal for all-sky surveys; here many of the resolved structures, "radio galaxies", are shown in separate postage stamp images on the border of the main field. Credit: Williams (Leiden). *Top Right*: LOFAR image of the active galaxy M87, showing the radio jets that are created by the expulsion of material from a central, supermassive black hole. Credit: de Gasperin (Leiden). *Bottom Left*: Artist's conception (left) and real LOFAR/XMM-Newton data showing the correlated radio/X-ray mode switching of the "Chameleon" pulsar B0943+10. For unknown reasons, this neutron star switches between two states of radio/X-ray emission. Credit: Hermsen (SRON/UvA). *Bottom Right*: Detection of a cosmic-ray air shower above the LOFAR Superterp. Good agreement between the data from individual low-band antennas (shown by the circles) and simulations (shown by the background colours) is illustrated. The colors indicate the different times at which the cosmic-ray air shower arrives at the ground. Credit: Nelles (Nijmegen).

A.3 - SKA and its science

For LOFAR, ground-breaking technologies as well as calibration and imaging techniques have been developed that are vital for the continued strong scientific impact of radio astronomy, and for maintaining the high profile of Dutch radio astronomy science worldwide. Building on this success, the Netherlands is a leading nation in the design of the next major international facility in radio astronomy, the Square Kilometre Array (SKA), which will be located in South Africa and Australia. LOFAR has greatly influenced the design of the first phase of SKA, i.e. "SKA1", which will feature both a high-frequency interferometric array of 15-metre reflecting dishes (SKA1-MID) and a sea of individual dipole antennas (SKA1-LOW) inspired by the LOFAR approach (Fig. 3). Signals from the individual telescopes and antenna stations will be transported to a central processing facility on-site in each hosting country, with a dedicated high-bandwidth connection to initial science processing and archiving centres in Perth (AU) and Cape Town (SA). Further processing by science teams is likely to take place in a federated and globally distributed network of Science Data Centres (SDCs) capable of handling the Big Data streams coming from the SKA. ASTRON is leading the way in defining the scope and function of these SKA SDCs. In part, this initiative is motivated by the immediate needs to deal with the data from LOFAR and WSRT, but these facilities will also be a test-bed for such centres in the era of the SKA and LOFAR2.0.

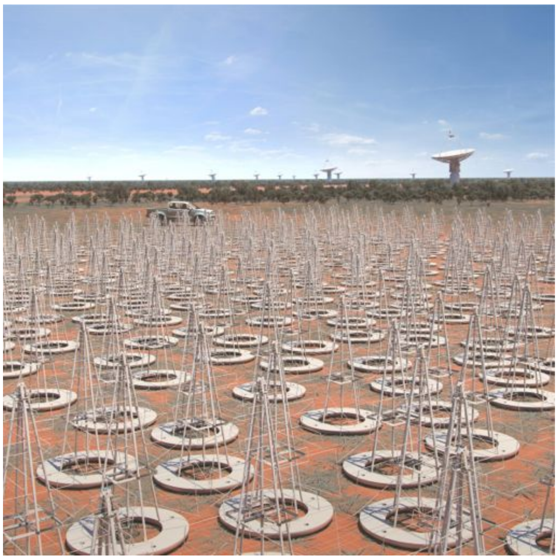


Figure 3: *Left*: Artist's conception of SKA1-LOW, showing a "sea" of individual antennas. *Right*: Artist's conception of the 15-metre reflecting dishes that will form SKA1-MID.

The NL-SKA consortium, which consists of ASTRON and astronomy departments at the Universities of Amsterdam, Groningen, Leiden and Nijmegen, was recently awarded 12 M€ by NWO from the Roadmap for Large-Scale Research Facilities to participate in the pre-construction phase of the SKA. JIVE is an associate member of the NL-SKA consortium. ASTRON is leading the international SKA design consortia responsible for the Low Frequency Aperture Array (LFAA) for SKA1-LOW. Teams at the Universities of Amsterdam, Groningen, Leiden and Nijmegen are also actively involved in the design effort – focussing for the most part on technologies that build on expertise developed for LOFAR (transient detection software pipelines, a processing pipeline for the detection of EOR/Cosmic Dawn signals, ionospheric calibration, station calibration). JIVE is concentrating on signal and data transport and has taken the lead in ensuring that SKA will have VLBI capabilities. These activities are motivated by the strong Dutch scientific interest in the SKA.

Following a science-driven re-baselining process, the scope of SKA1 has been scaled to fit within a maximum envelope of 650M€ (2013 value). SKA1 construction is due to start in 2018-19 and end in 2023-24. First data is expected a few years later. SKA1-LOW in Australia will consist of nearly 130,000 antennas, distributed over roughly 500 stations. Signals from the antennas in each station will be combined to form one or more "beams" (fields of view) on the sky. The operating frequency will be between 50 MHz and 350 MHz. SKA1-MID will be located in South Africa and will consist of 200 dishes (including 64 dishes from a precursor telescope called MeerKAT, currently under construction). An initial suite of three receivers will cover the 350 MHz – 14 GHz range of the spectrum.

The SKA science case is broad, and contains a number of key projects in which radio astronomy can make a unique contribution to our understanding of the Universe. Note that the prime science objectives for the SKA complement those of LOFAR/LOFAR2.0, with each facility bringing unique data. Dutch astronomers are leading in LOFAR, and are thus well placed to also play a prominent role in SKA science from day one.

While LOFAR/LOFAR2.0 can make the first *detection* of the EOR, SKA1 may provide the first opportunity to characterize its properties through direct *imaging*. It will also detect a significant fraction of the Galaxy's pulsars, enabling the most sensitive tests of gravity ever conducted, including a likely direct detection of gravitational waves. Deep, high-resolution radio continuum surveys will allow state-of-the-art constraints to be placed on a number of fundamental cosmological parameters, particularly when combined with optical/near-infrared data from the European Space Agency's upcoming Euclid mission. Through these continuum surveys, the SKA will also be a tremendously powerful tool for shedding light on the origin and evolution of cosmic magnetic fields.

Furthermore, neutral hydrogen emission surveys out to a redshift of 0.5 will allow the study of the evolution of gas in galaxies from five billion years ago to the present day, as well as placing further important constraints on the "Dark Energy"[5] equation of state and its evolution with redshift. New classes of transient and variable sources will be detected and identified, including the recently discovered "fast radio bursts", at a ground-breaking rate of several detections per day. Imaging of protoplanetary disks around young stars will also result in key breakthroughs related to the physics of planet formation, and in turn the origin of life itself.

In addition to the technical design of the instrument, the Dutch astronomical community is also taking a leading role in defining the scope of SKA science. Recently, the SKA Office (SKAO) published a 2000-page, 2-volume SKA Science Book[6] featuring 135 chapters from 732 contributors in 31 distinct nations. Fourteen of these chapters (i.e. 10%) were led by Dutch astronomers, and the 9% of contributors based in the Netherlands were co-authors on over 40% of the chapters. The Netherlands is clearly a big player on the world stage of radio astronomy, both in terms of technical development and scientific vision.

A.4 - Major Dutch radio astronomy facilities in 2025: Building on LOFAR and SKA1

The landscape of Dutch radio astronomy infrastructure over the next decade and beyond 2025 is dominated by the construction of LOFAR2.0 and SKA1, together with preparations for the construction of the second phase of the SKA, SKA2. LOFAR has been operating for 5 years, while SKA1 is currently in the detailed design phase and is planned to begin construction in the next few years. WSRT is close to completing an upgrade to the APERTIF receiver system, which will increase the field of view of the telescope tenfold by using multi-pixel cameras at the telescope foci. WSRT with APERTIF will remain state-of-the-art until approximately 2020; not too long afterwards, it is likely to be superseded by the SKA's wide-field, mid-frequency capabilities - though that will only be true in the Southern Hemisphere. The construction and commissioning of LOFAR2.0 will be ramping-up around that same time.

In this proposal, we describe the design and international context of LOFAR2.0. LOFAR2.0 naturally builds on the technical strengths of LOFAR, in order to deliver science objectives that were previously out of reach, while also taking existing studies to a new level. Sections A.6 and A.7 below detail the salient technical features.

A great strength of radio telescope arrays is that they are naturally extendable. By updating the data recording systems, which are largely computationally limited, it is possible to extract much more information from the radio waves received at each antenna. Supplementing the array with additional antennas naturally increases collecting area (i.e. sensitivity), but just as importantly it can also greatly improve the fidelity and resolution of the radio images that are synthesized. Leveraging the LOFAR infrastructure will be critical for remaining on the cutting edge and addressing the newest, most topical scientific questions in astrophysics, as well as posing new questions and opening novel research areas. When we consider the strategy for Dutch radio astronomy on the timescale up to and beyond 2025, it is clear that LOFAR evolving to LOFAR2.0 will be a cornerstone facility for metre-wavelength observations (see A.7 and B.2 for the relation to other telescopes that will be used by the Dutch community over the coming decade).

At the same time, it is important to realize that, more and more, radio astronomers are interacting less with the telescope directly, and more with the science data archives produced from these telescopes. ASTRON, along with Dutch and international partners, is leading the definition of Science Data Centres (SDCs; see A.9) for the SKA, which will enable both Dutch and international science with this instrument by providing flexible interfaces and low-latency access to the complex data sets as well as the in-house expertise to guide scientific interpretation. Hosting SKA data products in the Netherlands will give Dutch astronomers front-row seats for the world's largest radio telescope. LOFAR and WSRT/APERTIF are providing real-world test cases for the SDC, which will evolve to meet the needs of LOFAR2.0.

[5] Dark Energy is an unknown form of energy, which is hypothesized to exist throughout the Universe, and to accelerate its expansion.

[6] https://www.skatelescope.org/news/ska-science-book/

Science Case - *Geef een algemene introductie van de wetenschappelijke waarde van de faciliteit.*

A.5 - The context of radio astronomy and its Dutch heritage

The Netherlands was one of the first nations worldwide to undertake radio astronomical research, which blossomed in the aftermath of the Second World War under the guidance of the world-famous Prof. Jan Oort. For example, in 1944 a student of Oort, Hendrik van de Hulst, predicted that neutral hydrogen gas would create a 21-cm radio spectral line because of switching between the proton/electron spin alignment. This seminal discovery motivated the construction of the Dwingeloo telescope (Fig. 4) because the spectral line gave astronomers a unique and extremely powerful tool for studying the structure and motions of gas and galaxies (through the Doppler effect). In the 1960s, again inspired by Oort, the WSRT was built as the world's foremost aperture synthesis instrument, taking advantage of the blossoming technique of radio interferometry enabled by advances in computing technology. The Netherlands was also a founding member of the European Very Long Baseline Interferometry Network (EVN), and ASTRON became the host of JIVE. These remain cornerstone research tools, and the Dutch tradition of radio astronomy excellence and pioneering radio telescopes (Fig. 4) continues to this day.

Astronomy and astrophysics is to a large extent the study of the electromagnetic radiation produced by planets, stars, galaxies, and the matter in between them. The intensity, variability, spectrum and polarization of the light that these objects produce allows us to come to a detailed understanding of their physical properties, despite the fact that they are unimaginably distant. Different wavelengths of the electromagnetic spectrum – from low-energy radio waves to high-energy gamma-rays – provide different insights into, e.g., the temperatures, magnetic fields, and particle acceleration processes in these objects.

Optical astronomy, i.e. the study of astronomical objects using visible light, is one of the oldest existing scientific traditions. Radio astronomy, which studies the Universe using radio waves with wavelengths of millimeters to meters, is historically the first non-optical astronomy, but was only developed recently: largely in the aftermath of the Second World War, based on radar and communication technologies developed at that time.

Radio astronomy has a proud tradition of seminal discoveries: e.g., the Cosmic Microwave Background: an imprint of the Universe's structure not long after the Big Bang, which has been transformational in our understanding of cosmology (Nobel prizes in 1978 *and* 2006); and pulsars: neutron stars that are denser than an atomic nucleus and which provide unique laboratories for experimentally testing the physics of dense matter and gravitational theories (Nobel prizes in 1974 *and* 1993).

Radio telescopes are physically the largest scientific instruments ever created. Enormous collecting areas are required because astronomical radio signals are exceedingly weak. For example, a cell phone placed on the Moon would easily be the brightest radio source in the sky! Geographically dispersed radio telescopes are also crucial for obtaining enough angular resolution to separate individual radio sources from each other and to study the morphology of extended radio sources like supernova remnants. By linking multiple radio dishes or antennas into an interferometric array, it is possible to achieve an angular resolution that is inversely proportional to the maximum distance between the antennas (in units of wavelength). Radio telescope arrays that span the entire globe – and in one case out to a satellite radio telescope in space – thus provide the sharpest images ever obtained in astronomy: in some cases angular scales of only *nano*-degrees!

Modern radio telescopes also produce some of the largest data rates in all of science. For example, LOFAR routinely produces 5 gigabytes of data per second, and its science archive already contains over 20,000 terabytes of data. Radio astronomy is thus also a very data and computationally driven science. Radio astronomers collaborate intensely with high-performance-computing (HPC) and data transport experts (e.g. at SURFsara[7]), accelerate their processing using Field Programmable Gate Arrays (FPGAs) and Graphical Processing Units (GPUs), and are the heaviest scientific users of the Netherland's fibre ethernet infrastructure. This creates a very strong, and mutually beneficial link with industry, e.g. the DOME project, detailed later in B.4, has created the ASTRON&IBM Center for Exascale Technology[8]. A beautiful historical example is the contribution of radio astronomy to the development of Wi-Fi: as part of his work on applying Fourier Transform techniques to radio astronomy, John O'Sullivan (previously an engineer working on the WSRT in the Netherlands, and now employed by CSIRO in Australia) developed core technologies that enabled Wi-Fi. It's hard to understate the impact that this technology now has.

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7 http://surfsara.nl/

8 http://www.dome-exascale.nl

Enabling the next wave of transformational discoveries and technological advances in radio astronomy requires larger, more sensitive radio telescopes that are capable of processing much greater volumes of data and presenting complex data sets to astronomers via an easily accessible platform.

Figure 4: *Top Left:* Queen Juliana, accompanied by Prof. Jan Oort, inaugurating the Dwingeloo telescope in the 1950s. *Top Right:* Queen Juliana inaugurating the Westerbork telescope in the 1970s. *Bottom Left:* Queen Beatrix inaugurating the LOFAR telescope in 2010. *Bottom Right:* Nobel Prize laureate Prof. Joe Taylor, in 2014, re-opening the renovated Dwingeloo telescope, which is now a national historic landmark but still used by ASTRON and the radio amateurs club CAMRAS[9] for scientific outreach activities.

Beschrijf de wetenschappelijke voordelen en verwachte doorbraken.

A.6 - LOFAR2.0 science case

Like its predecessor, LOFAR2.0 will be a unique radio telescope with a broad and high-impact science case between now, 2025, and beyond. Once SKA1-LOW is built, it will be scientifically complementary and in no way redundant. Compared with the current telescope, LOFAR2.0 will:

- *LOFAR Enhancement 1*: Double the number of active LBAs per station and possibly change their design to increase sensitivity from 20-50MHz. This step is already being pioneered by the French LOFAR partners, building one hundred "mini-arrays" of 19 antennas optimised for the 10-90 MHz band (this facility at Nançay, NenuFAR, will be integrated into the LOFAR network, and is like LOFAR also an SKA pathfinder). By making a major step in the ease of calibration, this will enable an order-of-magnitude step in effective sensitivity and imaging capabilities at frequencies of 10-90MHz, thereby securing LOFAR2.0's pre-eminence as the world's best ultra-low-frequency telescope.
- *LOFAR Enhancement 2*: Allow observations that simultaneously use both the LBA *and* HBAs *already in the fields* (currently only one or the other can be used at any given time) and can process data in real-time, thereby enabling efficient studies over the full 10-240MHz LOFAR frequency range and fast processing of the data to enable rapid response to transient astronomical events.
- *LOFAR Enhancement 3*: Increase the number of HBA antenna stations in the LOFAR core in support of the EOR experiment, which needs a high "filling factor" (concentration of stations) to increase sensitivity to the EOR signal.
- *LOFAR Enhancement 4*: Along with European partners, increase the number of stations to obtain a sufficient number of baselines up to roughly 250-km distances, in order to enable arcsecond resolution images over the full field of view of LOFAR (4 x 4 degrees).

Each of these enhancements takes one of LOFAR's unique capabilities and improves it. They can be executed in a staged approach, and will have a significant impact on all of LOFAR's current Key Science Projects. Here we highlight some of the most transformational examples.

[9] www.camras.nl

A.6.1 - Discovering the "Cosmic Dawn" and characterizing the "Epoch of Reionization"

LOFAR2.0 will be the world's most sensitive telescope for probing the "Cosmic Dawn" - i.e. the epoch during which the first generation of stars and proto-galaxies were formed. Studying this fundamental era in the evolution of the Universe is critical for understanding how the observed structures in the present-day Universe took their shape. LOFAR2.0 can probe this turning point in the history of the Universe using the redshifted signal of neutral hydrogen. Neutral hydrogen produces a radio spectral line at 21 cm (a Dutch discovery; see A.5), and when one looks back in cosmic time this signal is stretched to longer wavelengths (i.e. "redshifted"). A similar approach is already being taken with the current LOFAR telescope in an attempt to make the first statistical detection of the "Epoch of Reionization" – i.e. the time after Cosmic Dawn in which the Universe became progressively more ionized by the irradiating sources that first turned on during the Cosmic Dawn. LOFAR2.0 will also provide an important step in characterizing the EOR, perhaps even allowing it to be imaged for the very first time.

Knowing at what frequencies the Cosmic Dawn and EOR will be visible is still a matter of hot debate. The most recent observational evidence (Planck Collaboration 2015: arXiv:1502.01589; Ellis et al. 2013, ApJ, 763, L7) suggests that the hydrogen reionization of the Universe in the EOR occurred largely at, or even below, a redshift of z~10, which was 500 Myrs after the Big Bang and corresponds to a neutral hydrogen signal at 129 MHz (in the LOFAR high band). The Cosmic Dawn signal is at lower frequencies, in the 10-90-MHz range of the LOFAR low-band, but the late stages of the Cosmic Dawn are possibly visible at the lowest frequencies reachable by the high-band antennas. A ten-fold increase of the LBA sensitivity with LOFAR2.0 (for which technology is being pioneered by NenuFAR; LOFAR Enhancement 1), however, could even make it possible to reach the Cosmic Dawn signals in the 50-90MHz range, prior to SKA1 coming online. The latter is limited to the >50 MHz range, hence in the case of a Universe that surprises us LOFAR2.0 might be the only game in town below 50 MHz for the coming decades.

Using the current LOFAR HBAs, the EOR Key Science Project is encroaching on the first statistical detection of the EOR. The deepest ever constraints achieved, soon to be published, are based on only 155 hrs of observations (Zaroubi et al. 2016, submitted). With 1000 hrs of LOFAR observations in hand, making a definitive detection may be possible once this massive data set is fully analyzed. Assuming a LOFAR EOR detection is achievable with the current telescope, an increase in the number of high-band antenna stations within the LOFAR core (LOFAR Enhancement 3) would allow an improvement of the detection significance such that the evolution of the EOR with redshift can be traced. One can then aim at imaging the EOR emission on angular scales of degrees, and to push for a detection of the 21-cm emission from the late stages of the Cosmic Dawn near z~11-12.

The sensitivity on large angular scales that will result from, say, an additional ten LOFAR-HBA stations within the central core area (baselines less than 500m), will be substantially improved for the same integration time, allowing one to reach faint, hitherto inaccessible signals. Increasing the number of LBAs per station from 48 to 96, and permitting simultaneous observations (on the same or on different fields) in the HBA and LBA bands, will allow ionospheric calibration in the LBA band, using the much more sensitive HBA data (LOFAR Enhancement 1). It will also enable very long (>1000-2000 hr/year) integrations on the *unique* North Celestial Pole (NCP) window, which is critical to CD/EOR work because this region of the sky provides several advantages for calibrating the data and avoiding systematics. Deep integrations, in combination with a doubling of the number of core stations will bring *direct (i.e. through imaging) detection* of large-scale features in the 21-cm emission (see Zaroubi et al. 2012, MNRAS, 425, 2964) within reach. All this can open a new discovery space for Dutch and European astronomers well before SKA1-LOW becomes fully operational; indeed SKA1 may only reach the required sensitivity for EOR/CD work around 2025, while LOFAR/LOFAR2.0 can guide the best SKA1 strategies well before this.

A.6.2 - Tracing galaxies through cosmic time

One of the major approaches that astronomers take in their research is through "surveys", which are a set of well-defined observations over the whole sky or some interesting region of it. An astronomical survey images or otherwise characterizes its area of sky to some level of sensitivity and with a certain spectral range and angular resolution. Surveys discover new individual astronomical sources of particular scientific interest, and they also provide large samples of objects for statistical studies of a particular source class. LOFAR's enormous field of view is a key asset for all-sky surveys. It is also capable of surveying the sky in a range of the electromagnetic spectrum that has previously been under explored compared to other wavelengths; LOFAR2.0 will keep such work on the cutting edge.

Through LOFAR Enhancement 1, LOFAR2.0 will dramatically improve LBA imaging performance. In terms of tracing the Universe through cosmic time, an all-sky survey at frequencies of 10–90MHz will pick-up where Cosmic Dawn and the EOR leave off (see A.6.1). By detecting and characterizing high-redshift radio galaxies (z > 2), clusters of galaxies, and determining the cosmic star-formation history, such a survey can map the assembly of the Universe up to the present day. With significantly improved image fidelity in the high-band and at the highest-possible resolution (down to sub-arcseconds; LOFAR Enhancement 4), LOFAR2.0 will study the detailed morphology of radio sources – e.g., in order to study how radio galaxies feed energy back into their environment, thereby influencing star formation and other processes. LOFAR Enhancement 2 will allow deep surveys that cover the whole 10-240MHz spectral range, and which benefit from the ionospheric calibration enabled by simultaneous and low/high-band data. For example, the astronomical source classes targeted in these surveys include:

High-Redshift Radio Galaxies: Most high-redshift radio sources are clearly visible at very low frequencies (De Breuck et al. 2002, A&A, 394, 59). LOFAR2.0 will enable the detection of the rare radio galaxy population at z > 6, when the Universe was less than 10% of its current age, and will allow us to observe the formation and evolution of the first massive galaxies and associated black holes. At lower redshifts these radio loud objects are often associated with protoclusters - the ancestors of nearby clusters of galaxies. Studying the environment of these very distant objects will allow us to detect the first collapsing structures in the early Universe. Radio spectroscopy targeting neutral hydrogen 21 cm absorption would, for the first time, determine physical characteristics of neutral gas of the first objects.

Galaxy Clusters: Galaxy clusters are the largest bound structures in the Universe. They are unique laboratories to study some of the most fundamental questions in astrophysics, related to the formation and evolution of galaxies, the physics of particle acceleration, the growth of large-scale structure, and cosmology. Currently approximately 50 galaxy clusters are known to contain enormous radio sources that are not associated with the individual galaxies themselves and which are visible only at low-frequencies (e.g., Feretti et al. 2012, Astron. Astrophys. Rev., 20, 54; Ferrari et al. 2008, Space Sci. Rev., 134, 93). The unique observing frequency and resolution of LOFAR2.0 will allow for the detection of hundreds of these diffuse cluster radio sources out to z = 1. This will address important questions like: What are the strengths and structures of magnetic fields in galaxy clusters? How do these relate to models of the origin and amplification of the fields? What are the origin and properties of cosmic rays? Since low frequencies trace old plasmas, LOFAR2.0 will study in unprecedented detail the way radio lobes of the radio galaxies and tailed sources interact with the intra-cluster medium (Bliton et al. 1998, MNRAS, 301, 609). This will provide unique information for understanding how the thermal balance in clusters is obtained, an essential process related to structure formation in the Universe.

Active Galactic Nuclei (AGN): Some galaxies host central supermassive black holes that are actively accreting material from the surrounding gas and launching gigantic jets back into space. Crucial questions relate to the nature of the different accretion processes, the properties of the host galaxies, the role of AGN feedback for galaxy evolution, and the relation with the environment. By surveying the sky with LOFAR2.0, all northern nearby radio loud AGN, from the very young (few hundred years) radio sources to the very old (roughly 10 Myears) giant Mpc-sized radio galaxies, will be observed at unexplored frequencies. Sensitive LBA observations will give us the best chance of seeing extended relics of previous and recurring AGN activity. A census of AGN relics will provide the rate and duration of the AGN radio-loud phase, allowing a comprehensive study of AGN evolution. Studying AGN relics can teach us about the triggering and quenching mechanisms of AGN (Shulevski et al. 2015, A&A, 579, A27). Finally, LOFAR2.0 will also be used to determine the evolution of black hole accretion over cosmic time.

Nearby Galaxies: LOFAR2.0 will detect many thousands of nearby galaxies. Their associated outflows and halos, which are visible only at extremely low frequencies, are unique proxies to detect the extended galactic magnetic field component. A detailed study of carbon radio recombination lines will yield the first picture of the physics of relatively cold (100 K) diffuse gas, which is expected to be a major constituent of the galactic mass (Morabito et al. 2014, ApJL, 795, L33).

A.6.3 - Cosmic magnetism in the nearby Universe and beyond

Magnetic fields are found in astronomical sources on all size scales that can be probed with existing telescopes, up to and potentially including the grand scale of the "cosmic web" (Vazza et al. 2015, A&A 580, 119) that forms the backbone of the Universe itself. Understanding the role of magnetic fields is key, and LOFAR2.0's low frequencies allow a unique and powerful probe of magnetic fields in a variety of astrophysical contexts.

It is becoming increasingly clear - both through observations and detailed magnetohydrodynamic simulations - that magnetic fields play an important role in the dynamics of the interstellar medium of galaxies, and the formation of stars (e.g. Crutcher et al. 2012, ARA&A, 50, 29). Magnetic fields are best traced using radio observations that are sensitive to synchrotron radiation emitted by relativistic particles as they are accelerated along magnetic field lines. Observing at progressively lower frequencies provides increasing sensitivity to weakly magnetized cosmic structures such as the cosmic web and the far outskirts of galaxies and galaxy clusters (Mulcahy et al. 2014, A&A, 568, 74). By extending to the even lower frequencies that will be accessible with

LOFAR2.0 thus provides a unique chance to study the influence of magnetism on the Universe at its largest scales. Magnetic fields in the most distant objects can best be probed at the low frequencies, so through LOFAR Enhancement 1, LOFAR2.0 will provide a unique glimpse of the earliest development of magnetism in galaxies.

The polarization state of the synchrotron radiation provides crucial information about the structure within the magnetic field, and in this area LOFAR2.0 will extend and complement the capabilities of the SKA. At progressively lower frequencies, magnetic fields can be studied in polarization to increasingly higher precision through the technique of Rotation Measure Synthesis (Brentjens & de Bruyn 2005, A&A, 441, 1217). In this way LOFAR2.0 will provide the highest-precision magnetic field measurements and thus the most stringent tests of magnetic field models of the Milky Way and extragalactic sources. By studying polarization over vast frequency ranges, detailed modeling can reveal the complicated internal state of the magnetized gas within galaxies and clusters (Heald et al. 2015, AASKA14, 106). Here, LOFAR2.0 will expand the already strong potential of the SKA by enlarging the available observing window to provide detailed information about the magneto-ionized interstellar medium immediately surrounding Earth within the Milky Way. Moreover, the superb angular resolution provided by LOFAR2.0 (LOFAR Enhancement 4) allows the same benefit to be utilized in the study of distant extragalactic objects, building on the detailed knowledge of our own galaxy to better understand the full range of the galaxy population throughout the Universe.

A.6.4 - Transients and serendipity

Various types of astronomical sources, collectively termed "transients", can drastically change their brightness and spectrum - sometimes in only a fraction of a second. In some cases such sources may only be detectable for a short period, e.g. after an explosive event. Studying the properties of astronomical sources as a function of time is an important approach for studying the Universe. "Time-Domain Astronomy" is enabled by telescopes that can rapidly respond to alerts and that make their archival data easily accessible for comparative purposes. For example, transient radio emission associated with supernova explosions, the disruption of stars venturing too close to a black hole, or the cataclysmic merger of two neutron stars allows us to understand the late phases of stellar evolution as well as some of the most energetic and extreme astrophysical events. Extreme objects like the neutron stars called "pulsars" serve as probes of extreme gravity and particle physics - well beyond the regimes testable in an Earth-bound laboratory (e.g. Demorest et al. 2010, Nature, 467, 1081; Antoniadis et al. 2013, Science, 340, 448).

With the notable exception of pulsars (e.g. Hermsen et al. 2013, Science, 339, 436), transients are proving to be rare at LOFAR HBA frequencies (110-240 MHz; e.g. Carbone et al. 2016, MNRAS, in press). However, at the lower frequency of 60 MHz, and on timescales of minutes, LOFAR has detected the first short duration, low-frequency radio transient from an unknown origin (Stewart et al. 2016, MNRAS, 456, 2321), clearly demonstrating the existence of such a population. Non-detections of these transients at higher frequencies show that the low-frequency capabilities and increased instantaneous sensitivity on short to intermediate baselines of LOFAR2.0 are important for the discovery of more, and identifying the progenitor, of this newly discovered transient population. On the very shortest imaging timescales of 1 second, the ERC-funded AARTFAAC (Amsterdam-ASTRON Radio Transients Facility And Analysis Centre) uses the central 12 stations of the existing LOFAR facility to produce all-sky images at 60 MHz. Increased sensitivity on the shortest baselines (LOFAR Enhancement 3) will enable AARTFAAC to probe fainter transient populations, while the improved capabilities of the full LOFAR2.0 will enhance follow-up observations to capture a fading counterpart of these sources. Many of these counterparts may last little longer than the events themselves, and so to enable true multi-wavelength examination of these enigmatic events LOFAR2.0 will also have the goal of processing transients data with the lowest possible latency, so-called near-real-time detection. It will also alert other observatories of detected transients in a fast, automated fashion, and similarly develop the capability to respond to alerts from other telescopes.

In addition to searching for unknown sources, LOFAR 2.0 will target known exoplanets in an attempt to directly detect their emission. We note that Jupiter is one of the brightest objects in the low-frequency radio sky. Scaling the properties of the magnetic fields associated with planets in our own Solar System to known exoplanets, shows that LOFAR2.0 should be able to detect low-frequency radio emission from some nearby sources. This would open studies of the magnetic fields around exoplanets. Improvements in imaging will enhance image plane searches for rare pulsars, such as those in 'black widow' and 'redback' systems (e.g. Broderick et al. 2016, MNRAS, 459, 2681), and aid in constraining the intermittent pulsar population. For the longer timescales, months to years, there are a number of transient populations that are expected to emit at low radio frequencies (e.g. gamma-ray bursts and tidal disruption events). With the increased sensitivity and improved imaging performance of the full LOFAR2.0 at 10-90 MHz (LOFAR Enhancement 1), LOFAR2.0 will be able to search for their faint counterparts, enabling constraints to be placed on the emission models for these sources.

Beschrijf hoe deze faciliteit zich verhoudt tot alternatieve faciliteiten/onderzoeksmethoden.

A.7 - Comparing LOFAR2.0 to other telescopes

In terms of comparing LOFAR2.0 to other facilities, the important telescope parameters affecting science output are: radio frequency range, field of view, sensitivity, angular resolution and image fidelity. Different science goals give different weighting to these parameters; however, raw sensitivity is almost always a major limitation because astronomical radio sources are exceedingly weak. Conversely, below SKA's observing band, LOFAR2.0 will exploit an exciting niche at frequencies of 10-50MHz, a spectral window that is virtually unexplored in radio astronomy; LOFAR2.0 will furthermore complement the SKA with crucial higher (sub-arcsecond) resolution imaging in the low-frequency bands.

Technical case **-** *Geef op hoofdlijnen een technische beschrijving van de faciliteit. Hoe zit de faciliteit in elkaar en hoe werkt het?*

A.8 - Description of the LOFAR2.0 facility

After 5 years of LOFAR operations, there is a clear sense of the scientific opportunities available in extending LOFAR, and the technical challenges that they will entail. LOFAR2.0 science stands on its own merits, and the telescope is explicitly being designed to provide scientific complementarity and synergy with SKA1 (which will operate on roughly the same timescale) and SKA2 (which will come at least 5 years later). This complementarity is inherent to the different instrument designs, but also, importantly, because LOFAR2.0 will be located in the Northern Hemisphere while SKA1 and SKA2 are in the Southern Hemisphere. This provides access to different regions of the sky, and sometimes also different matching to complementary instruments at other wavelengths.

The Dutch astronomical community has been intimately involved in the planning of LOFAR2.0, e.g. through dedicated discussions at the annual Users' Meeting and regular KSP Principal Investigators meetings. LOFAR2.0 will be implemented in a staged approach, where each stage will enable one or multiple of the science goals stated above (see LOFAR Enhancements 1-4; A.6). This also comes with practical advantages in terms of design and construction work, and financing.

From a technical development point of view, in the same way that LOFAR was a critical step towards the design of SKA1-LOW, LOFAR2.0 will be a critical pathfinder for SKA2-LOW because it will again push the envelope in terms of data volumes, observing modes, calibration techniques, ionospheric mitigation, etc. As such, LOFAR2.0 will also give the Dutch community a strong position in the design and science exploitation of SKA2 because of the in-house technical and analysis expertise that can be applied.

Thinking about LOFAR2.0, it is obvious that we need to maximally leverage the already existing LOFAR infrastructure, while also evolving towards an upgraded telescope that will remain scientifically world-leading and unique even in the era of SKA1/SKA2 and possibly also upgrades to other radio telescopes like the Jansky Very Large Array (JVLA), Long-Wavelength Array (LWA) and Murchison Widefield Array (MWA) in the coming decade. Finding the right niche and building something that complements other next-generation telescopes is critical.

Careful consideration leads to the conclusion that, in the next decade and beyond, LOFAR2.0 can be a unique and scientifically powerful telescope if it builds on its strengths at the lowest frequencies (10-90MHz) and longest inter-station baselines (hundreds to thousands of kilometers). From a technical point-of-view, this could be achieved with a re-design of the low-band antennas (LBAs) used in the array (LOFAR Enhancement 1) along with a major upgrade to the station electronics – possibly enabled by using FPGA-based Uniboard2 technology (developed at ASTRON & JIVE) to double the number of antennas per station and/or enable simultaneous low and high-band observations at full bandwidth (LOFAR Enhancement 2). Expanding the number of international stations will further improve what is already the world's best long-baseline (~1000-km), low-frequency interferometer. At the same time, a judicious choice of stations on intermediate baselines (50 - 250km) will enable arcsec imaging over the full field of view of LOFAR (LOFAR Enhancement 4). Filling in the Superterp (the central part of the array) with more HBA collecting area is also highly attractive for Epoch of Reionization and pulsar experiments (LOFAR Enhancement 3).

A.9 - Science Data Centre

The Science Data Centre (SDC) will be an integral part of the LOFAR2.0 facility. It will allow expert users to run advanced and experimental algorithms on the data, and it will provide easy access to calibrated data products for novice users - thereby maximizing the exploitation of these instruments by the broad, multi-wavelength astronomical community (see B.2).

In 5 years, LOFAR has already generated a 20-Pbyte archive - the largest volume radio astronomy data anywhere in the world. The scale of the accumulated science data for the SKA will go an order of magnitude further. Based on current projections from the Science Data Processor (SDP) design consortium, SKA1 is expected to produce an archive of standard data products with a growth rate on the order of 50—300 Pbytes per year. Although the management and processing challenges associated with populating and maintaining the SKA science archive are already impressive, these standard data products actually represent only the first part of the full science extraction chain. Storage and computing resources associated with the SDP and science archive, however, are expected to be highly constrained in order to keep up with SKA operations. Any further processing and subsequent science extraction by users will require significant High Performance Computing (HPC) resources outside of the SKA telescope sites, in the form of Regional Science & Data Centres (RSDCs).

Beschrijf welke onderdelen/technieken beproefd zijn en welke geheel of gedeeltelijk nieuw?

A.10 - Technology and technique readiness

LOFAR2.0 is based on the technique of "aperture synthesis radio interferometry", which is a well-understood and proven technique for radio imaging. LOFAR2.0 is a natural extension of LOFAR, which in its 5 years of maturity has solved most of the initial challenges the technology entails.

Nonetheless, algorithmic development is still a hot research area in radio interferometry because the high sensitivity of facilities like LOFAR2.0 necessitates more accurate and comprehensive calibration methods to reap the full benefit of the telescope's massive collecting area. Furthermore, at LOFAR's low observing frequencies, accurately modeling ionospheric turbulence is still a significant challenge in terms of achieving the sharpest possible radio images (such techniques continue to be pioneered in the Netherlands).

Algorithmic development is also needed in order to increase the efficiency of the data processing. This necessitates very clever solutions, which are actively being worked on (see ASTRON&IBM collaboration below). Reducing the power consumption needed for the data transport, storage, and processing is also crucial to keep costs under control.

Uitdagingen en risico's - *Beschrijf de belangrijkste technische knelpunten en geef aan hoe deze opgelost zouden kunnen worden.*

A.11 - Technical challenges and risks

LOFAR2.0 aims to increase the per-station processing and output data rate by a factor of 2-3 (needed for LOFAR Enhancement 1 and 2). Achieving this in a cost effective way will require using a different approach than currently used in the station electronics. One of the most interesting solutions is to leverage the FPGA-based Uniboard technology that ASTRON and JIVE have developed and are currently using for applications such as WSRT+APERTIF. A possible replacement of the current LBAs with antennas better focused on the lowest observing frequencies (LOFAR Enhancement 1) is not seen as a major technical challenge as several hardware options already exist; notably the French extension to LOFAR being built now, NenuFAR, will have 10-90 MHz antennas with very promising characteristics.

Increasing both the total number of LOFAR stations (LOFAR Enhancement 3 and 4), as well as the data rate each station produces, will also increase the required capacity of the central correlator by a factor of 2.5 - 4. Given that the problem is parallelizable, Moore's Law is likely sufficient to provide the extra capacity by 2020. Some risk is associated with the current dependence of the processing software on x86 chip architecture and its limited further scalability. Effort is required to utilize more efficient computational technology such as GPU's. Work within the EOR and Transients KSPs is pioneering the use of GPU architectures for LOFAR data processing, and achieving order-of-magnitude speed-ups.

With financial support from the KNAW, an analysis has been made of the central ICT infrastructure and wide-area network (WAN) needed for LOFAR2.0. Summarizing a few important points from this study:

- Efficient and intelligent data migration between fast and slow storage tiers will be essential for serving the different science cases. These optimized data storage strategies are a key area of research within the DOME project (see B.4).
- Cloud services can be a cost-effective way to provide temporary infrastructure for specific scientific projects. The central LOFAR2.0 ICT infrastructure must be designed such that it can easily connect to such services. Software defined networking will be a key functionality for this.
- The required increase in network capacity will be cost neutral on the timescale of 2020.
- LOFAR2.0 central processing should be modular and use standardized cluster building blocks to provide the necessary CPU/GPU processing and storage. A SKA regional data center hosted in the Netherlands is expected to be several factors larger. Due to expected cost and performance developments, we estimate that the costs of much of the ICT infrastructure are comparable with current LOFAR, despite LOFAR2.0's expanded data rates.
- In general, offering the scientific data generated by LOFAR2.0 to the community in such a way that scientists can concentrate on analysis and interpretation and not be hampered or even overwhelmed by the scale of the data will be one of the biggest challenges for the Science Data Centre.

The 20-page study ("LOFAR SDP & SDC roadmap") includes a proposed high level architecture for the IT infrastructure for LOFAR2.0 and indicative costing scenarios to substantiate the feasibility of the facility.

Beschrijf de belangrijkste risico's.

- Managing man-made radio frequency interference (RFI), which can corrupt a fraction of the observed data.
- Mitigating the effects of the ionosphere in order to achieve the theoretical sensitivity and angular resolution at the lowest observing frequencies.

B. INBEDDING

Hoe past dit voorstel in het (internationale) landschap van grote onderzoeksfaciliteiten?
Hoe wordt de nationale toegang gegarandeerd?

B.1 - Dutch access to LOFAR2.0

Access to LOFAR2.0 for the full Dutch astronomical community will be assured through a dual formalism, similar to that for the present LOFAR. In that formalism, participation in the design, construction, and operation leverages access to the observing time for the community involved, while scientific merit is strictly guarded. Specifically, both facilities enable large, cohesive observing programs, called Key Science Projects, that typically involve substantial numbers of researchers at multiple institutes, and are executed over a significant amount of time (several years); a sizeable fraction of the total observing time is reserved for such projects. The Key Science Projects and the executing groups are selected and monitored under rigorous scientific peer review, but they may be accessible only to scientists from partners (countries) that contribute directly in the financing and governance of the consortium/observatory that is developing and operating the facility. In addition, LOFAR enables smaller PI-led observing projects, directed at scientific questions of high topical interest that can be addressed with more modest observing time. Such projects are selected through regularly scheduled, competitive proposal rounds that are based only on the scientific merit of the proposed research. A moderate percentage is open to the full international community. This approach assures "return-on-investment", and facilitates the major "flagship" projects detailed in Section A, while also leaving room for novel ideas and smaller projects that can also make excellent use of the telescope and allow it to be even more scientifically productive.

For the present-day LOFAR, observing proposals are accepted twice a year. Of the total observing time, 45% is assigned by a single panel based purely on scientific merit, open to all qualified astronomers internationally. The remaining 55% of the observing time is reserved for allocation by panels within each of the national consortia, of the Netherlands and the other nations participating in the International LOFAR Telescope; national shares are set taking into account the numbers of stations and the amount of operational support contributed from those nations. In the last LOFAR review cycle, 47% of the observing proposals were led by Dutch Astronomers, and basically all accepted proposals had strong Dutch involvement. This is no surprise because four out of six LOFAR Key Science Projects are (co-)led by ASTRON and the Dutch universities: i.e. Transients (Amsterdam/ASTRON), Surveys (Leiden), EOR (Groningen) and Cosmic Rays (Nijmegen/Groningen). All time allocation panels are instructed to aim to assign roughly 40% of their time to long-term projects, subject to scientific merit. Access to LOFAR2.0 observing time is planned to be an evolution of this approach, and may bring in more international partners if LOFAR's longest observing baselines expand into new member countries.

Sluit het aan op reeds bestaande faciliteiten?

B.2 - Connections with other astronomical facilities

LOFAR2.0 will provide unique meter-wavelength radio data to complement multi-wavelength observations from the world's premier list of existing and planned centimeter (SKA, VLA), millimeter (ALMA), optical/infrared (VLT, JWST, Euclid, E-ELT, LSST), X-ray (Chandra, XMM-Newton, Athena) and gamma-ray (Fermi, CTA) telescopes. As described earlier, understanding the physical processes at work in astronomical systems very often requires data from multiple wavelengths. As a concrete example, the correlation in radio and X-ray brightness allows one to study the nature of accretion flows in systems where matter is being dumped onto a neutron star or black hole (e.g. Gallo et al. 2003, MNRAS, 344, 60). Moreover, studies of transients are enhanced significantly by strong links between facilities at different wavelengths: the sending of external alerts, and rapid robotic responses to triggers, are critical for the most complete picture of many explosive phenomena (e.g. Fender et al. 2015, MNRAS, 446, L66).

Enabling access to multi-wavelength facilities has received a major boost from the successful 15-M€ Horizon 2020 proposal ASTERICS (Astronomy ESFRI & Research Infrastructure Cluster). ASTERICS, led by ASTRON, aims to bring together all the astronomy facilities currently included in the ESFRI (European Strategy Forum on Research Infrastructures) list of opportunities - this includes the SKA, Cherenkov Telescope Array (CTA), European Extremely Large Telescope (E-ELT) and the KM3Net neutrino detector. The thrust of the project is to identify and address problems that are common to all of these facilities, in particular the Big Data challenge and the ambition to properly interface telescope data products with the Virtual Observatory (a utility for astronomers to access data from multiple telescopes). Pathfinder facilities like LOFAR provide real world platforms on which the project can deploy prototype systems.

Zijn er voor zover bekend vergelijkbare ideeën (of al bestaande faciliteiten) in het buitenland? Zo ja, zou Nederland een aparte nationale faciliteit moeten hebben of betreft dit een internationale faciliteit op Europees of mondiaal niveau?

According to currently known planning there will be no telescopes, anywhere in the world, with the same envisioned observing capabilities as LOFAR2.0 – at least on the timescale of 2025. LOFAR2.0 will therefore be an unrivaled, world-leading facility in its own domain.

Hoe past het voorstel bij de NL sterktes van onderzoek?

B.3 - Supporting an area of Dutch research excellence

Dutch astronomy is world renowned, and the Netherlands punches far above its weight compared to similarly sized countries. For example, the Netherlands produces, per capita, the largest number of PhD students who go on to win the most prestigious postdoctoral fellowships offered in the United States[10]. The Dutch University astronomy departments are united into NOVA[11], the "Nederlandse Onderzoekschool voor Astronomie". NOVA has existed since 1991, and since 1998 it has been recognized as one of only a handful of Dutch "Top-onderzoekscholen". This distinction reflects the world-class quality and impact of Dutch astronomy, and radio astronomy is a cornerstone of NOVA's scientific output and strategic planning towards 2025.

Specifically in radio astronomy, the Netherlands has world-leading research groups working on merging galaxy clusters (e.g. van Weeren et al., Science, 330, 347), radio observations of active galactic nuclei (e.g. Morganti et al. 2013, Science, 341, 1082), pulsars (e.g. Hermsen et al. 2013, Science, 339, 436), cosmic-rays (e.g. Buitink et al. 2016, Nature, 531, 70), transients (e.g. Deller et al. 2015, ApJ, 809,13), the epoch of reionization (e.g. Yatawatta et al. 2013, A&A, 550, 136), and cosmic magnetism (e.g. Gaensler, Haverkorn et al. 2011, Nature, 478, 214). These are all recent, high-impact results led by Dutch radio astronomers; the same astronomers who will exploit LOFAR2.0.

Astronomers with a major emphasis on the use of radio telescopes have been spectacularly successful in securing major European and national research grants. Recent examples include: ERC Advanced (De Bruyn 2013, Falcke 2008, Van der Hulst 2012, Morganti 2012, Röttgering 2012, Wijers 2010), ERC Consolidator (van Leeuwen 2014), ERC Starting (Koopmans 2010, Hessels 2013), Spinoza (Falcke 2011), NWO-TOP (De Bruyn 2010, Röttgering 2010, Van Leeuwen 2013, Tielens 2013), VICI (Verheijen 2015, Koopmans 2014, Zaroubi 2011), and VIDI (Haverkorn 2011, Hessels 2013).

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10 http://www.astronomie.nl/media/medialibrary/2015/07/NOVA_Vision_2015-2025.pdf

11 www.astronomie.nl

Beschrijf de voordelen/belang voor NL indien zo'n faciliteit zou worden gerealiseerd. Dit mogen zowel wetenschappelijke als economische of maatschappelijke voordelen zijn.

B.4 - The advantage for the Netherlands

The direct scientific impact of LOFAR2.0 has been described above, but there is also an important indirect benefit for Dutch radio astronomers through the attraction of international research talent and the training of new experts in the field. LOFAR, as well as Westerbork before it, have shown that if you build a world-class radio telescope then young, bright researchers will come to the Netherlands as PhD students, postdocs, and junior faculty. These people will also become the next-generation "black-belt" radio astronomers, who significantly strengthen the existing Dutch groups at home and enable them to exploit international facilities in new and exciting ways. Like all areas of astronomy, radio astronomy is a great tool for getting kids and high-school students interested in the sciences, which is important to strengthening the Dutch "knowledge-based economy". The thousands of visitors that come to ASTRON's regular Open Day are an example of the public interest.

In the course of the original LOFAR project (1998-2010), ASTRON developed a very successful form of Public-Private Partnership that allows companies of all sizes – from start-ups to Small and Medium-sized Enterprises (SMEs) and even major multi-nationals – to become involved in the development of technology for large research infrastructure projects. While ASTRON benefits from this collaboration by having access to state-of-the-art industrial processes, knowledge is transferred back to the companies and strengthens their ability to compete in the (public) procurements, allowing them to win contracts for construction. This approach results in a network of well-equipped companies that can efficiently and effectively collaborate in high-tech projects.

LOFAR2.0 provides strong links to Dutch industry and commercial applications in the areas of network communication, time synchronisation, and high-performance computing. This is demonstrated by ASTRON's partnership with IBM through the DOME project[12], which funds the ASTRON&IBM Center for Exascale Technology. Here ASTRON and IBM are researching the technologies that will enable LOFAR2.0 and the SKA, and which touch on three main themes: i. Green Computing, ii. Data & Streaming and iii. Nano-photonics. The link between these three themes is *efficiency*, both in power consumption for intensive data processing and long-distance transport but also in terms of how to optimally store data for later use or to process it on-the-fly. These are critical steps for the realization of a scientific instrument on the scale of LOFAR2.0 and the SKA, but these are also important technological advances that will find broad application in the consumer market, thus strengthening the competitiveness of the Dutch economy in the world market. This includes not just major players like IBM, but also Small and Medium Enterprises (SMEs).

C. ORGANISATIE

Organisatie - *Geef aan welke partijen/expertise nodig zijn voor de ontwikkeling van deze faciliteit. Geef ook aan of en zo ja hoe deze al zijn betrokken.*

C.1 - Partners and knowledge base

ASTRON (Netherlands Institute for Radio Astronomy) is the central hub in the Netherlands for the development of radio astronomical instrumentation and new techniques, and for the exploitation of radio astronomy facilities (telescopes, science data centre). ASTRON is a world-leading institute in radio astronomy with a standing of many decades, and has wide-ranging in-house experience and expertise pertinent for both design and exploitation. There are also strong radio astronomy science groups in each of the four Dutch University astronomy departments, which have led the scientific exploitation of LOFAR and, often in collaboration with ASTRON, have focussed research in the area of novel processing algorithms. As an example of the current collaboration between institutes, the SKA NWO Roadmap proposal includes work packages led by each of these institutes. Another important partner is the Joint Institute for VLBI ERIC (JIVE), which is co-located with ASTRON in Dwingeloo. Very-Long-Baseline Interferometry (VLBI) combines telescopes across the globe, more and more often in real-time, using wide-band international fibre connections. JIVE operates the central data processor for the European VLBI Network (EVN), and is a world-leading centre of expertise to support astronomers in analysing the data. Furthermore, collaborations with centres of expertise in high-performance computing in the Netherlands will only intensify, notably including SURFsara and the NWO institute CWI.

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12 http://www.dome-exascale.nl/

Beschrijf de (mogelijke) organisatiestructuur. Geef ook aan of er al een begin van organisatievorming is.

C.2 - Organisational structure

The LOFAR2.0 organisational structure will likely be an evolution of the structure already in place for LOFAR.
The International LOFAR Telescope (ILT, Director Rene Vermeulen of ASTRON) is jointly operated through contributions by the partners in the countries where antenna stations are located. The Netherlands, with 38 of the currently 50 stations, is the dominant partner in the ILT. The Board of the ILT (Chair Heino Falcke of RU Nijmegen) brings together the Dutch and European partners, and determines policy. Operation and maintenance are coordinated on behalf of the ILT by the ASTRON Radio Observatory department (also directed by Rene Vermeulen), liaising with local staff of the international stations and at the participating archive/high-performance compute centres as appropriate. Proposing, observing, intensive central data processing, and data access for users of the LOFAR Long-Term Archive are all handled through unified interfaces, handled by the Science Support Group of the Radio Observatory at ASTRON. Scientific exploitation is ultimately in the hands of astronomers who are successful in applying for observing and processing time, but the six Key Science Projects (KSPs) give structure to the major science domains.

D. VERDERE ONTWIKKELING

Beschrijf wat er moet gebeuren om deze faciliteit verder te ontwikkelen. Ga in op de belangrijkste knelpunten die opgelost moeten worden.

D.1 - Development milestones

- Determine the optimal design for the new low-band antennas.
- Determine the optimal location for new stations.
- Determine the architecture for the Science Data Center
- Decide on hardware solution for increasing each station's processing capacity.
- Decide on hardware solution for increasing the capacity of the central correlator and beam-former.

Geef aan wat de ontwikkeltermijn voor deze faciliteit ongeveer zou kunnen zijn.

D.2 - Rough timeline

We have described a coherent strategy and roadmap towards a major Dutch facility in the area of radio astronomy on the timescale of 2025. Building on the infrastructure already in place, LOFAR2.0 will explore the Universe at the lowest observable radio frequencies and with unprecedented angular resolution.

- 2016-2018: detailed design and proposals for funding first stages.
- 2019-2020: construction and early commissioning.
- 2020-2021: detailed commissioning; design effort continues, and further funding sought for completion of remaining stages.
- 2021-2025: full operations and first full observing cycles.

Appendix - List of abbreviations, acronyms and technical terms

ALMA - Atacama Large Millimeter Array
ASTRON - Netherlands Institute for Radio Astronomy
Baseline - Distance between telescopes
Beam - One of the fields of view created by a radio telescope
CD - Cosmic Dawn - the epoch during which the first generation of stars and proto-galaxies were formed
Correlator - Central supercomputer which combines signals from the telescopes in an array
DA - Dark Ages - Period in which there were no stars or galaxies and the Universe was dominated by pristine primordial clouds of neutral hydrogen gas.
Dark Energy - Dark Energy is an unknown form of energy which is hypothesized to exist throughout the Universe, and to accelerate its expansion.
DOME - Project, supported by grants from the Dutch EL&I Ministry and the Province of Drenthe, which fund the ASTRON & IBM Center for Exascale Technology
EOR - Epoch of Reionization - Period in the Universe's history when it was reionized by the first generation of stars and other irradiating sources
ERIC - European Research Infrastructure Consortium
FPGA - Field programmable gate array
GPU - Graphical processor unit
HBA - High-band antenna (of LOFAR)
HPC - High-performance computing
ICT - Information and communication technology
Interferometer - An instrument that compares the signal phases delays between elements. A radio interferometer does this for multiple dishes or antennas
JIVE - Joint Institute for VLBI ERIC
JVLA - Jansky Very Large Array
LBA - Low-band antenna (of LOFAR)
LFAA - Low-frequency aperture array
LOFAR - Low-Frequency Array
LWA - Long-Wavelength Array
MeerKAT - The SKA1-MID precursor in South Africa
MWA - Murchison Widefield Array
NCP - North Celestial Pole
RSDC - Regional Science Data Centre
SDC - Science Data Centre
SKA - Square Kilometre Array (used to refer to both Phase 1 and 2)
SKA1 - Phase 1 of the Square Kilometre Array
SKA2 - Phase 2 of the Square Kilometer Array
SKA1-LOW - The low-frequency (50-350MHz) component of SKA1
SKA1-MID - The mid-frequency (350MHz-14GHz) component of SKA1
SKA2-LOW - The low-frequency (50-350MHz) component of SKA2
SURFsara - Supports research in the Netherlands by developing and offering advanced and sustainable ICT infrastructure, services and expertise
Superterp - Central core of the LOFAR telescope array
VLBI - Very-long-baseline interferometry
Wi-Fi - Wireless Fidelity (IEEE 802.11b wireless networking)
WSRT - Westerbork Synthesis Radio Telescope