German LOFAR

White Paper

Compiled by the
German Long Wavelength Consortium
(GLOW)

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Abstract

We propose a significant German participation in **LOFAR**, the *LOw Frequency Array*, which is under construction in the Netherlands. The German contribution should consist of about **six early LOFAR Remote Stations** and a **LOFAR Science Network**. In order to reach the required resolution and sensitivity in "Phase II" (2009-2012) another 6 stations or more should be established in Germany. Under the leadership of the Max-Planck Institute für Radioastronomie in Bonn the newly established **GLOW** (*German LOng Wavelength consortium*) consortium is willing to coordinate the German LOFAR activities and negotiations with international partners. This ***White Paper*** outlines the science interests in LOFAR of the German astrophysical.

Zusammenfassung

Eine signifikante Beteiligung Deutschlands an **LOFAR**, dem ***LOw Frequency Array***, das zur Zeit in den Niederlanden aufgebaut wird, sollte mit etwa **6 frühen LOFAR-Stationen** und einem **LOFAR Science Network** beginnen. In Phase II (2009-2012) sollten mindestens weitere 6 Stationen hinzukommen, um die angestrebte Winkelauflösung und Empfindlichkeit zu erreichen. Unter der Führung des Max-Planck Instituts für Radioastronomie in Bonn ist das neu gegründete Konsortium **GLOW** (*German LOng Wavelength consortium*) bereit, die Koordination der der deutschen LOFAR Aktivitäten zu übernehmen. Dieses ***White Paper*** umreisst die wissenschaftlichen Interessen deutscher astrophysikalischer Institute im Hinblick auf die neuen Beobachtungsmöglichkeiten mit LOFAR.

1 Executive Summary

LOFAR stands for ***LOw Frequency Array*** and is a new radio telescope under construction by ASTRON in the Netherlands operating between 10 and 240 MHz. In this largely unexplored frequency range, LOFAR will be the dominant telescope over the next decade. The improvement in sensitivity and resolution by a factor of 100−1000 compared with present-day telescopes will open a new window to the Universe.

LOFAR leads the way for a new generation of radio telescopes that consist of a multitude of small and cheep antennas. As there will be no moving parts, the costs for mechanical maintenance are low. The radio waves are sampled digitally, the signal is transmitted over large baselines to a high-performance computing facility, where the radio images are synthesized in real time. This innovative design based on digital beam-forming will allow to point the telescope simultaneously at several positions on sky. In principle, the whole visible radio sky can be monitored continuously. Furthermore, efficient suppression of disturbances by artificial signals (RFI) and the ionosphere that strongly limit present-day observations at low frequencies is simpler with a digital telescope such as LOFAR. The LOFAR design can be extended to a *Wide Area Sensor Network* which can serve a broad range of science activities in fields such as geophysics or meteorology.

This ***White Paper*** outlines the LOFAR-relevant science interests of the German astrophysical community in the fields of extragalactic astronomy & surveys, Galactic astronomy, solar system science, variable & transient sources, and astroparticle physics, where the German community has long-standing experience.

The key benefit of a German participation lies in the large baselines which, in turn, will lead to a dramatic increase of the power of this telescope and its astronomical applications. The currently funded first phase of LOFAR only extends to the Dutch border. A German participation with a rather modest amount of stations would provide an excellent spatial resolution for surveying the Universe.

LOFAR will serve as the low-frequency precursor for a European and, in particular, a German participation in the *Square Kilometer Array* (SKA), the next-generation international radio telescope, which is envisaged for the years beyond 2015. The SKA is planned to cover the whole radio window accessible from the ground, from 100 MHz to about 25 GHz. The experience gained with LOFAR is essential for a significant German participation at the SKA.

A number of groups at German universities and Max Planck institutes with strong interests in LOFAR have decided to form a collaboration called **GLOW** which stands for *German LOng Wavelength Consortium*. Under this umbrella a community has formed with multifarious interests in long wavelength observations and the related technology. The prime goal of this consortium is to coordinate the German LOFAR activities and to represent German interests within the LOFAR project.

Here we propose that in the first stage from 2006-2009 (“Phase I”), the German contribution should consist of about **six early LOFAR Remote Stations** with locations in Bremen, Effelsberg-Bonn, Garching, Hamburg, Jülich, Tremsdorf-Potsdam, and possibly Göttingen, and a **LOFAR Science Network**, starting with six nodes in Bochum, Bonn/Cologne, Bremen, Garching, Hamburg and Potsdam. These coordinate German research interests in solar physics, Galactic astronomy, all-sky surveys, galaxies and galactic halos**,** polarization / magnetic fields, active galactic nuclei (AGN), large-scale structures, cosmology, Epoch of Reionisation, technology, and software infrastructure. In order to reach the required resolution and sensitivity, in “Phase II” (2009-2012) another 6 stations or more should be established in Germany. In “Phase III” an extension of LOFAR to further European countries may follow, providing even larger baselines and better resolution.

The MPIfR Bonn is willing to coordinate the German LOFAR activities, observations by German astronomers with LOFAR, and represent German LOFAR interests in negotiations with ASTRON.

The first aim is the realization of the stations and the establishment of the Science Network. The total costs for Phase I are 5 Million € for the 6 early stations and 725 k€ per year for the Science Network. The next 6 stations for Phase II will cost another 5 Million €. Central funding is essential, to be followed by applications at local organizations. Commitments for resources (personal and land) have been offered by all contributing institutes.

Next steps

2005:

1) Exploration of central funding opportunities in Germany (BMBF, MPG, *Länder*, etc)
2) Detailed project planning for funding and construction of the early stations
3) Exploration of local funding opportunities
4) Discussion of the project with the general German astronomical community (RDS, AG)
5) Presentation of the project to the astronomical and general public on the General Assembly of the *Astronomische Gesellschaft* (AG) in Cologne (Sept 26-30)

2006:

6) Definition of German Key Science Projects
7) Detailed project planning and negotiations with ASTRON
8) Formal cooperation agreement with ASTRON
9) Begin of construction and operation of the early stations.

2 Why LOFAR?

2.1 A Unique Radio Telescope in the Heart of Europe

LOFAR, the ***Low Frequency Array***, is a new radio telescope under construction by ASTRON, part of the Dutch National Research Council (www.astron.nl). The project is funded by the Dutch government and the SNN (Samenwerkingsverband Noord-Nederland), providing a total subsidy of 74 million €, and 18 organizations (universities, research institutions and business). Construction starts in 2006, completion of the Dutch LOFAR Phase 1 is expected in 2008.

LOFAR is currently one of the most innovative astrophysical projects. It promises revolutionary new insights into the cosmos and is a driver for the information and communication technology industry. As a predecessor to the *Square Kilometer Array* (SKA) planned to be constructed after 2015 (www.skatelescope.org), it has a broad impact on the future of radio astronomy and astrophysics that goes well beyond the current project. With a 100-1000 fold improvement in sensitivity and resolution in a largely unexplored frequency range it will to produce outstanding new astrophysical discoveries.

LOFAR constitutes a conceptional change with respect to earlier radio telescopes resulting in a significant reduction in cost. This has been achieved by going from steel to silicon: classical large dishes which focus the radiation are replaced by a multitude of small and cheep antennas that sample radio waves digitally, transport them over next generation internet connections to a fast supercomputer, where one or several large telescope are synthesized in real time. This offers the additional benefit of an enormous flexibility as one can steer an electronic beam across the sky within microseconds, look back in time if data is buffered to see explosive events, and even look into multiple directions at once. LOFAR antennas will have no moving parts and hence are cheap to build and easy to maintain.

The way LOFAR is set up, the concept can readily be extended to a *Wide Area Sensor Network*, consisting of an array of geographically distributed sensors that are connected by a self-organizing, partly wireless network and an ultra-high speed backbone to a distributed super computer. LOFAR is the first attempt to implement such a concept in the real world on a large scale. The radio antennas of LOFAR are only one of many possible sensors that observe the world surrounding us. Other sciences or technological applications can easily be integrated into this system. Thus, it will pioneer the next level of distributed computing and networking and provide significant visibility for the technology partners involved.

An overview of LOFAR (in German) was given by Falcke (2004).

2.2 German Involvement

LOFAR builds on ideas and science developed in the Netherlands, with some contributions from Germany. As described in detail in Section 4, the scientific goals of LOFAR are closely related to the goals and expertise of Germany's astrophysical community. In this document we wish to argue that the high scientific and technological benefits of LOFAR combined with the proximity of LOFAR's core call for a German involvement. Most importantly, the added benefit of a German involvement lies in the larger baselines which, in turn, lead to a dramatic increase of the power of this telescope. The currently funded part of LOFAR only extends to the Dutch border. A German involvement with a rather modest amount of stations would provide a drastically increased spatial resolution for surveying the Universe. Moreover, LOFAR heavily relies on distributed data centres to obtain, archive, and distribute scientific data products. We argue that Germany ought to participate and form its own scientific network.

3 LOFAR and German Telescope Activities

3.1 Perspectives for German Radio Astronomy

The priorities for astronomical research in Germany for the next 10-15 years have been outlined in the *Denkschrift Astronomie* which was commissioned by the *Deutsche Forschungsgemeinschaft* (DFG) for the purpose of developing and formulating a common vision among German astronomers and astrophysicists for the next decade.

The *Denkschrift* identifies 4 areas of research (origin and evolution of the Universe, galaxies and black holes, cycle of matter and stellar evolution, formation of stars and planets) and gives a list of telescope projects in national and international cooperations.

In the radio regime, the *Denkschrift* names the *Square Kilometer Array* (SKA) as the most important long-range development. In this regard, LOFAR should be seen as a precursor, for a European and in particular a German participation in the SKA for which a lot of the critical technology will be developed. Not least, technological claims will be staked out. Scientifically several key areas that are highlighted in the *Denkschrift* and in the *Key Science Projects* (Table 1) outlined in the *SKA Science Case* (Carilli & Rawlings 2004) can be addressed over the next few years with LOFAR.

Given these developments in adjacent and other wavebands, LOFAR presents the unique opportunity for German radio astronomy to secure a substantial part of the leadership towards the construction of the full SKA.

Project	**Method**
Evolution of galaxies & cosmic large-scale structure	Redshifted HI, continuum
Probing the Dark Ages – the first black holes & stars	Redshifted HI+CO, VLBI
Extreme test of general relativity with pulsars and black holes	Pulsars, VLBI
The origin and evolution of cosmic magnetism	Polarization, Faraday rotation
The cradle of life	SETI, biomolecules, thermal emission

Table 1: SKA Key Science Projects.

In related developments, the *SKA Design Study* (SKADS) project represents a wider European activity funded under the EU FP6 program. The goal is to obtain the best-possible design for the SKA and to utilize the potential of "early science" operation with the demonstrator prototype EMBRACE, to be completed around 2010. SKADS and LOFAR again ought to be seen as complementary, because EMBRACE will operate at higher frequencies (100 MHz − 1.4 GHz) and with less stations (4) than LOFAR but will rely on the experience gained with LOFAR. We expect that the final SKA design will consist of a low- and a high-frequency part, where the former will naturally be comprised of a system that is a further development of the LOFAR array. Currently SKADS and EMBRACE are dominated by other nations, but a common investment in LOFAR is an excellent chance to develop similar techniques in Germany and to increase the involvement of German radio astronomy in planning the future.

Future Projects in Radio Astronomy

- **The Giants: Effelsberg upgrade and Green Bank Telescope (GBT):**


- **Very Large Array (VLA) and MERLIN upgrade:**

- **Atacama Large Millimeter Array (ALMA):**

- **Submillimeter VLBI:**

- **Low Frequency Array (LOFAR):**

- **Square Kilometer Array (SKA):**

The LOFAR development has to be seen in the general context of the evolution of astronomy in general and radio astronomy in particular. This development on a national level is closely linked to the developments on the European and global levels. In the following these developments are summarized.

3.2 Observing capabilities

It is generally accepted that the enormous success of astrophysics over the last decades was closely linked to the rapid expansion in observing capabilities. This has led to a continuous and breathtaking revolution of the way we view our world and will continue to do so over at least a few more decades.

Traditionally, expansion in observing capabilities can proceed in three fundamental ways: increased sensitivity, increased spatial resolution, and expansion of the observable frequency range. A fourth and fifth development path has become important in recent years: polarization, which opens another dimension in the phase space of observations, and flexibility.

While these five development paths apply to astronomy in general we briefly discuss them here with the related radio telescope projects.

3.2.1 Frequency Range

Historically, astronomy started in the optical band – first with the naked eye and later with increasingly more powerful telescopes and detectors. This has provided us with many new insights, even though the optical wavelength range makes up only a tiny fraction of the entire electromagnetic wavelength range. After World War II, radio astronomy initiated the first expansion of the accessible wavelength spectrum for astronomers. This uncovered a completely new universe, as many astrophysical processes reveal themselves at very different frequencies. This revolution led to a number of fundamental discoveries (microwave background and Big Bang, HI emission and dark matter, synchrotron emission and magnetic fields, quasars, black holes and high-energy particle accelerators, pulsars and dense states of matter, organic molecules) and was rewarded with four Nobel prizes. Nowadays astronomy has successfully expanded into other domains of the electromagnetic spectrum, such as infrared, X-rays, and γ-rays. Opening up a new frequency window has always led to unexpected discoveries.

In the past the momentum within radio astronomy was directed towards higher frequencies. As a result, there are today essentially two largely unexplored regions: the submm-wave part of the spectrum at THz frequencies and the low-frequency region at 10-300 MHz. The latter has been largely neglected due to problems with man-made radio frequency interference and distortions by the Earth's ionosphere that now can be dealt with through modern information technology; the former is now accessible due to huge improvements in THz receiver technology.

An example for the expansion in frequency capabilities is the Effelsberg 100-m dish that was originally designed in the seventies for 10 GHz and now operates up to 100 GHz. Yet higher frequencies require special telescopes surfaces and high-altitude sites. This is covered in Europe by the IRAM telescopes (30-m dish on Pico Veleta, interferometer on Plateau de Bure). The low-frequency regime (20-200 MHz) is scarcely covered by modern telescopes. The Indian *Giant Metrewave Radio Telescope* (GMRT) is a first step but its sensivity and angular resolution are not significantly better than that of the VLA. Current developments are the LOFAR project in the Netherlands and plans for a *Long Wavelength Array* (LWA) in Australia (MIT, USA) and/or New Mexico (Naval Research Lab).

German astronomy's future path into low and high frequencies is well defined. The *Atacama Pathfinder Experiment* (APEX), operated by the MPG/MPIfR together with the *European Southern Observatory* (ESO) and the *Onsala Space Observatory* (OSO), has begun to do early science (spectroscopy and wide-field mapping) at the Atacama desert in Chile. This will be followed by the *Atacama Large Millimeter Array* (ALMA), a joint project of ESO to which German astronomers will have access through their ESO participation.

For the German community the low-frequency Universe will be mainly uncovered through LOFAR which will be the dominant telescope at these wavelengths over the next decade. Going to frequencies significantly below 10 MHz or above one THz is not feasible from the ground and would require space- or lunar-based telescopes. Based on the results of ALMA and LOFAR such options will need to be evaluated for the next decade.

3.2.2 Sensitivity

Another important factor for telescopes is sensitivity. The source density population of astrophysical sources is typically described by a power law distribution. This effectively means that only very few sources are very bright, while fainter sources are becoming more and more numerous. Hence, an increase in sensitivity leads to an increase in the number of sources that can be studied. The first few radio sources had several hundred Janskies (1 Jansky (Jy) = 10^{-26} W m^{-2} Hz^{-1} as the flux density unit) while in big radio surveys now we are dealing with about a few million sources in the mJy range. Moreover, a higher sensitivity allows the observation of fainter structures in known bright sources and allows a higher frequency resolution when taking frequency spectra.

Originally, higher sensitivities were achieved by making telescopes bigger. This has led to giant telescopes such as the German *Effelsberg* 100-m telescope or the non-movable *Arecibo* 300-m dish (USA). Additional sensitivity can be gained by improving surface accuracy, receiver performance, and by increasing the usable band width for continuum sources. This will be achieved for the 100-m dish with the upgrade program *Effelsberg 2004+* financed by the MPG.

Further improvements would require larger collecting area. Larger structures are, however, difficult to realize in a single dish and hence a further increase in sensitivity can only come from interferometry. This was realized for example in the *Westerbork Synthesis Radio Telescope* (WSRT) in Dwingeloo (NL), the *Multi-Element Radio Linked Interferometer Network* (MERLIN) in the UK, or the *Very Large Array* (VLA) in New Mexico (USA). Further significant increase in collecting area is not foreseen for these arrays.

At high frequencies the increase in collecting area will come through ALMA with its many submm-wave dishes, while at low to high frequencies the final goal is the *Square Kilometer Array* (SKA) with a target date around 2015. The combination of many small receiver elements will provide a large collecting area. At low frequencies the SKA will most likely rely on LOFAR-like technology and hence LOFAR will be a major pathfinder experiment for the SKA. LOFAR itself will provide a hundred-fold improvement in collecting area compared to earlier telescopes.

3.2.3 Resolution

Clearly, increased image resolution, i.e. sharper vision, is always an improvement for every telescope. Resolution is an essential ingredient to "see" how astrophysical sources work, to identify their internal structure, and to separate sources from each other that are close on the sky. Higher resolution is obtained with larger telescopes and higher frequencies (smaller wavelengths). Again, since telescopes cannot become excessively large, the increase in diameter is realized by utilizing an array of telescopes (interferometer), where the resolution is proportional to the distance of the telescopes. The highest resolution in astronomy is achieved today by *Very Long Baseline Interferometry* (VLBI) where radio telescopes operating at mm-waves are distributed over the entire planet. The European VLBI network (EVN) consists of a number of individual big telescopes, such as Effelsberg, Jodrell Bank, and the WSRT. The direct competitor for the Europeans in this field is the *Very Long Baseline Array* (VLBA) in the US.

Further improvement in resolution can be achieved through baselines that are larger than Earth. This would require radio antennas in space as successfully demonstrated by the Japanese HALCA mission some years ago. Alternatively, higher frequencies can be used. This is well demonstrated by mm-VLBI where the MPIfR in Bonn is a leading institute. Further improvement will come from a usage of ALMA as part of a mm-VLBI network. This will allow imaging of the event horizon of black holes with an image resolution of a few microarcseconds. At the lowest frequencies LOFAR will deliver at least a ~100-fold improvement in image resolution compared to earlier experiments in this wavelength range. With a baseline of 400 km the expected resolution is 0.5 arcsec at the highest frequency of 240 MHz. If the baseline is only 100 km long, the resolution is merely 2.4 arcsec at 240 Mhz and 6 arcsec at 100 MHz.

3.2.4 Polarization

Polarization is an extra dimension in the phase space of observations. Most astronomical objects look totally different in polarized light. In the submillimeter, infrared and optical spectral ranges the degree of polarization and the polarization angle yields information about the size and shape of the emitting or scattering dust grains. An even more important application of polarization observations is the detection of cosmic magnetic fields, either via Zeeman splitting of spectral lines or via synchrotron emission. The intrinsic degree of linear polarization of synchrotron waves is ≈70%. This number is reduced by various processes related to turbulence in the emitting region or in the foreground medium, but observed degrees of polarization in the radio range are still much larger than in optical or infrared light. Cosmic magnetic fields are one of the science drivers for the SKA (Table 1).

LOFAR will be the first radio telescope to measure weak magnetic fields in intergalactic space and in the first structures in the early Universe. These are best observable at low frequencies.

3.2.5 Flexibility and Field of View

Finally, the scientific return of a telescope can be greatly improved by increasing its versatility and flexibility. A significant improvement of large surveys of the sky can also be achieved by having multiple observing beams on the sky – either through digital beam-forming or a multi-horn system with focal plane array receivers. For example, going from a traditional single-horn receiver to a 100-element focal plane array will increase the survey speed by a factor of hundred.

Consequently, focal plane arrays are a main topic of ongoing research within the European RADIONET consortium. At the highest frequencies ALMA has a rather limited field of view and single dish telescopes with bolometer arrays may continue to play a role for some time.

The most drastic improvement of flexibility and field of view will, however, come from LOFAR. With its digital beam-steering, raw data buffer and all-sky monitoring capabilities, it will revolutionize the way radio telescopes are being used. Some of the new capabilities will also play a role in the SKA and hence LOFAR will again be a vital test bed for the next generation radio telescopes.

3.2.6 Future extensions of LOFAR

The extension of LOFAR to further European countries (“Phase III”) would increase the baselines to several 1000 km and hence improve the resolution by another order of magnitude. LOFAR-type stations on the backside of the Moon (Section 5.4.) would extend the observable frequencies to even below 10 MHz.

3.2.7 Summary

Currently the focus of German radio astronomy lies on existing facilities: Effelsberg, IRAM telescopes + APEX, VLA/MERLIN/Westerbork. This focus will shift within the next 10-15 years as new international projects emerge:

In the cm-wave range the SKA will significantly expand the observing possibilities that are currently covered by Effelsberg, VLA, Merlin, & Westerbork. The current instruments remain competitive with the upgrades that are under way. With a more focused role, the big European single dishes will also remain an important part of the European VLBI network. The submm-wave range will see a dramatic evolution in the next few years with ALMA. Until then APEX will be an important proving ground. The European millimeter-VLBI efforts shall seek inclusion of ALMA in long baseline, high-resolution experiments.

At the low frequencies LOFAR clearly has the potential to become the premier instrument for radio astronomy at these wavelengths. It will also be an important pathfinder for the SKA.

	Frequency Coverage	**Sensitivity Improvement**	**Resolution Improvement**	**Polarization Purity**	**Flexibility+ New features**
LOFAR (2006-2015)	20-200 MHz	~100-1000	~100	≥ 30 dB	Digital pointing frequency agility, all-sky FOV, time buffering
SKA (>2015)	0.1-20 GHz	~100	~10	~ 40 dB	digital + mechanical pointing, frequency agility, large FOV
submm-VLBI	40-600 GHz	~10	~10	≥ 20 dB	
ALMA (2008-2020)	40-1000 GHz	~10-100	~10	≥ 20 dB	Fast mechanical pointing, frequency agility

Table 2: Overview of the major radio astronomy projects of the coming decades and its characteristic frequencies and improvements compared to present-day telescopes.

4 Astrophysical Science Interests of the German Community relevant for LOFAR

4.1 Extragalactic Astronomy

4.1.1 The Epoch of Reionization

The onset of galaxy and star formation marks the time at which the early Universe emerged from the so-called “Dark Ages”. At this time, which is referred to as the **Epoch of Re-ionization** (EoR), the first sources start ionizing the surrounding gas and eventually drive the Universe to the transition from neutral to ionized. Uncovering the timing, morphology and duration of this event is one of the outstanding issues in current cosmology, and is the subject of much theoretical investigation. The LOFAR design will provide an unprecedented observational probe into the high-redshift Universe and directly map the physical conditions of early structure formation.

After recombination at a redshift of ~1100, the baryonic matter in the Universe remained neutral until the first stars and galaxies formed. The nature of the sources responsible for the re-ionization of the intergalactic medium (IGM) is still the subject of a lively debate but most theoretical models adopt stellar sources. These have to be constrained on the basis of the available observations: (i) the value of the IGM temperature from the Lyman alpha forest at $z \sim 2$-4, (ii) the abundance of neutral hydrogen at $z > 6$ from the spectra of high-redshift quasars (QSOs), and (iii) the measurements of the Thomson scattering optical depth by the WMAP satellite. The last condition suggests that the IGM reionization occurred at $z > 10$ (an upper limit to the reionization redshift, $z < 30$, is set by the observations of Cosmic Microwave Background (CMB) temperature fluctuations which would otherwise be suppressed.)

Several alternative processes/contributions may enhance the high redshift ionizing photon emission have been proposed. In addition to stellar-type sources, a contribution to the ionizing photon budget could also come from an early population of miniquasars powered by intermediate-mass black holes. Finally, another possible contribution to reionization at high redshift could come from decaying particles and neutrinos.

Detection of Spatial and Spectral Structure

Prior to full re-ionization the intergalactic medium was most likely a mixture of neutral, partially ionized, and fully ionized structures. It is believed that the low-density regions will be fully ionized first, followed by regions with higher and higher densities. A patchwork of neutral hydrogen emission will result in structures up to a degree in size. Rather than being a global, all-sky feature, this patchwork of emitting and absorbing structures will give rise to brightness temperature fluctuations in the sky on angular scales of 1'- 30' and in narrow bandwidths (few MHz). While remaining an extremely challenging project, the detection and imaging of the 21cm intensity fluctuations with LOFAR in both frequency and angle will provide a three-dimensional map of re-ionization and is within range of the planned LOFAR sensitivity. Long integration times (approaching weeks or more) may be required. However, LOFAR’s multi-beaming capability enables the simultaneous imaging of large areas of sky, effectively permitting very long integrations. The biggest hurdles to overcome are the removal of discrete and diffuse foreground emission components that would otherwise dominate the signal at these wavebands. Fortunately, most these contaminants have give rise to spatial but not frequency structure, while the ionization signals have both. Moreover, any residual galactic signal is expected to show a rather non-uniform distribution over the Galaxy and should not show a preference for a particular spectral range. These are powerful discriminators between the “uninteresting” contaminants and the real cosmological signals. The output of this experiment should be a large set of narrow-band images over a wide area of the sky (hundreds of square degrees), and over a wide frequency range, containing fluctuations due to HI emission and/or absorption.

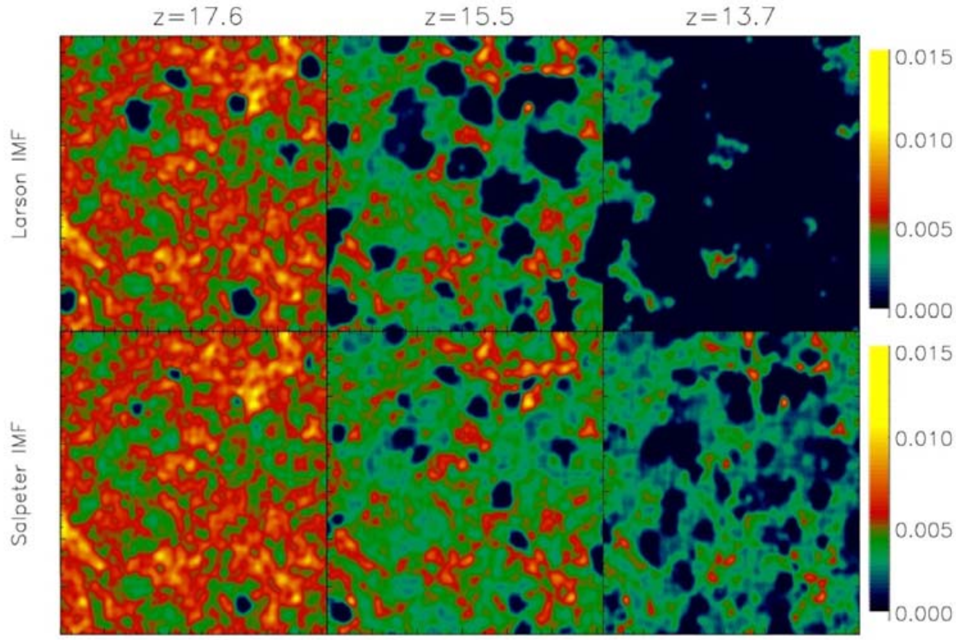


Figure 1: Slices of simulations of reionization showing the number density on neutral hydrogen HI at different redshifts. Top panels for a Larson IMF, bottom panels for a Salpeter IMF (from Ciardi, Ferrara & White 2003).

Detection of a Global Reionization Signature

The radiation signature that LOFAR may be able to detect was emitted in a period preceding full re-ionization. The signal is expected to be similar in all directions, i.e. it is a global signal. In the cool, still neutral regions of the Universe, the medium was heated by the ionizing sources (stars, quasars or mini-halos) and the hydrogen spin temperature decoupled from the CMB emission (from the Big Bang). This effect caused a small step in the temperature of the background radiation. The predicted spectroscopic signature is generated at the rest frequency of the neutral hydrogen (HI) line (1420 MHz) but redshifted to LOFAR frequencies by the expansion of the Universe. Therefore, the exact frequency at which the temperature step is detected is linked to the time in the past at which it occurred.

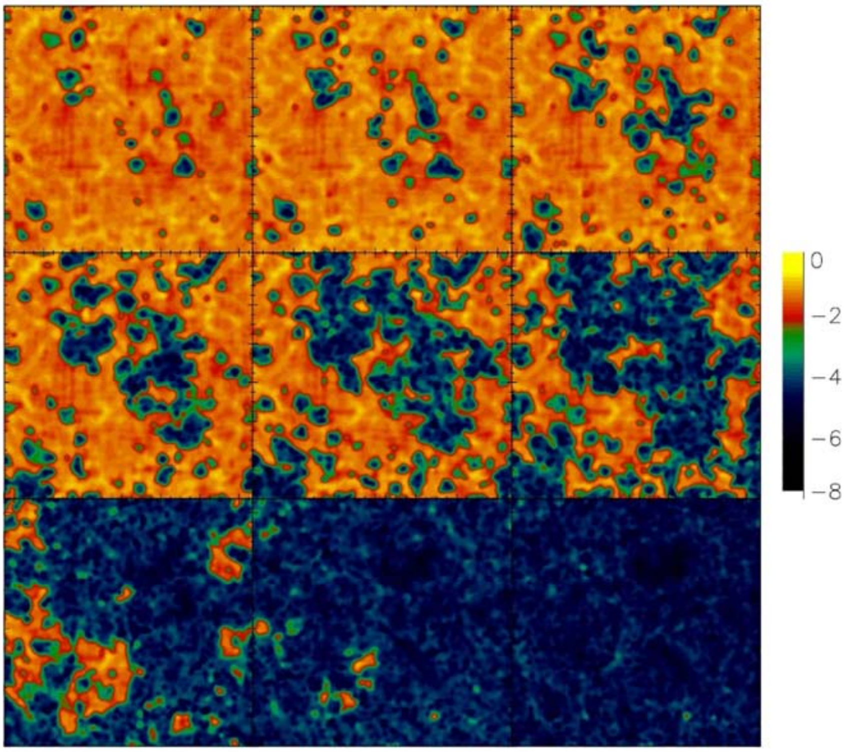


Figure 2: Maps of differential antenna temperature for HI 21cm line emission, derived at different redshifts from the above simulations of reionization (from Ciardi & Madau 2003)

To investigate this transition phase LOFAR will be equipped with dipoles optimized for the 110-250 MHz band. Because the transition is expected to occur globally, i.e. in all directions at about the same time, the LOFAR collecting area at these frequencies in principle need not be very large. The expected signal, about 15-20 mK in brightness temperature, with a spectral width of about 5-10 MHz, does not depend on aperture size. Calibration of this faint signal, however, will dictate a telescope with a substantial collecting area. Collecting area and resolution are also important to deal with the crucial aspect of this experiment of foreground removal. The longer baselines of LOFAR are needed to assist in the identification and spectral characterization of discrete sources in the field(s) of view being observed for the spectral decrement. In both cases − use of the inner portion of LOFAR to search for the spectral decrement and exploiting the high angular resolution of LOFAR to identify foreground contaminants − the broad-band nature of LOFAR will be essential. A second contaminant is the diffuse non-thermal Galactic foreground emission, which is responsible for the bulk of the radio noise from the sky at LOFAR frequencies. Fortunately, this diffuse emission has very little structure on the 0.5 degree angular scales at which a global signal will be sought. Faint Galactic foreground fluctuations that do exist are expected to be spectrally broad, thus permitting them to be modelled. As was pointed out above, the epoch of reionization, and therefore the frequency of the spectral decrement, is uncertain. The broad band nature of LOFAR would enable a search for this effect over a finely spaced grid of frequencies, ensuring detection of the EOR transition, provided it falls in the redshift range 5-12.

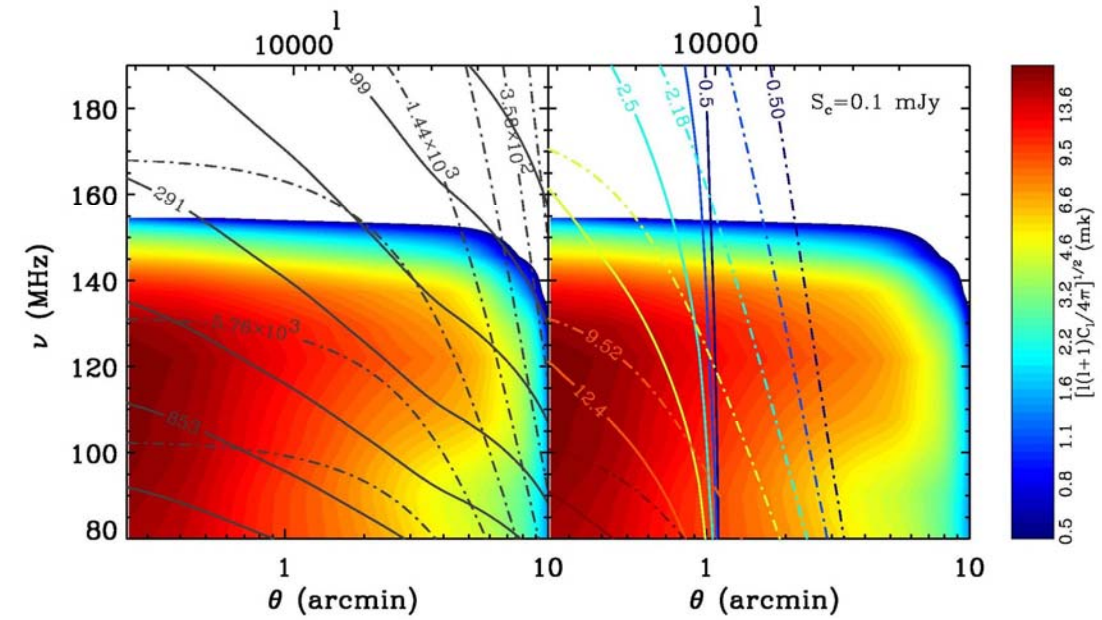


Figure 3: Contour plots with comparison between HI 21cm line emission (coloured) and foreground contamination from radio galaxies (solid lines) and radio halos (dashed-dotted), with no bright source removal (*left panel*) and after removal of sources above 0.1 mJy (*right panel*) (from di Matteo, Ciardi & Miniati 2004).

The German scientific competence

The astrophysical community in Germany is very well positioned in order to play a major role in the science exploration of the EoR with LOFAR. The Max-Planck-Institute für Astrophysik (MPA) is one of the international leading centres for cosmological large-scale structure formation, galaxy formation, and cosmological radiative transfer simulations. The MPA and also the nearby European Southern Observatory (ESO) have demonstrated expertise in the area of 21cm EOR signal prediction via numerical simulations, analytical descriptions and detailed assessment of the contaminating foreground signal. The International University Bremen (IUB) has expertise in modelling of the instrument signal chain and the Galactic and ionospheric artifacts. The Max-Planck-Institut für Radioastronomie (MPIfR) has longstanding experience with interferometric radio astronomy and with observations of the foreground emission from our Galaxy.

Therefore, Germany could significantly contribute to all stages of the LOFAR data processing pipeline to extract the EoR signature and to analyze its cosmological implications. Additionally, Germany can provide important software infrastructure because of the Process Coordinator software development team located at MPA, and the data mining technology developments within the *German Astronomical Virtual Observatory* (GAVO) consortium.

Germany would strongly benefit from such an involvement through the exchange of vital expertise and technologies: Germany would give astrophysical expertise, knowledge on ionospheric and signal processing artifacts, and process coordination software. In return it would gain knowledge on signal extraction techniques, experience with a next generation computers and networks, and last, but not least access to the scientifically extremely interesting observational data on the Epoch of Reionization.

4.1.2 Structure and Evolution of Galaxies

Models of galaxy evolution require an understanding of star formation in galaxies on scales that range from star-forming cores of dense molecular clouds to feedback processes on lengths scales of the whole system. The different components of the interstellar medium (ISM) trace the different stages of stellar evolution: from molecular clouds that provide the material for new stars to the metal-enriched hot medium produced by supernovae. Among the different constituents of the interstellar medium cosmic rays and magnetic fields play an important role. Cosmic rays and magnetic fields support or even drive the formation of galactic halos, and their role for the formation of spiral arms is possibly more important than previously thought.

Cosmic rays and magnetic fields are best traced at low radio frequencies since the continuum spectrum of spiral galaxies is dominated by synchrotron radiation. One important result of previous studies is the radio continuum / far-infrared luminosity relation that characterizes star formation in galactic disks. A similar relation was also found between the radio continuum and the mid-infrared luminosities, and even for the surface brightness in both spectral ranges on spatial scales below 1 kpc within spiral galaxies. This relation demonstrates the role of radio emission as an unbiased tracer of star formation. However, the origin of this relation is far from being understood, especially the effect of magnetic fields on the process and efficiency of star formation. Furthermore, it is not clear below which scales in space and time the relation breaks down. Very young starbursts may not have generated cosmic rays that radiate in the radio range; hence the first starburst galaxies in the Universe may have been radio-quiet. Finally, an extension to high-z galaxies is essential to understand the radio-IR relation.

In this discussion the low-frequency end of the spectrum is of particular importance. The observed non-thermal synchrotron component is not contaminated by the thermal component which starts to become dominant in the 10 GHz regime. Furthermore, the emission at low frequencies emerges from cosmic ray electrons at lower energies.

Another discovery from the low-frequency regime is that many galaxies are surrounded by huge radio halos (Fig. 4), sometimes much larger in extent than in any other spectral range. The origin of cosmic rays and magnetic fields in such halos is unclear. The relativistic particles may diffuse from the disk, or may be transported together with the gas in a galactic wind flow, or may be accelerated by turbulent processes in a wind flow. The cosmic ray spectrum observed via the radio spectrum allows to study and to understand the origin and propagation of cosmic rays.

The strength and structure of magnetic fields in galactic halos are problems of special interest. Equipartition arguments for estimates of the field strength may not hold in dynamic halos, so that additional data are required, e.g. from Faraday rotation and Faraday depolarization of polarized radio waves. Faraday effects decrease strongly with increasing frequency, so that at high (GHz) frequencies the degree of polarization is large, but the steep radio spectra of halos decrease the signals considerably. As a result, very little is known about the large-scale structure of magnetic fields in halos. Only a few exceptionally bright halos have been detected in polarization (Fig. 4). At low frequencies the degree of polarization is small, but still observable. With multi-channel spectro-polarimetry one can deal with Faraday depolarization and increase the polarized signals significantly. With LOFAR's high sensitivity and large number of spectral channels this method can be applied to much fainter and much more distant galaxies.

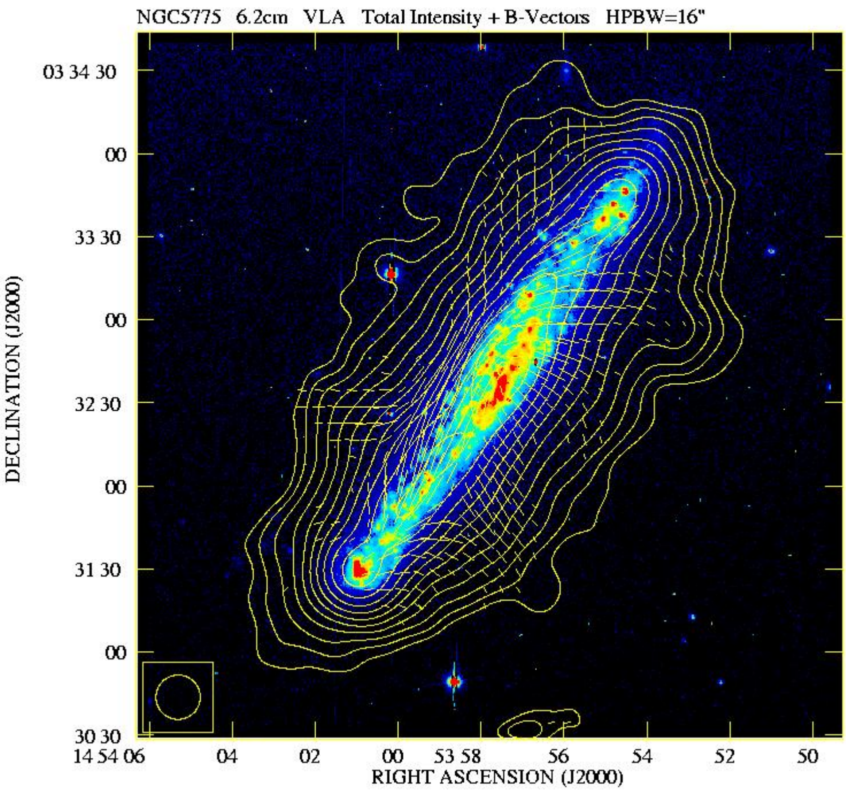


Figure 4: Total intensity (contours) and polarization (B vectors) map of NGC 5775 at 6.2cm from combined total power maps obtained with the Effelsberg and VLA radio telescopes (Tüllmann et al. 2000).

The low-energy/low-frequency regime is not well studied, mainly because few experiments have allowed for sufficient angular resolution at these wavelengths to resolve external galaxies. With the angular resolution and sensitivity of LOFAR it will be possible to obtain low-frequency maps to provide completely new information on cosmic rays in nearby galaxies. An attempt to combine high- and low-frequency maps is shown in Fig. 5. This spectral index map shows small-scale structure in the cosmic ray spectrum and may also indicate gradients in cosmic ray propagation. LOFAR observations could also solve the problem of missing cosmic rays in dwarf galaxies. If their spectra are very steep, existing radio telescopes may just have missed the emission. LOFAR may also detect polarized emission from galactic halos, which would allow us to understand the origin of large-scale magnetic fields.

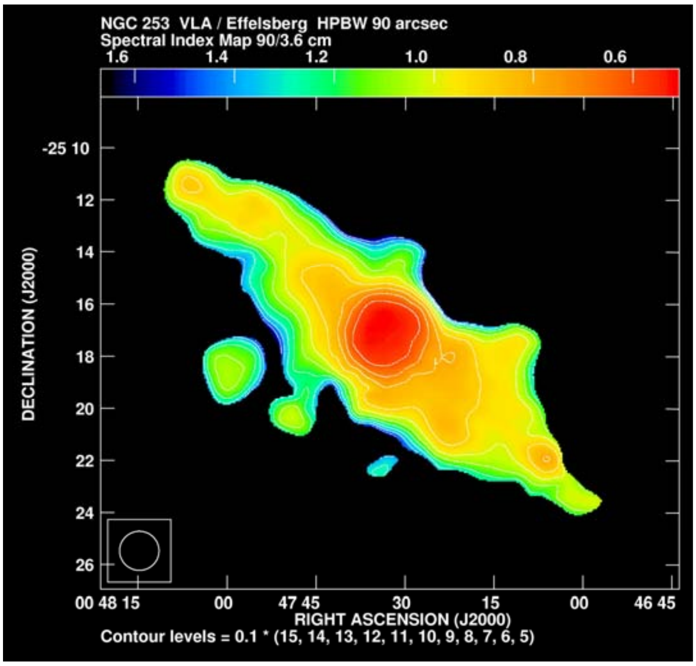


Figure 5: Spectral index map between 90cm and 3.6cm from combined total power maps obtained with the Effelsberg (3.6cm) and VLA (90cm) radio telescopes. Substructure and gradients can be attributed to cosmic ray propagation processes and magnetic field structures (Heesen, Krause & Beck, in prep).

The German scientific competence

Radio continuum studies of galaxies have a strong tradition in German radio astronomy and several groups (MPIfR, Radioastronomisches Institut der Ruhr-Universität Bochum (RAIUB), Astronomisches Institut der Universität Bonn (AIRUB)) are actively involved in ongoing projects. Theoretical studies and observational work in the optical and infrared spectral ranges on galaxy structure and evolution done at the Universitätssternwarte Göttingen, the Landessternwarte Heidelberg and the MPIA Heidelberg are also directly relevant for this subject. The access to LOFAR would strengthen these activities and help maintain their internationally recognized position. Studies in this area are closely related to similar aspects of the Milky Way (Section 4.2).

4.1.3 Evolution of AGNs, Jets, & Radio Lobes

One of the most intriguing problems in modern astrophysics concerns the processes by which galaxies and groups of galaxies formed from the smooth Universe seen in the microwave remnant of the Big Bang. These processes involve the formation of the massive black holes seen today at the centres of many galaxies, and they involve bursts of star formation. Together, the black holes and starbursts power the enormously energetic explosive events occurring in active galactic nuclei (AGN).

Three classes of objects hosting AGN will be observed by LOFAR:

(i) luminous radio sources and jets, produced by black holes in the nuclei of massive forming galaxies,

(ii) starbursts in infant galaxies and

(iii) diffuse and extended radio lobes that can be used to probe intergalactic gas.

Luminous but rare radio sources at high redshifts will be found in large-area surveys looking for their characteristic steep radio spectrum. They are valuable to help trace the ionization history of the Universe; they are distant beacons against which we can see HI absorption from foreground gas. The HI absorption occurring in the protogalaxy itself gives information on the spatial distribution and dynamics of the absorber, from which one can follow the growth of the host galaxy. The large surveys will naturally include many low to intermediate redshift AGNs as well, hence providing galaxies at all evolutionary stages for study. The large sample size and wide redshift range will allow one to watch the development of jets and radio lobes through the clustering of AGNs with decreasing redshift. Moreover, older periods of activity decay into ultra-steep-spectrum large-scale structures around AGNs, which can be seen only at the lowest frequencies. Observations with LOFAR enable tremendous improvement in sensitivity to faint AGNs, which are stronger at low frequency. Much larger numbers of these faint sources will be found than are known at present, and the improved sample statistics may lead to the discovery of new populations of rare objects. Reaching the faintest flux densities to discover these sources means reducing the confusion limit which requires long baselines, hence the importance of LOFAR stations in Germany.

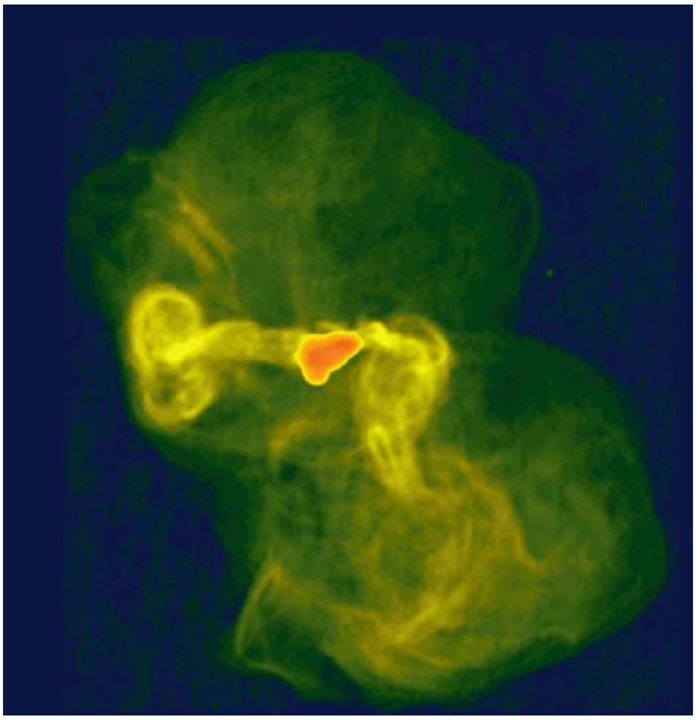


Figure 6: 90cm radio image of M 87 as obtained with the VLA showing the large radio halo 200000 light years across seen only at low frequency. Image courtesy of NRAO/AUI (Owen et al. 2000).

Synchrotron emission from jets shows spectral breaks, which reveal the magnetic field strength of the jet. However, the break generally occurs at frequencies that are poorly covered by telescopes today. LOFAR will cover the low frequencies with continuous frequency coverage, allowing much improved age and magnetic field measurements for distinguishing between different classes or stages of activity. Multi-frequency studies with continuous spectra from 10 GHz down to 10 MHz of AGN cores will also show low-frequency absorption processes like the Tzytovich-Razin effect or free-free absorption. These yield independent estimates of the magnetic field strength and thermal electron densities.

The extent of the large-scale radio lobes in galaxies is determined by important factors, such as the pressure in the jets and detailed properties of the ISM with which the jets collide. Their largest extent is seen only at the lowest frequencies (Fig. 6). Thus LOFAR will allow unprecedented observations of the intergalactic medium.

The German scientific competence

AGN research is a well-established focus of research programmes at many German institutes (e.g. at the Universities of Göttingen and Heidelberg and the MPIA Heidelberg), using and operating instruments spanning most parts of the wavelength range, from radio, sub-mm, IR, optical, X-ray to γ-rays over which AGNs radiate. Considerable experience with radio interferometry is centred at groups at the Universities of Bonn, Cologne and Heidelberg, the MPA Garching, and the MPIfR Bonn. Theory groups at the Universities of Bochum, Heidelberg and München, the MPA, and the MPIfR address relativistic plasma physics, accretion processes, jet formation, radio lobes and black hole formation. This positions Germany well to exploit the new opportunities offered by LOFAR.

4.1.4 Cosmological Large-Scale Structure in the Radio

During the formation of cosmological large-scale structure enormous amounts of energy are released. A significant fraction of this energy goes into the acceleration of particles to relativistic velocities. These particles accumulate within galaxy clusters and filaments and may constitute a large part of the energy density in these structures. Consequently, these populations of relativistic particles may play a crucial role in the formation of large-scale structures.

The electron component of the relativistic population has been observed for nearly three decades in the radio band. Many clusters of galaxies host a diffuse, steep-spectrum radio halo that is produced by synchrotron emission of ultra-relativistic electrons in intergalactic magnetic fields. About two dozen radio halos are known and LOFAR is expected to observe on the order of thousands new ones. The exact origin of radio halos is still shrouded in mystery. The responsible electrons have too short radiative lifetimes to be produced directly at the shock wave. Therefore, they need to be either re-accelerated in situ, e.g. by turbulence, or to be freshly injected. A promising candidate for injection is a long-lived relativistic proton population. These protons collide with the thermal gas and produce secondary electrons via pion production.

In a sense a galaxy cluster can be regarded as a cosmic-sized particle detector. The shock wave acts as an accelerator for protons, the intergalactic gas as the target, and the magnetic field as a “scintillator” which produces the electromagnetic signal that can be read out with a sensitive radio telescope such as LOFAR on planet Earth.

Because of their low surface brightness, halo sources are difficult to find; extensive searches have so far brought to light no more than about ten. The low-frequency radio emission of these halos has a steep spectrum (spectral index $\alpha < -1.0$) so that low-frequency surveys are ideal to renew the search for these enigmatic objects, especially in the thousands of clusters at $z > 0.5$ that X-ray observatories and large-area CCD cameras will find in the coming decade. Measuring the halo emission from these distant objects will help explain the halo phenomenon and also help unravelling merging activity associated with possibly still forming clusters. The luminosities of the presently known haloes suggest that a LOFAR survey could detect several hundred halo sources in the $0.5 < z < 1$ interval, if they exist. If halo sources are a clear signature of clusters that are in the process of merging, the frequency of their occurrence will be much higher at greater distances.

Particle acceleration has also been observed directly at the positions of the shock waves of structure formation. At the locations of several shocks very extended, steep-spectrum radio sources have been observed. Owing to the lack of any visible galaxy counterpart, the sources have been termed cluster radio relics. There seem to be two separate populations of radio relics which presumably have different origins even though they both appear to be associated with shock waves.

The first kind is many megaparsec across and is probably generated by Fermi I acceleration of thermal electrons at the shock. In the course of this acceleration one would also expect, at least as a by-product, a relativistic proton population.

The second kind of relics is smaller and has a filamentary morphology. They are believed to be compressed and thereby energised remnants of formerly radio-emitting plasma that has been produced in large quantities by active galactic nuclei in radio galaxies. Due to the short radiative life time the radio emission of this plasma fades quickly and leaves behind a radio ghost. When such a radio ghost is compressed by a shock wave the electrons gain energy and the magnetic field is amplified so that the radio emission in observable bands rises again. So far only about a dozen radio relics of this kind have been observed. This points to a large gap in our knowledge of the late phases of radio galaxy evolution. However, a sensitive low-frequency radio telescope, such as LOFAR, is expected to unearth thousands of such sources.

The existence of radio ghosts was confirmed very recently by high-resolution X-ray observatories which have detected spherical cavities in the surface brightness profiles of galaxy clusters. In some cases these cavities are associated with remnant, low-frequency radio emission. The cavities are interpreted as bubbles of relativistic gas that have been inflated by the central AGN. The relativistic gas has pushed away the thermal gas thus causing depressions of the x-ray emission. As these underdense but high-pressure bubbles expand and rise through the intracluster medium they do mechanical work on the ambient gas. The injected mechanical energy is eventually dissipated and heats the cluster. Recent research suggests that the energy released by the bubbles balances the radiative losses of the intracluster medium. Thus they prevent the cooling catastrophe in the cool cores of galaxy clusters and explain their temperature profiles. LOFAR will cause a revolution in the observation and understanding of these high-energy components of the cosmic large-scale structure because it is ideally suited to observe extended, steep-spectrum sources in point source confused fields. Thus, it will allow studying many examples of radio halos, and relics in great spatial and spectral detail. LOFAR will provide us with statistically meaningful samples of these tracers of ongoing large-scale structure formation in the Universe. It will provide a powerful complement to the study of the important process of cluster formation. The large number of remnants expected at redshifts around 2-3 makes this a powerful tool of a phase in cosmic history when the IGM was moving deeper and deeper into the potential wells formed by dark matter when the X-ray emission was still building up.

The German scientific competence

In Germany, there exists a vibrant community that has pioneered large parts of the science described above. Currently these communities are concentrated at the MPA Garching and the MPIfR Bonn and at the International University Bremen. Most of the theoretical work concerning relics, halos as well as most numerical studies of clusters of galaxies has been done in these groups. Moreover, German institutes are amongst the world leaders in large-scale structure simulations.

4.2 Galactic Astronomy & Surveys

Low-frequency high-resolution observations of Galactic emission with LOFAR will complement several aspects of Galactic high-frequency work carried out at the Effelsberg 100m telescope of the MPIfR. LOFAR covers the relatively unexplored low-frequency range, where some key information about the interstellar medium can be obtained.

4.2.1 Thermal Absorption and Recombination Lines

At frequencies below 100 MHz thermal gas, which exists in diffuse form throughout the Galaxy as well as in discrete HII regions, gets optically thick and absorbs emission from the background depending on electron density and temperature. It is essential to resolve the absorption to disentangle the different components of the thermal gas which are mixed along the line of sight. Cold thermal gas close to about 1000 K is known to exist from recombination line observations. It is a fully or partially ionized low-density gas (1-10 cm^{-3}) with 50-200 pc size, surrounding classical HII regions. Its distribution and contribution to the total ionized gas mass is unknown and its effects on the ISM dynamics remain to be determined. Combining Faraday Rotation Measure data (see below) with thermal emission in the direction of SNRs allows to estimate the magnetic field strength and its dependence on thermal electron density and temperature. High-frequency polarization observations, for Rotation Measure determinations, with the Effelsberg telescope will be combined with future LOFAR data for a common interpretation.

Another application of thermal absorption is tomography of the total synchrotron emission. At low frequencies HII regions absorb all emission originating from behind and the remaining signal is attributed to synchrotron emission within the distance to the optically thick HII region. Thus HII regions at different distances allow to trace the synchrotron emissivity as a function of distance. With a sufficiently large number of HII regions with known distances to be observed by LOFAR a detailed distribution of the synchrotron emissivity within a few kpc distance from the sun can be derived. Modelling the radio emission of the Galaxy requires precise knowledge of its local distribution. Recent Effelsberg results indicate that the local emissivity has been significantly underestimated previously. As a consequence, the size of the halo of the Galaxy is smaller or its emissivity is lower than assumed so far.

4.2.2 Low-frequency Polarization

The polarization capabilities of LOFAR for a wide frequency range open new possibilities to study details of the local Galactic magnetic field on sub-parsec scales. In the Galactic plane detection of low-frequency polarized emission is limited to a few hundred parsec (or even less) due to Faraday depolarization effects, while the total emission is a superposition of components extending over the entire Galaxy. Detailed structures of the local magnetic field become visible in linear polarization, complementing studies of larger scales in nearby galaxies (see Section 4.1.2).

Faraday rotation provides additional information of the magnetic field component along the line of sight. Faraday rotation increases with λ^2 and becomes rather strong in LOFAR's frequency range. Narrow channel polarimetry as will be provided by LOFAR allows a precise determination of Rotation Measures (RM) components along the line of sight. In this way polarization tomography of the local magneto-ionic medium can be performed. Bandwidth depolarization becomes significant for a channel width of 1 kHz at 30 MHz only for RMs exceeding about 100 rad m^{-2}.

A critical issue in the context of polarization analysis is to take properly into account large-scale emission, which generally is filtered out to some extent by interferometric observations. Other than for total intensities, where missing large-scale emission always is a scalar offset, in polarization vectors are added. Missing large-scale emission affects polarized intensities and angles on *all* scales so that the resulting polarization maps may be misleading. The LOFAR concept allows to obtain low-resolution all-sky maps which provide the emission on largest scales. LOFAR's technical concept also provides the required absolute polarization calibration, which is technically difficult at high frequencies.

Faraday depolarization may also affect the distribution of polarized Galactic emission. Faraday dispersion allows to estimate the size and spectrum of turbulent cells in the magnetized ISM. The detailed theory of these effects has been developed as a collaboration project between the MPIfR, the University of Moscow and the University of Newcastle. Application towards a realistic numerical model of the magnetized ISM is being developed in a new collaboration project supported by DFG. If magnetic fields, thermal gas and cosmic rays are mixed, the effect of differential Faraday rotation causes total cancellation of polarized signals at certain values of the observed mean Rotation Measure. Together with missing large-scale emission this may mimic filamentary magneto-ionic structures ("canals"). These, however, do not correspond to real features. LOFAR's multi-channel capability allows to detect differential Faraday rotation as a broad distribution along the line of sight of Rotation Measure values around its mean value. Real magnetic filaments, on the other hand, should generate sharp Rotation Measure signals along the line of sight.

If Faraday rotation occurs in the magneto-ionic medium in front of the emitting source, this is called a Faraday screen. Small variations in electron density and/or magnetic field strength are reflected as modulations of the polarized background by the foreground screen. The excellent resolution of LOFAR in its full extent will allow to study such fluctuations on previously unprecedented scales of a few 10^{-3} pc.

At high Galactic latitudes Rotation Measures are very low and observations at long wavelengths are needed to trace them. The existence of thermal gas at high latitudes is known from Hα surveys. The mechanism of excitation of high Galactic latitude gas is not well understood at present. The thermal electron density decreases with latitudes, while its filling factor increases on average as derived from pulsar dispersion measures. Rotation Measure studies could provide more detailed information of the distribution, density and filling factor of thermal gas. In areas where Hα surveys have insufficient sensitivity, thermal gas of e.g. density 10^{-3} cm^{-3}, distributed over 1 kpc in a regular magnetic field of 1 μG, causes a Rotation Measure of just 0.8 rad m^{-2}. This is undetectable with present-day instruments, but can easily be traced with LOFAR in the frequency range below 150 MHz.

4.2.3 Supernova Remnants

LOFAR is an ideal instrument to study supernova remnants (SNRs) at low frequencies, thus complementing high frequency observations carried out with the Effelsberg dish. For instance it will become possible to extend the frequency range for studies of the spectral index distribution across SNRs. LOFAR will be sensitive enough to detect numerous weak low-surface brightness SNRs, where actual SNR catalogues are highly incomplete. Low-surface brightness SNRs are evolved large-diameter objects, where particle acceleration in the shock front is inefficient and enhanced synchrotron emission is from compressed Galactic magnetic fields. Furthermore, SNRs exploding in the hot interstellar medium reach quickly a large diameter and have weak shocks and low surface brightness. However, LOFAR observations will only be successful when the dominating confusing sources in the field are accurately subtracted. This requires observations with the largest possible baselines to pick up confusing background sources with high angular resolution.

4.2.4 All-Sky Surveys

A basic task of the LOFAR radio interferometer will be surveys of the galactic and extra-galactic radio sky. Their importance is well illustrated by large surveys in other frequency ranges (e.g. ROSAT in X-rays, IRAS in the infrared) which regularly led to outstanding astronomical discoveries. Surveys provide a basic input into modern astrophysics and the opening of new frequency ranges is especially apt to uncover previously unknown physical processes or unknown source populations. Radio surveys started at low frequencies (Cambridge Surveys at 151 MHz, Texas survey at 365 MHz) with typically 1000-10,000 sources. The radio sky at very low frequencies was explored by the Cambridge 38 MHz radio survey (8C), which detected about 5000 sources with flux densities >1000 mJy. More recent surveys searched the radio sky at higher frequencies. The VLA Sky Surveys at 1400 MHz (NVSS and FIRST) provided already approx. 3 million sources with flux densities >1-3 mJy. New radio continuum surveys now explore the low frequency range again, such as the *Westerbork Northern Sky Survey* (WENSS) at 326 MHz with ~54" resolution and 18 mJy detection threshold and the *VLA Low-Frequency Sky Survey* (VLSS) at 74 MHz with 80" resolution and a typical sensitivity of 0.1 Jy/beam.

LOFAR will set new benchmarks for surveys in the low-frequency regime extending the sensitivity by two orders of magnitude and the resolution by one order of magnitude. In

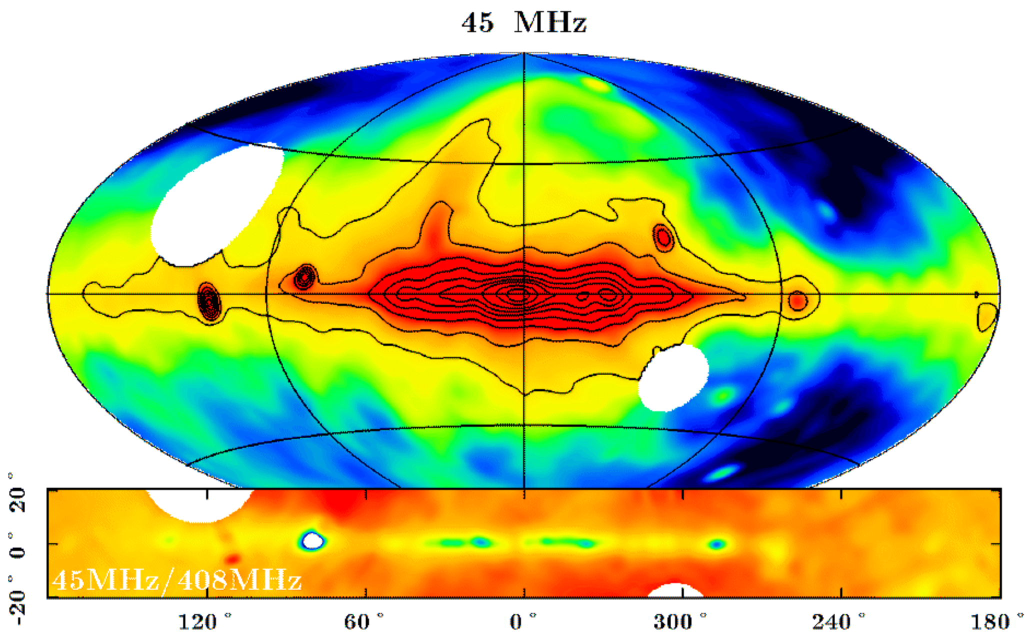


Figure 7: Radio continuum 45 MHz map at 5° resolution, composed from northern sky data from Maeda et al. (1999) and the southern sky map from Alvarez et al. (1997) shown together with a spectral index map of the Galactic plane between 45 MHz and 408 MHz (from P. Reich, MPIfR). Absorption of distant synchrotron emission by thermal gas at 45 MHz causes a spectral flattening (shown blue).

addition, LOFAR revolutionizes survey work by exploring the time domain as a new survey parameter. Intensity variations of radio sources can be detected on timescales from seconds to years, and even the detection of variations on timescales of decades is in the realm of possibility.

LOFAR’s harvest from surveys will be a great variety of galactic and extragalactic sources. There will be discoveries of objects from known classes as for example radio galaxies, which harbour supermassive black holes in their centres. Because of their steep radio spectra with maximum emission at rest frequencies of approx. 1 GHz, detections at very high redshifts ($z > 4$) require low-frequency surveys. The vast majority of the extragalactic radio population at mJy level and below will consist, however, of faint, low-luminosity radio sources ($L < 10^{23}$ W/Hz) associated with star-forming disk galaxies. The study of these objects will open a new opportunity to disentangle the role of star formation and assembling of black holes during galaxy evolution at cosmological distances.

LOFAR’s wide field-of-view and high sensitivity will allow to map the distribution of radio source populations and to probe the interstellar medium through the entire Galaxy. Its capability to detect transient sources and to follow processes varying in time will prompt patrol surveys to detect radio bursts for example from active stars, exo-planets, Gamma-ray bursts, or radio supernovae. The harvest will also contain yet rare specimens of extragalactic objects, such as Mpc-sized radio galaxies, radio remnants from past radio galaxy activity periods, and radio halos in galaxy clusters, which are known only in small numbers today.

Multi-channel all-sky surveys at low frequencies, with unresolved compact extragalactic sources removed, allow to derive detailed spectral index information of the diffuse Galactic emission across the sky. Diffuse Galactic emission consists of a mixture of thermal radiation and synchrotron emission, whose fraction varies as a function of Galactic coordinates. Galactic synchrotron emission is almost everywhere optically thin, but the power-law spectrum steepens towards higher frequencies reflecting the steepening of the energy spectrum of the cosmic ray electrons. At higher frequencies thermal emission is optically thin and dominates the Galactic emission in the Galactic plane. Towards lower frequencies increasing optical thickness modifies the observed spectral indices (Fig. 7).

All-sky radio emission and spectral index information, together with the magnetic field structure derived from radio polarization data, will allow to construct a 3-D model of the Galactic cosmic rays. The distribution of cosmic rays over geological times at the position of the Sun in the Galaxy received recently (again) attention from geosciences, since effects of cosmic rays may well result in a contribution to climate changes on Earth.

If the history of scientific discovery is any example, the excitement of LOFAR will not only be in the study of well known or emerging populations, but in the yet to be made discoveries of new phenomena. It is this prospect that makes the time-consuming and extensive work on surveys a fascinating field of research.

The German scientific competence

Experience with large surveys is available in Germany. At the Hamburger Sternwarte two large-scale objective prism surveys using Schmidt telescopes were made. Large surveys of radio sources were made with the Effelsberg telescope. Experience with compilation and analysis of radio source catalogues is available at the MPIfR Bonn. A number of all-sky radio surveys in the cm-range have been carried out at the MPIfR. Spectral index maps of the Galactic radio emission need absolutely calibrated data and careful consideration of baseline levels. Such expertise is available at the MPIfR. Spectral index maps in the frequency range between 45 MHz and 23 GHz are already available on degree-scale angular resolution.

4.3 Solar System Science: Solar Physics, Space Sciences, & Ionosphere

4.3.1 The Sun

The Sun is a very intense radio emitter in space. The non-thermal radio radiation is a sensitive indicator of solar activity. There is a huge variety of solar activity concerning spatial and temporal scales, the 11-year cycle being the best-known signature of solar variability. During flares a huge amount of energy ($\approx 10^{25}$ J) is suddenly released within a time period of few hours. A flare appears as a local, strong lightening on the disk of the Sun (Fig. 8 top left). Here, magnetic field energy is transferred into plasma heating, particle acceleration, and mass flows. Furthermore, a large amount of coronal material is injected into the interplanetary space, a phenomenon called Coronal Mass Ejections (CME) (Fig. 8 top right). All these different phenomena of solar activity have their special signatures in the solar radio radiation (Fig. 8 bottom). Thus, the study of solar radio radiation provides very important information on

- magnetic energy release (flares)
- electron acceleration
- coronal shock waves
- coronal mass ejections.

All these processes are of general astrophysical interest but can be studied best on the Sun.

Generally, it is assumed that the solar radio radiation in the low frequency range is generated by plasma emission. Here, energetic electrons excite high frequency electrostatic plasma waves, which convert by interaction with the background plasma into escaping electromagnetic (radio) waves. Thus, the emission takes place near the local electron plasma frequency. Due to the gravitationally stratified solar atmosphere, the high and low frequencies are emitted in the low and high corona, respectively. LOFAR will be able to measure the radio radiation in the frequency range ~10-240 MHz. These frequencies correspond to radial distances of 1.2 and 2.5 solar radii, respectively. The low-frequency boundary will depend on the state of the ionosphere determining the ionospheric cut-off frequency. Thus, LOFAR will be able to monitor the corona and the region of its transition into the near-Sun interplanetary space. This region is very important since the solar processes that are relevant for the solar-terrestrial relationship take place there.

The Sun is the source of our human life. The huge solar events in October/November 2003 (Fig. 8), i.e. during the declining phase of the present solar cycle, have recently shown the tremendous public interest in solar activity. Solar activity influences Earth’s space environment in mainly two different ways:

- CMEs can impinge on the Earth's magnetosphere in a period of 1-3 days after their launch in the corona. This leads to magnetic storms disturbing the navigation of ships and airplanes as well as the intercontinental radio communication.

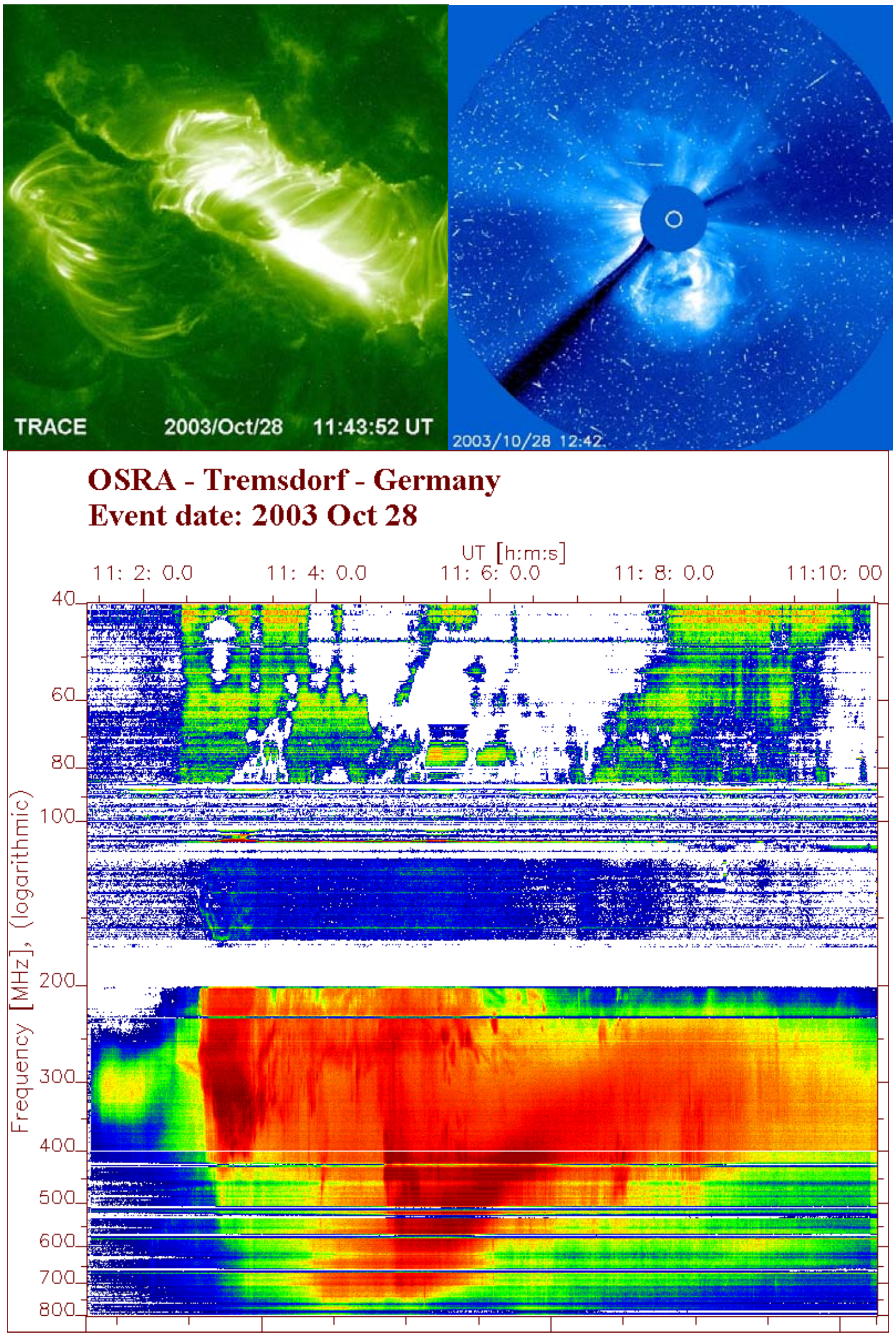


Figure 8: The solar event on October 28, 2003 was one of the hugest solar events ever observed. The local lightening was observed by the spacecraft TRACE in the EUV light (top left). The Sun also emitted a large amount of radio waves during this event. The corresponding dynamic radio spectrum is shown at the bottom. It was recorded by the radio spectral polarimeter of the AIP. A huge CME was also launched during this event as seen on the white light image of the coronograph (LASCO) aboard the spacecraft SOHO (top right) (from Warmuth & Mann 2005).

- The solar energetic particles generating by flares reach the environment of the Earth after a few ten minutes. They are responsible for the northern and southern lights. These (also called) solar cosmic rays are also dangerous for the health of astronauts (e.g. at the ISS) and can lead to disturbances of electronic equipments on satellites, medical hospitals, etc. This demonstrates the importance of the understanding of solar activity with respect to our human and socio-economic life.

Furthermore, one should refer to the LOFAR *Outrigger in Scandinavia* (LOIS) (http://www.lois-space.net). Bo Thide (Institutet foer Rymdfysik in Uppsala, Sweden) is the PI of LOIS where German groups are Co-Is. LOIS intended to do active radar sounding of coronal structures, especially CMEs.

Consequently, LOFAR is able to provide contributions for a better understanding of basic astrophysical processes, e.g. particle acceleration, magnetic energy release, stellar activity, and for solar terrestrial relationship, i.e. Space Weather, which is of general social relevance.

The German scientific competence

The Astrophysikalisches Institut Potsdam (AIP) has a long tradition in solar radio astronomy. Its expertise concerns solar activity and related phenomena such as coronal mass ejections, solar energetic particles, and X- and γ-ray radiation of the Sun, as well as their influences on the Earth's environment.

4.3.2 Ionospheric Science and Space Weather

Initially LOFAR has been conceived as an astronomical instrument, but it may well serve as a powerful laboratory for studies of the ionosphere and interstellar plasmas using extraordinary temporal and spatial sampling. Through its involvement in EISCAT the German community has got significant expertise in these areas.

The process of correcting for ionospheric propagation of data for high-fidelity imaging of astronomical radio sources beyond the Earth atmosphere requires iteratively solving for ionospheric phase delays in many directions at each of the LOFAR stations. At each station a time-dependent 2-D ionospheric mask will be produced for correcting the field of view for the eight station beams. In addition, the ray paths from individual LOFAR stations will overlap, permitting high-precision tomography of the ionosphere above the array. For example, a total of 1,000 calibration sources for each of the 100 LOFAR stations will generate 100,000 independent ray paths with accurate phase measurements every few seconds, providing a rich data set for three-dimensional ionospheric mapping and space weather applications. This data set allows studies of processes on linear and temporal scales far smaller than is now possible. The early days of LOFAR will be dominated by the generation of a comprehensive global sky model (GSM) using accurate phase delay and amplitude measurements toward a large number of known bright sources, and from a large number of LOFAR stations. The combination of LOFAR with existing terrestrial transmitters, such as FM stations, can be utilised for passive radar imaging of ionospheric irregularities. In addition, ionospheric radars may actively modify and probe the ionosphere. The physical layout, digital technology, and high sensitivity of the array will result in the most advanced passive radar system ever developed.

Interplanetary scintillation (IPS) measurements of the thousands of sources accessible to LOFAR offer the prospect of high-resolution studies of the interplanetary plasmas, the solar wind and coronal mass ejections (CME). Tomographic techniques and IPS observations have already been successfully combined for 3-D imaging of a CME.

4.4 Variability & Transients

Its large coverage of the low-frequency sky makes LOFAR a precious tool to find bursting and transient radio sources. Among these are the most spectacular explosions in the Universe since the Big Bang, such as supernovae (SN) or gamma-ray bursts (GRB). Moreover, its unique capability to focus “a posteriori” to some specified event (say after some trigger from other instruments) allows to uncover the low-frequency emission directly prior to the explosive event and to gain information about the progenitor system and the involved radiation mechanisms that are inaccessible by other means.

Gamma-ray bursts (GRBs) are short and intense flashes of γ-rays that outshine, for a short moment, the whole rest of the γ-ray sky. They fall into two classes that are well distinguished by both their durations and their spectral properties. The short bursts have typical durations of 0.3 s, while their long-duration cousins typically last for about 30 s. Short bursts do exhibit substantially harder spectra than long ones. Generally, the observed non-thermal spectra imply bulk Lorentz factors of several hundreds making GRBs the most relativistic events in the universe.

GRB science was plagued for more than two decades by the ignorance of the research community concerning the distance scale to the sources and thus about the involved energy budget of the explosion. Suggestions ranged from galactic sources over halo populations out to events occuring at cosmological distances. The pivotal role in settling this issue was played by the final observation of GRBs in a different wavelength-band: in 1997 “afterglows” were detected in X-rays, the optical and radio that finally proved the cosmological origin of long bursts.

What can LOFAR do?

Triggered by other instruments such as the satellite mission SWIFT, LOFAR can reprocess the data in its buffer and provide nano-second time-resolved signals over some time interval prior to and after the burst. Thus one may determine the progenitor emission directly prior to the burst, crucial information to understand both the mechanism behind GRBs and the progenitor system.

Short-duration GRBs, however, have so far only been detected in γ-rays, to date there is not a single afterglow observation of a short GRB. Thus, their distance, energy budget, beaming and in particular the central engine behind the explosion are not known with certainty. The most promising candidates are compact binary systems consisting of either two neutron stars (NS) or a neutron star and stellar mass black hole (BH). The possible radio afterglow detection with LOFAR could provide us with clues to the environment of short bursts, information that is crucial to identify the central engine.

If the progenitors of short GRBs are indeed compact binary systems then they will produce for about 15 minutes a “chirping” gravitational wave signal in the frequency range (10 - 1000 Hz) accessible to ground-based detectors. Such a detection would be one the greatest events in the history of physics. Triggered by a gravitational wave detector, LOFAR could follow the evolution of the low-energy emission during the last minutes of the in-spiral. Due to tidal heating the temperature in binary neutron stars is expected to rise from negligible values up to 10^8 K prior to the merger. The monitoring of the emission evolution during this period will yield unprecedented information about the neutron star microphysics such as the nuclear equation of state, the viscosity, magnetic fields, and the involved radiation mechanisms.

Detailed simulations of neutron star binary (Fig. 9) suggest that a supra-massive, metastable neutron star forms that is temporarily stabilized by its rapid differential rotation. Endowed with the seed magnetic field of a typical neutron star, such an object is expected to amplify magnetic fields via dynamo action within fractions of a second to field strengths close to equipartition. Such a −probably very short-lived− object is expected to drive a magnetized wind that will produce radio emission with a frequency of the spectral maximum at about 10 MHz. So at least the high-energy tail produced by this magnetized wind will be in the range accessible to LOFAR. LOFAR will thus allow these theoretical ideas to be confronted with observations.

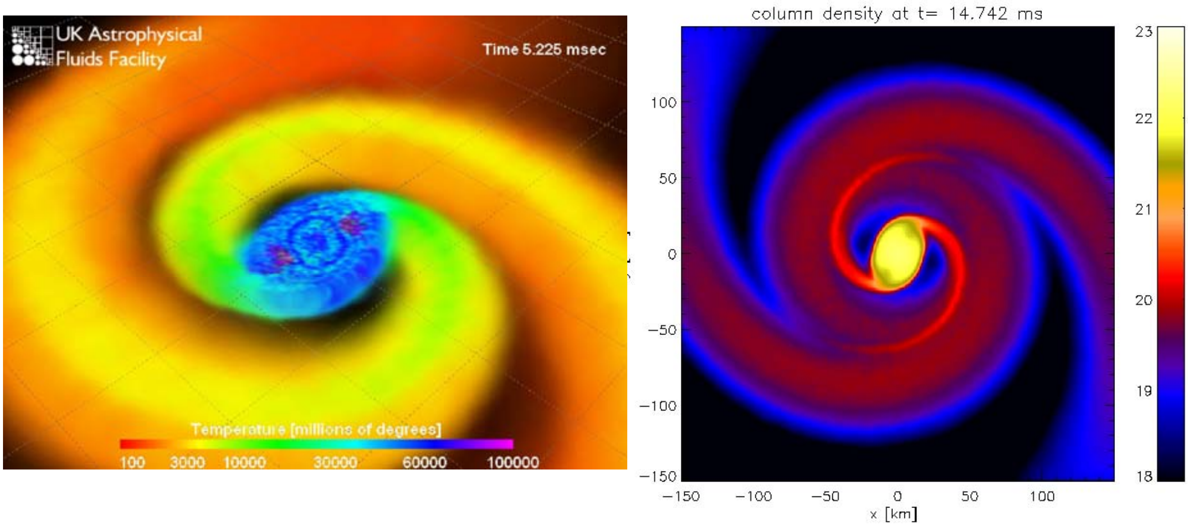


Figure 9: *Left:* Cut through the remnant of a merged neutron star binary. Colour-coded is the temperature distribution. *Right:* Mass distribution in a merged neutron star binary. Colour-coded is the column density (from Rosswog & Davies 2002).

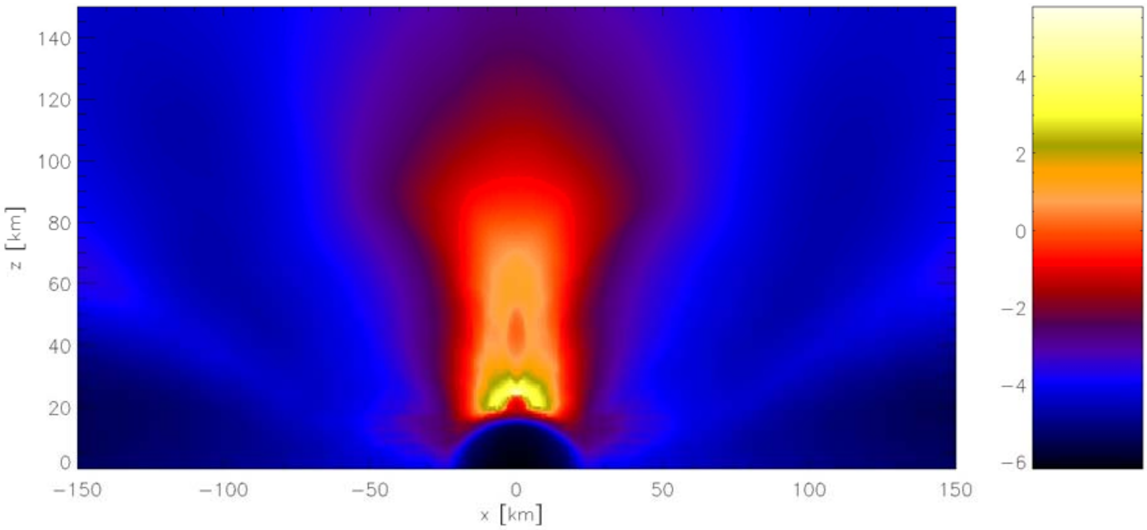


Figure 10: Jet formed via the annihilation of neutrino-antineutrino pairs emitted from a merger remnant of neutron stars. Colour-coded is the Lorentz factor (from Rosswog et al. 2003).

The main operating radiation mechanism in GRBs is thought to be synchrotron. As the electrons lose energy the emission is decreasing to lower and lower frequencies. The absorption at low frequencies may reduce the observable flux but still LOFAR should be able to find relics from GRBs and their afterglows. These will provide a wealth of information about the spatial distribution of GRBs with respect to their host galaxies.

It is generally believed that compact binaries should, due to kicks received at birth, on average be further away from star forming regions than, for example, collapsing massive stars that are thought to be the progenitors of long-duration bursts. Thus such relic maps could distinguish between possible progenitor systems. If the binary nature of short GRB-progenitors should be confirmed by other means (e.g. gravitational wave detections), this spatial distribution will give insights into so far only very poorly understood areas of binary evolution (such as initial separations, neutron star kicks in binary systems, etc.).

The most advanced numerical models for the central engines of short GRBs (NS-NS and NS-BH) encounters stem from German groups from the Max-Planck-Institut für Astrophysik (in collaboration with University of Edinburgh) and the International University Bremen.

4.5 Astroparticle Physics (Cosmic Rays & Neutrinos)

On the national and international level astroparticle physics has been recognized as an exciting and rapidly emerging new field in recent years. It brings together the scientific vision, experience and techniques of particle physicists and astrophysicists. Progress in both fields has reached such a level that now the Universe has become the prime laboratory for pushing particle physics into the frontiers of the extreme. Prime examples for this are cosmic particles and photons of the highest energies: ultra-high-energy cosmic rays up to 10^{20} eV and above, ultra-high energy neutrinos, and photons in the TeV regime.

LOFAR will play an important role by mapping the space distribution and energy spectrum of cosmic ray electrons. In addition, LOFAR will observe the diffuse cosmic ray gas in the Milky Way and compare it with the results of high-energy γ-ray telescopes. The Galactic non-thermal synchrotron emission, dominating at low frequencies, arises from the interaction of cosmic ray electrons with the Galactic magnetic field (Sect. 4.2.4). The same cosmic rays will also interact locally with the interstellar medium and produce γ-ray emission via pp-collisions and pion-decay. Comparisons with observations of the distributed Galactic γ-ray emission (such as observed by OSSE and EGRET and with the proposed GLAST mission) follow naturally and provide important tools for decoupling the matter, cosmic ray, and magnetic field distributions in our Galaxy.

However, it has recently been realized that radio telescopes such as LOFAR are also ideal experiments for direct detections of the highest cosmic rays. Ultra-high energy cosmic rays with energies up to and beyond 10^{20} eV are at the focal point of big astro-particle physics experiments. The nature and physics of these particles is one of the big mysteries in astrophysics today. When they collide with particles in the Earth’s atmosphere the collision has a centre-of-mass energy well above what can be achieved in the largest particle accelerators on earth, allowing one to probe new particle interaction physics as well. The resulting particle cascade rushes as an extensive air shower through the atmosphere and can be detected with particle or optical air fluorescence detectors. The rather lower incidence of these relativistic particles, however, requires large detector arrays. Leading experiments in this field with significant German participation are *KASCADE-Grande* in Karlsruhe/Germany and the *Pierre Auger Observatory* in Argentina.

As the air shower, containing a large fraction of electron/positron pairs, rushes through the Earth's magnetic and electric field (the latter only being relevant during thunderstorms), the particles are deflected and start producing radio emission. Since the emitting shower "pancake" of a few meter's thickness is less then the wavelength below 100 MHz, the radio emission is coherent and greatly amplified. This process has been simulated extensively with a new Monte Carlo code developed in Bonn. An experimental test of the radio emission from extensive air showers is under way with the LOPES experiment at the FZ Karlsruhe. The experiment utilizes LOFAR prototype antennas in conjunction with the particle detectors of the KASCADE array. First successful detections have been made (Falcke et al. 2005).

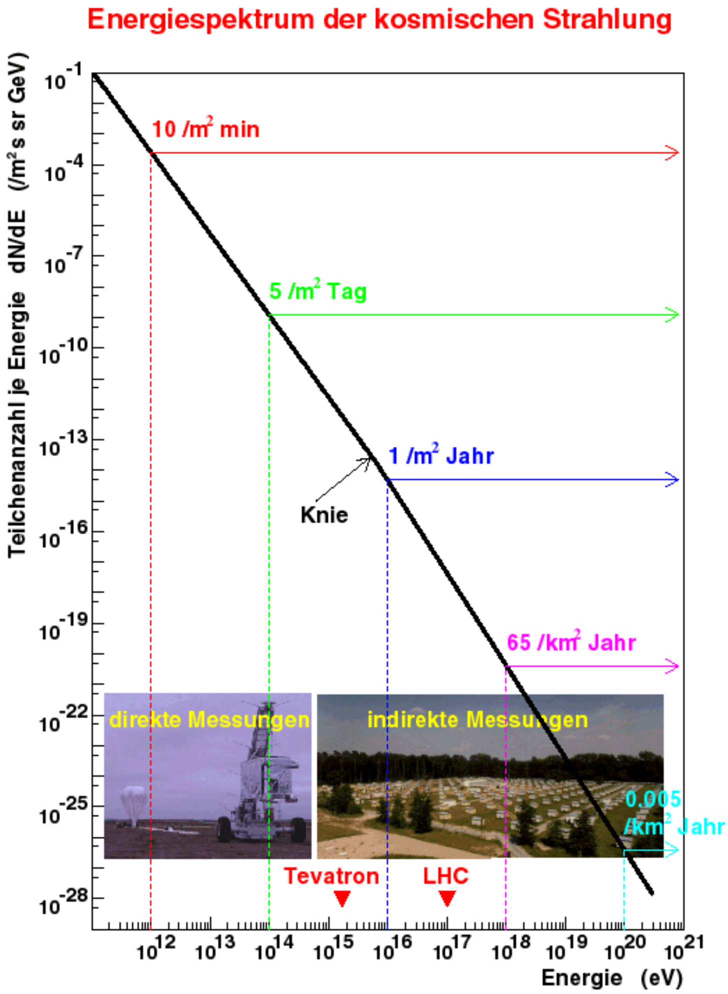


Figure 11: Energy spectrum of comic rays observed from Earth.

Alternatively one can use LOFAR itself as a large cosmic ray detector. The design has been modified due to these new considerations to make this well possible. Estimates indicate that LOFAR can observe cosmic rays over the entire range from 10^{15} to 10^{20} eV. This makes it a very competitive cosmic ray experiment. Its advantages are that the power in radio pulse from the geomagnetic effect should be directly proportional to the primary particle energy squared. Since radio photons do not suffer absorption in the atmosphere all particles in the shower will contribute and even highly inclined showers can be seen. This is of particular interest also for neutrino-induced showers that are expected to exist at high energies.

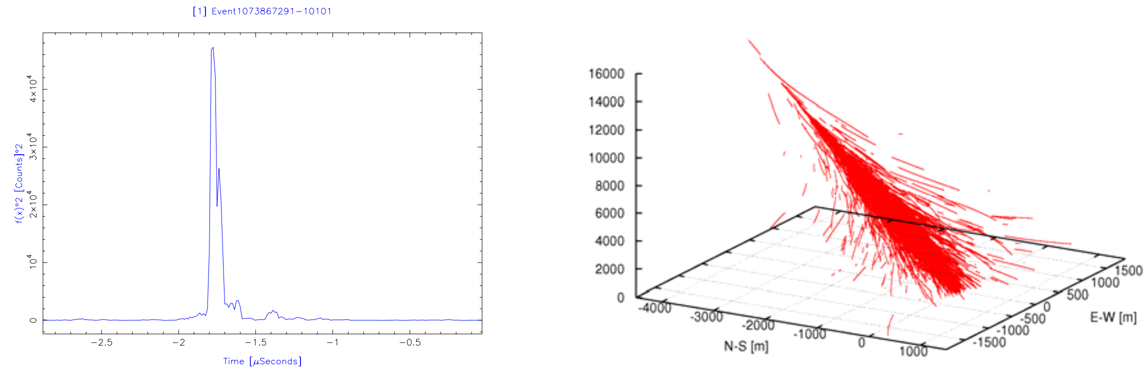


Figure 12: Left: Radio pulse from a Cosmic Ray air shower detected by the LOPES experiment at KASCADE-Grande (from Horneffer et al. 2004). Right: trajectories of e^+/e^-- pairs deflected in the earth magnetic field from a Monte Carlo code simulating the radio emission from extensive air showers (from Huege & Falcke 2005).

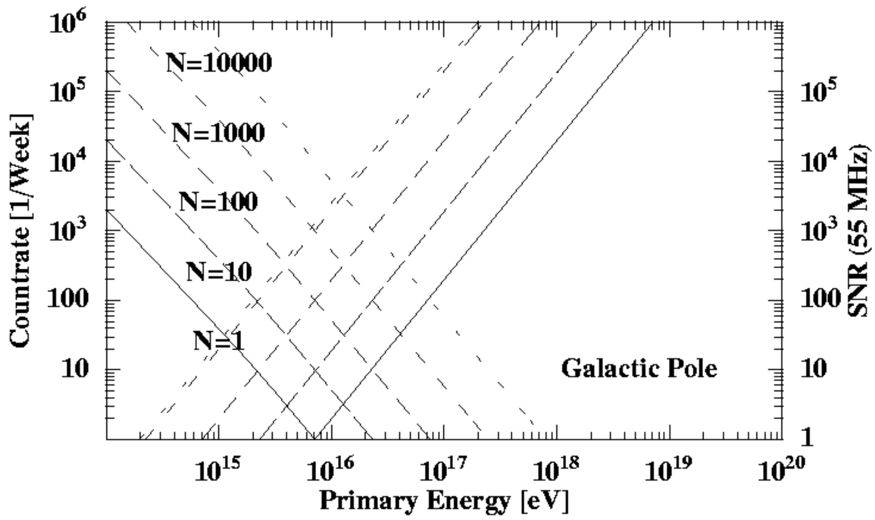


Figure 13: Signal-to-noise (right axis, lines slanted to the right) for radio detections with N dipoles and expected count rates (left axis, lines slanted to the left) of cosmic rays as a function of cosmic ray energy. The intersection of the two sets of lines with the x-axis delimits the theoretically useful cosmic ray energy range for an array of these dimensions. It is assumed that the antennas have a gain of g=3 and are densely packed with an assumed cosmic ray collecting area of only $(c/\nu)^2$ for each antenna. The system temperature is T_{sys}=300 K and the noise is dominated by the sky background. The bandwidth is 16 MHz for bandwidth-limited pulses at 55 MHz. The SNR does not increase beyond N=1000 because the dipoles fall outside the beamed emission of the air shower. The calculation assumes a zenith angle of 30°, a geomagnetic angle of 45°, and an offset of 110 m from the shower core. For the count rates we have formally considered only air showers where the shower core intersects the effective area of one dipole (~30 m^{2}). Since the air shower is larger than this effective area, configurations with N<100 would actually see much higher count rates (from Falcke & Gorham 2003).

Additionally, the detection of the radio emission in the atmosphere is sensitive to the longitudinal development of the air-shower in contrast to particle detectors on ground. This makes the technique comparable to the observation of Cherenkov or fluorescence light detection in moonless, clear nights, but with the advantage of 24 hours per day observation.

The range of energies that can be observed with LOFAR as an astroparticle physics experiment can be greatly expanded in the future once one is able to use isotropic signals, such as radar reflections from the ionization trails of air showers. This is applicable to energies above 10^{20} eV and allows one to survey a much larger detector volume. Finally, radio observations of the moon to search for neutrino induced shower from the subsurface will allow one to constrain the cosmic neutrino flux at the very highest energies. Similar experiments (GLUE) with conventional radio telescope now provide the best limits on ultra-high energy neutrinos and have ruled out some of the most exotic for ultra-high energy cosmic rays and neutrinos.

5 Engineering Science and Technological Aspects

5.1 Networks

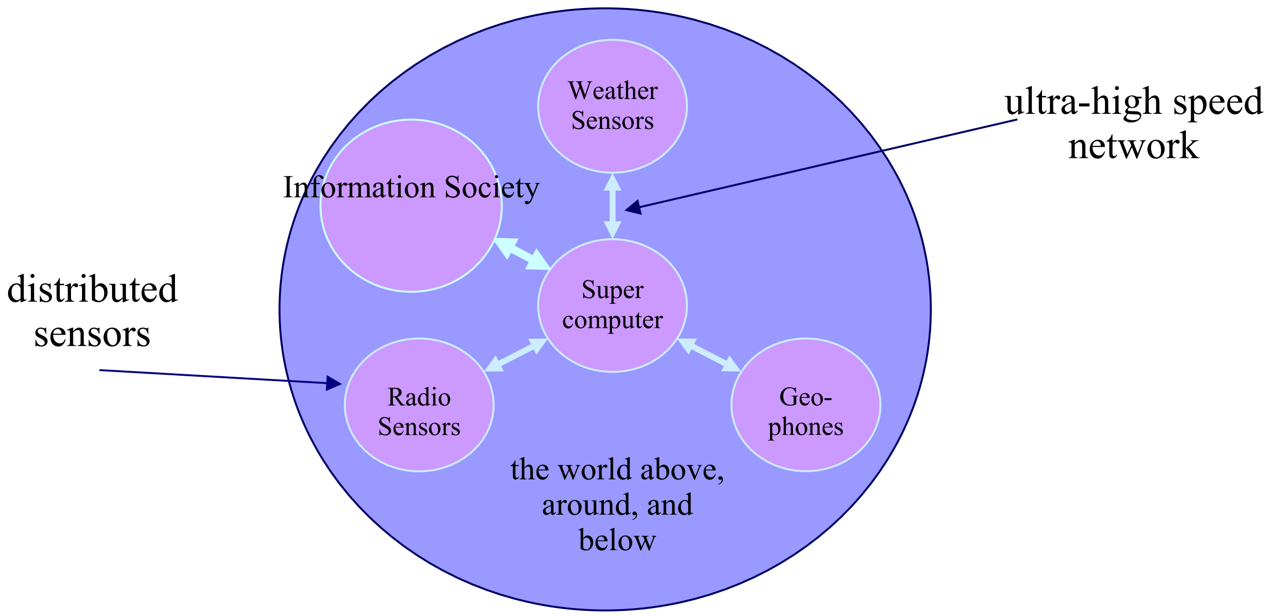
5.1.1 Wide Area Sensor Networks

In the course of the R&D for LOFAR it was realized that the concept of LOFAR went beyond astronomy and fundamental science. As the technical concepts matured, the interest from other scientific communities and from commercial parties steadily increased. The main aspects that make the LOFAR project attractive for other fields are:

- With a dedicated high-speed network and >10 extended stations, additional sensors can be added at only a small additional cost.
- Digital sensors are a main driver for high-speed networking and supercomputing, exceeding the demands and vision of multi-media applications or computer-to-computer networking.
- On the scale of LOFAR a genuine WASN has never been realized.

The additional cost for this expansion of LOFAR is the burden of increased flexibility and a wide range of user demands in terms of bandwidth, robustness, interconnectivity, and services. For example, radio astronomy has a high demand on bandwidth and synchronization. Geophones, microphones, weather station have low-bandwidth but may require local pre-processing. Agricultural sensors can be widely distributed and non-stationary. High-energy particle detectors for astroparticle physics applications need special triggering and synchronization. All applications may also demand differently spaced network access points. As a result an interdisciplinary knowledge consortium is

With the huge amount of information being generated by a large set of continuously streaming sensors, a WASN has demands beyond traditional high-bandwidth networks and applications. Different user groups demand different sensors, bandwidths and modes of operations. Currently planned examples of sensors required by different user groups are:



- **radio dipoles** for radio astronomy creating a virtual telescope, studying: cosmology, space weather, ionosphere, high-energy particles
- **particle detectors:** measuring cosmic ray induced particle showers
- **geophones** for monitoring tectonic activity and ground water levels through micro-earthquakes
- **weather stations** for real-time weather and storm evolution monitoring
- **microphones** for infrasound applications
- **water level sensors** for enabling precision agriculture.

5.1.2 What is needed?

There are numerous specific tasks for potential partners in the project. Some of those specific to the WASN testbed concept include, but are not limited to:

- Lay out the LOFAR network on scales of 2, 50, 300 km distance with newly installed fibers (inner region) or using unmanaged dark fibers provided by a partner. For LOFAR in Germany this is an obvious task for national network providers.
- Provide LOFAR nodes and stations with advanced GbE network equipment, GSM/GPRS links, GPS receivers, etc.
- Provide various categories of sensors (e.g., measuring environmental parameters)
- Develop protocols for simultaneous use of these sensors and secure communication protocols (IPv6 based - multitude of sensors, high performance secure transport of heterogeneous data, dynamic behavior through radio links or “ad hoc” behavior of some sensor types).

All these tasks are an ideal opportunity for German and European industry to participate in R&D activities.

To summarise: a wide area sensor network is a new and innovative approach to sensing the physical world. It is a technology that drives bandwidth demand to a new level. The real world will always provide more information than we can handle in any virtual world, hence smart information reduction and processing is the key for a WASN. A European testbed, realized through LOFAR in the Netherlands and Germany and driven by demanding users, will push this technology.

5.2 Data Links & Transport

5.2.1 Collaboration with *Geant* and *Grande*

Early discussions with T-Systems have indicated an interest on their side to collaborate with the LOFAR project. A new generation of research networks that are being proposed or built might solve that data transport needs of the German LOFAR stations and the connection of the German data and competence centres.

5.2.2 Wireless Connection of LOFAR Stations

The LOFAR system will consist of about 10.000 antennas with about 100 antennas per station. Each station has to be connected to an ultra-high speed optical fibre backbone network. The last mile connection of these stations is very expensive. Therefore, it seems ideal to use wireless links to connect those stations. The fact that the channel between the two connection points can be considered as time-invariant eases the problem when compared to the requirements of conventional wireless systems.

The required data rate for the connection of a LOFAR station is in the range of 5 – 10 Gbps. With the state-of-the-art wireless technology it is not possible to achieve these data-rates. The latest enhancements in wireless access technologies such as multicarrier transmission, or alternatively ultra-wideband transmission, MIMO technologies and link adaptation might be employed to develop a high-speed wireless access system for the connection of the LOFAR stations. Such a system could serve as a cut-edge demonstrator for very high-speed wireless communication. Therefore, the LOFAR system seems an ideal platform for such a development – in particular the planned LOFAR station in the Bremen region.

5.3 Software

5.3.1 Software Infrastructure for Distributed Data Processing

An enormous computational task is involved in transforming the radio signal from the sky to the final data products, such as maps, catalogues, spectra, and light curves. For this task a large number of different computer programs written in a number of different languages and running on a variety of computer platforms in different locations have to digest Terabytes of data in a coordinated, efficient, and transparent fashion. Automatic documentation of the data flow and processing are essential to allow later reconstruction of the history of any science data product. With its computational requirements, LOFAR is currently unique among astronomical telescopes, but it should be seen as a precursor for future experiments such as the *Square Kilometer Array* (SKA), which will have even more extreme needs.

A similar, but somehow smaller computational challenge was faced by the PLANCK satellite project. As a solution to this problem, it was decided to build a software package, the *Process Coordinator* (ProC), which provides the necessary software infrastructure to build, administer, and execute complex data processing pipelines. The ProC is a work-flow engine that coordinates the various computational processes and data streams, while allowing efficient usage of the available, distributed computational resources. The software is under construction by a professional development team located at the *Max-Planck-Institut für Astrophysik* in Garching. A prototype exists and is already used by PLANCK data processing centres to build and test their software pipelines for data analysis.

The design of the ProC is generic and can be used in other projects. The LOFAR experiment, with its very demanding needs in terms of computing power and data flow rates, would − on the one hand − strongly benefit from such a software package, and could − on the other hand − be a strong driver for the ProC project to turn into a generally used platform for complex data processing of future and computationally even more demanding science projects.

An adaptation and application of the ProC to LOFAR data processing would provide a synergy between two ambitious radio astronomical science projects with German participation, one in space − PLANCK − and one on Earth − LOFAR. Thus, an extension of the German efforts to develop the ProC coordinator as a tool for demanding data processing and for interfacing data bases and GRID computing technologies would position Germany extremely well for the next-generation astronomical experiments. Such a software tool is intended as a reliable and comfortable workhorse, which could easily be used for complex computational tasks in many other science applications, e.g. in bioscience for software pipelines analysing genetic information, for data analysis in particle physic experiments, and for the *German Astronomical Virtual Observatory* (GAVO) as a framework to provide web services. Therefore, the LOFAR project can also be an important interdisciplinary technology platform in the area of supercomputing software development.

5.3.2 Usage of Grid Technologies for Data Distribution and Processing

LOFAR requires enormous computational resources to collect, transfer, automatically annotate and store radio antenna data, and to compute scientifically interpretable information. Scalable and high performance distributed data storage and computing strategies will be essential to operate the data collection, analysis and distribution. The idea behind GRID computing is to provide a new level of worldwide information and computer resources. Originally motivated by the huge amounts of data arising from future high–energy physics experiments, GRID technologies are suited to meet the expected computing requirements of LOFAR.

The development of GRID technologies is mainly based on two ideas: *Cooperative usage of distributed computer resources* can provide the short–term accumulation of huge computer capacities to solve novel scientific problems; *virtualization* allows the exchange of components and resources on the fly and conceals technical details and geographical distribution from the user.

The first stage of processing LOFAR data from the antennae will be performed in the *Central Processing Site* (CPS) that integrates the distributed antennae into a telescope. However, most of the scientific post-processing, archiving and storing will need to be done in a distributed fashion. The same is true for the dissemination of the extracted data products. Therefore, the establishment of *Expert Data Centres* (EDC) is essential for obtaining the maximum scientific return from the LOFAR data.

Moreover, the various EDC should be able to combine their processing facilities to operate on arbitrary parts of their data products. The EDC should also be in charge of the long-term storage of LOFAR data.

The design concept for the CPS already refers to the *DataGrid* developments as a means for managing the data products. The interaction between EDC and CPS, e.g. for event-based operation mode, require the employment of grid-technology as well.

The EDC thus face three challenges besides the development of their respective scientific goals:

1. interoperability of the computational facilities of EDC and CPS and between the EDC

2. interoperability of their data archives

3. provide data compliant to Virtual Observatory (VO) standards or develop VO standards where lacking.

Within the German astronomical community the Astrophysical Institute Potsdam (AIP) is developing methods for managing robotic telescopes with grid technology. Here the focus lies on event-based triggers, and methods to combine cluster-computing facilities over high-bandwidth networks. The Solar Radio Group at the AIP has expertise in the area of Grid technology as well as in the development of Virtual Observatory compliant data archives.

Secondly, the John von Neumann Institute for Computing at the Forschungszentrum Jülich is a leading research institute for Grid middleware technology. It coordinates the development of the well-known UNICORE system which is used to access supercomputer resources worldwide and provides a dCache System with more then 2 PetaByte tape storage capacity. The John von Neumann Institute for Computing is experienced in the provision of state-of-the-art supercomputer capacity and GRID services for the computational science communities in Germany and Europe.

Furthermore, *CampusGrid* at the Forschungszentrum Karlsruhe, Institute of Scientific Computing, provides a seamless IT environment supporting the research activities in astronomy, physics, bioinformatics, nanotechnology and meteorology. The distributed computing and storage capacities within *CampusGrid* are continuously extended and will be used to serve LOFAR's computational appetite. The *D–Grid Integration Project* starting in October 2005 will build up a GRID infrastructure covering Germany for the German scientific community. Besides the configuration and management of virtual organizations (e.g. the LOFAR Science Network, see below), authentication and security, the data access will be standardized independent of the underlying database systems.

At the Forschungszentrum Karlsruhe, Institute for Data Processing and Electronics, software based on GRID technologies for real-time data processing and analysis is developed. Currently a distributed *Web Services Toolkit for High Throughput Data Processing and Analysis* is established, providing authentication, database access and computational and networking power. Additional LOFAR specific software, e.g. scientific data extraction from CPS data products, may be installed as web services available for the LOFAR community or executed locally. All web services can easily be integrated into the Process Coordinator ProC (at the MPI für Astrophysik Garching) to build up complex data processing pipelines.

Secondly, desktop computer systems are dynamically integrated into the GRID. Idle or switched–off (e.g. during night) computer systems provide a huge but unused computing power resource in every organization. Parts of the computational expensive tasks of the web services toolkit will be transferred to the desktop computer systems. This will help to satisfy the LOFAR computing power requirements.

Since the GRID research is aimed to support many research communities, participation is a logical step to provide GRID access, databases and data analysis capacities to the German LOFAR Science Network.

5.3.3 Cellular Engineering and Signal Processing

The main overall scope of research at the wireless and cellular communications group at the International University Bremen is the development of air-interface access technologies for future high data-rate wireless communication systems. The envisaged data-rates of next generation cellular systems is up to 1Gbps. Therefore, a number of key enabling technologies are being developed and investigated. These include investigation of:

- Multiple antenna concepts: MIMO (multiple input multiple output) and beamforming techniques with the associated signal processing
- Dynamic channel assignment algorithms for multiple access systems
- Multicarrier transmission systems using orthogonal frequency division modulation (OFDM) and polyphase filters
- Relaying, ad hoc and multihop transmission
- Navigation algorithms exploiting the base station signals of a cellular system
- Spectrum sharing techniques for increased spectrum efficiency
- Link adaptation (adaptive modulation and incremental redundancy) for increased spectrum efficiency
- Non-linear signal processing using neuronal networks for signal-to-noise-ratio enhancement and adaptive channel assignment
- Ultra-wideband transmission (UWB).

5.3.4 RFI Suppression

In cellular systems interference suppression is a key issue as the same radio frequency channel is reused in some neighbouring cells causing the so called co-channel interference. Therefore, the existing research expertise in this area can be utilised for the RFI suppression issue in the LOFAR project.

Due to the frequency range of interest (10 MHz – 240 MHz) the effects of man-made interference on the performance of LOFAR are significant. Therefore, LOFAR will be one of the first, or perhaps the first, radio telescope(s) in which RFI mitigation techniques will form an integral part of the system design. It is inherent to man-made interference that the level of interference can vary significantly making the interference hard to predict. The interferer might be of narrow band nature, i.e. interfering with a single sub-carrier, or of broad band nature, i.e. interfering with multiple sub-carriers. In addition, RFI might be bursty or continuous. Therefore, in order to eliminate interference it is important to develop statistical models to characterise interference in this frequency range. Using the statistical models, new *adaptive* interference mitigation algorithms can be developed.

While there exist two basic approaches to eliminate RFI: (1) fixed nulling of interference using the antenna array, (2) and switching off highly interfered sub-carriers, there is still the issue of interference detection, characterisation and tracking. These mechanisms form the basis for adaptive interference cancellation algorithms which are to be investigated. New research is required to develop such efficient RFI mitigation algorithms. One possible and interesting approach could be the use of *Echo-state Networks* (ESN) for this purpose which has been developed at the IU Bremen.

In addition, the polyphase filterbank approach for the beamforming causes interference between sub-bands. This interference causes signal distortion. Therefore, research is required which aims at developing appropriate prototype filters for the antenna beamforming.

5.3.5 **Ionospheric Corrections**

The frequency range which is planned to be used by the LOFAR project extends down into the HF bands. Radio wave propagation at these frequencies is affected by the Earth's ionosphere (Sect. 4.3.2). The diffraction of radio waves is proportional to the inverse of the squared operation frequency. This means that these effects are most pronounced at the lowest frequencies used by LOFAR. In particular, potential disturbance of such measurements are due to, for example, ray bending, phase and group path delays, Faraday rotation, absorption, and phase and amplitude scintillations.

It is envisaged that these effects need to be investigated and quantified by a special feasibility study. This study should also include investigations how these potentially detrimental effects could be eliminated or ameliorated by means of developing and applying sophisticated methods, preferably in quasi-real-time mode. There exists deep experience in Germany on the ionosphere effects on radio wave propagation, which resides in the present and former EISCAT user community.

EISCAT is the European Incoherent Scatter Scientific Association operating radars in northern Scandinavia for studies of the Earth's atmosphere, ionosphere and magnetosphere. German scientists have, in international collaboration, valuably contributed to this field direction and have experimentally and theoretically studied the scattering and propagation of radio waves in the ionosphere. The expertise of these scientists will be essential in understanding the influence of the ionosphere and in interpreting LOFAR observations.

6 Teaching and Training

Astronomical, and in particular radio-astronomical, interferometry is both, a fundamental and complex concept in scientific imaging. Resting upon the principles of Fourier optics, radio interferometry and aperture synthesis bear a large conceptual overlap with a manifold of scientific research and engineering branches, reaching into fields like radar techniques and telecommunication (“IT”), tomography, geodesy, seismography, and image reconstruction in general (e.g. archaeology). A thorough comprehension of synthesis imaging hence provides a firm basis to gain expertise in a variety of modern branches of fundamental and applied research. A natural consequence is that synthesis imaging has had a significant impact on developments in other research areas. In radio astronomy, technological advancements are driven by the rapidly increasing demands on the performance of digital correlation, owing to the bursting speed and volume of the data streams. Extension of interferometry to the low-frequency (LOFAR) and to the mm/submm (ALMA) regime as well as the quest for very large baselines (VLBI) necessitates even larger efforts both, in hardware technology as well as on the software side.

These considerations immediately illuminate the significance of a thorough and comprehensive training of students being educated in the field of (radio) astronomy. The quality of this education lives and dies with the presence or lack of facilities to gain practical experience. Teaching interferometry in the classroom is the first important step towards a solid understanding of this complex subject. However, in order to gain the expertise required for an optimum exploitation of the data products or even for participation in technical developments in this field, practical training is indispensable. Radio interferometry is a prime example for “learning by doing”.

With a LOFAR station near at hand, students will have the unique opportunity for a thorough practical training using a complex and versatile, new-generation instrument doing radio synthesis imaging. With its widespread distribution of stations, LOFAR will provide this scope to a large number of training centres and institutions, which must not be restricted to astronomy. The interdisciplinary aspect of radio synthesis imaging pointed out above makes the proximity of (a) LOFAR station(s) rather attractive for students of physics and engineering sciences in general (e.g. polytechnics and technical universities).

Since we have stepped into the era of information technology already at the end of last century, the “confrontation” with information technology naturally happens at the school age. High-school pupils generally have a sufficient background in mathematics and physics to comprehend the basics of wave reception on the one hand, and (digital) signal processing on the other. LOFAR will be an ideal instrument to convey to the interested young generation how an optimum combination of astronomical instrumentation with modern digital communication can be furnished.

Astronomers and educators at all levels notice the interest of the general public in astronomical research and it can be expected that this will be true for results obtained with LOFAR, too. Astronomy is also recognized in schools as one of the main vehicles to motivate students for fundamental questions in natural sciences, from the simple mechanical problems of planetary motions to effects of general relativity close to black holes or the relation of nuclear fusion technology to the energy production in stars. While in optical astronomy the multitude of smaller telescopes allows to provide access to dedicated research-class telescopes for schools and undergraduate students, the situation in radio astronomy is different, partly due to the much smaller number of available telescopes and partly due to the more difficult process of *image* formation. The option to have several independent beams with LOFAR now offers the chance to provide access to the radio sky through one such beam for public outreach, students, and schools.

Therefore, in addition to existing curriculae in astronomy, education and training towards an optimum use of LOFAR requires more specialized modules in interferometry as well as courses providing the scope for the interdisciplinary applications. Dedicated centres formed by institutions with relevant expertise will provide the platforms for joint efforts in graduate education and postgraduate training, e.g. in international graduate schools or training networks.

LOFAR as an international project also offers a truly European perspective for education and training of students and young researchers. Jointly run international institutions in astronomical research have traditionally been used as an ideal training ground for future generations of observational astronomers. Already for decades the fellowship and PhD programs at ESO and JIVE are recognized and prestigious and in recent years the international mobility of young researchers is significantly supported through several EU programs. The international LOFAR collaboration will certainly also provide a fruitful environment stimulating the exchange of young researchers. ASTRON already now offers up to 10 spaces for the temporary training of LOFAR related PhD projects.

7 Organization

7.1 The GLOW Consortium

This *White Paper* has arisen from a series of meetings in which a diverse group of scientists, astrophysicists, solar physicists and electrical engineers has met to define their common interest in a German involvement of LOFAR. These meetings took place at the International University Bremen (9 Feb 2004), at ASTRON in Dwingeloo (22/23 April 2004), at the MPIfR in Bonn (15 Dec 2004), and at the University of Cologne (8 Sep 2005). Groups from the following German institutions participated:

Astrophysikalisches Institut Potsdam

Forschungszentrum Jülich

Forschungszentrum Karlsruhe

International University Bremen

Landessternwarte Heidelberg

Max-Planck-Institut für Astrophysik Garching

Max-Planck-Institut für Radioastronomie Bonn

University of Bochum

University of Bonn

University of Cologne

University of Göttingen

University of Hamburg

ASTRON was present on each meeting with several representatives. ASTRON's international project scientist (Heino Falcke) is also responsible for the contacts to Germany.

The interest, both in the scientific benefits of LOFAR as well as in the running of the telescope itself, was tremendous. Consequently, these groups have decided to collaborate in a consortium named **GLOW** (*German LOng Wavelength*). Under this umbrella a vibrant community has formed with multifarious interests in long wavelength astronomy that had not existed in such an organized form before. The prime goal of this consortium is to coordinate the German LOFAR activities.

7.2 LOFAR Science Network

The LOFAR *Science Network* is envisaged to form a *virtual organization* that concentrates competence in the various fields and administrates a distributed user community with inhomogeneous access rights to the available facilities. The resources are the telescope time, the operational modes for observations, the data storage to buffer the incoming flow of raw data, the computational facilities to process the data, and the data bases for final and public data products. There will be users of the system with a spectrum of different roles as scientists organized in different sub-projects, software developer to build and maintain the data processing pipelines, administrators of the various resources, guests and trainees from schools and universities, and the general public accessing the public archive. The now initiated German *GRID* initiative of the BMBF is going to evaluate, to bundle, and to install the required software and administrative infrastructure to facilitate such *virtual organizations.* The *GLOW* consortium will therefore be one of the first applicants in Germany of this new concept of distributed collaboration and thereby a driver for further development of technology-based organizational tools in scientific projects.

Six institutes are willing to serve as the first "nodes" of the Science Network, with fields of competence as listed below. Further institutes may follow in future. The network has no exclusive right to work on these fields; any German institute is encouraged to participate.

7.2.1 Bochum: Galaxies and galactic halos

The Astronomical Institute at the Ruhr-Universität Bochum has built up expertise in multi-wavelength studies of nearby galaxies with the specific goal to address the role of feed-back processes between star-formation on small scales and properties of the interstellar medium on galactic scales. For the very topical question of the formation of galaxies such processes are of importance to explain the observed mass and size distribution observed in the local Universe from hierarchical clustering. At Bochum, the global properties of all species in the interstellar medium – from diffuse ionized H^+ to the X-ray hot gas – are studied, specifically with regard to their role in the disk-halo connection, the supernova driven exchange of matter between the disk and the halo. This in turn requires to use observational techniques covering all relevant energies - from the of X-ray satellites to radio continuum observations. The latter is of special importance since magnetic fields and cosmic rays contribute to the pressure, as detailed in Sect. 4.1.2. The Bochum group will therefore use LOFAR to complement existing surveys of nearby galaxies with most valuable data at the lowest radio frequencies. LOFAR will allow for the first time to study the population of low energy cosmic rays with sufficient sensitivity and angular resolution.

The Astronomical Institute at the Ruhr-Universität Bochum plans to invest one scientific position into LOFAR.

7.2.2 Bonn/Cologne: Polarization, Galactic radio emission, & AGNs

LOFAR will complement many aspects of Galactic observations as carried out since long with the Effelsberg 100-m telescope of the MPIfR (see Sect. 4.2). Various Effelsberg surveys of Galactic emission including linear polarization have been carried out recently and in the past. The MPIfR Survey Sampler (www.mpifr-bonn.mpg.de/survey.html) provides open access to the maps. Software as well as expertise is available to analyse these large data sets. In general multi-frequency data are needed for a physical interpretation of the various emission components and the radiation transfer in the interstellar medium. Low-frequency Galactic observations with LOFAR are thus a perfect addition to Effelsberg ISM projects and will clearly gain by taking these results into account. LOFAR observations, on the other hand, may well trigger new Effelsberg follow-up observations. The observation and interpretation of polarized emission from the Milky Way and other galaxies, especially concerning magnetic fields, is another main area of MPIfR research (see the *Atlas of Magnetic Fields in Nearby Galaxies* on www.mpifr-bonn.mpg.de).

The MPIfR also has a strong interest in studies of active galactic nuclei (AGN), formation and evolution of supermassive black holes, nuclear activity and its effect on the evolution of galaxies and the intergalactic medium. LOFAR will expand the scope of the current studies to higher redshifts and, in combination with high-resolution observations of centimeter wavelength emission, will provide an excellent tool for studying the earliest stages of supermassive black holes and galaxy formation.

The MPIfR Bonn has already made concrete plans to host a LOFAR station at the site of its Effelsberg 100-m telescope (Fig. 14), which is located about 40 km south of Bonn. The Effelsberg telescope is placed in a valley, shielded by mountain against terrestrial interference and is open to the south. There is a sufficiently large area available to place a LOFAR station on the ground belonging to the MPIfR. When funded the installation of the hardware components can be done on short time scale. Most of the necessary infrastructure like power supply, storage container for the computing equipment and working space in the observatory is already available. This keeps the cost of a LOFAR station at the Effelsberg site lower than that quoted by ASTRON for a typical station. The long distance of 250 km of the Effelsberg station to the central core of LOFAR will increase the angular resolution of LOFAR substantial. It seems essential for the entire project to start the first long baseline test observations during the solar minimum in 2006/2007 for a reduced ionospheric influence on these tests.

The MPIfR is also planning for the necessary fibre link connection to the MPIfR Bonn. From the Bonn area a GByte/sec data transfer to the central processing at Dwingeloo is already possible. The fibre connection from Effelsberg is also needed for the 100-m telescope to participate in the European eVLBI network.

The MPIfR is willing to take over the coordination of German LOFAR observations and data exchange and serve as the German partner for ASTRON. The MPIfR plans to invest one scientific, one engineer and one PhD student position into LOFAR.

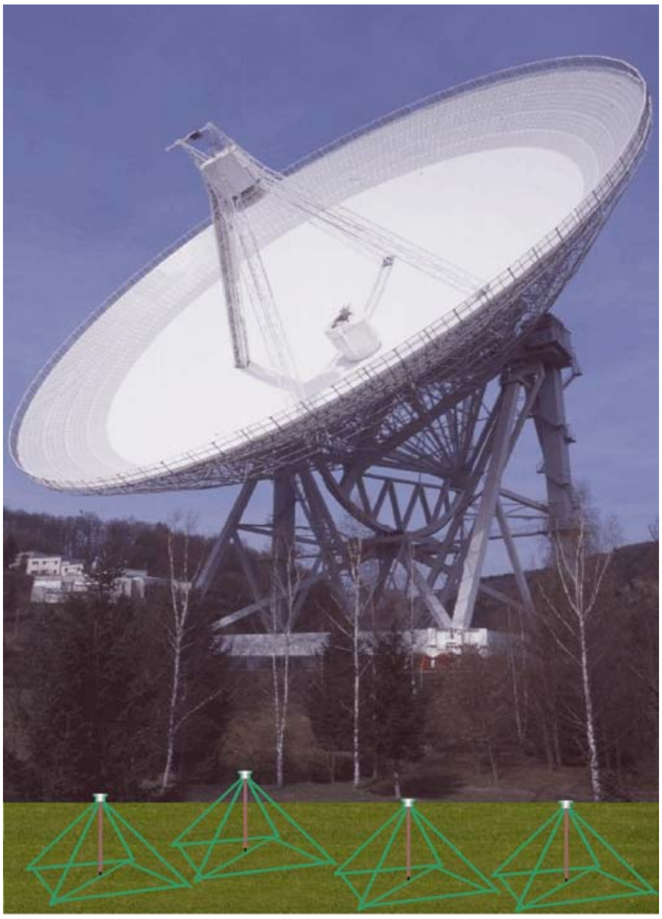


Figure 14: Scheme of a possible location of a LOFAR station in Effelsberg.

The I. Physikalisches Institut of the University of Cologne is actively participating in a broad spectrum of interferometric activities. These include a participation in the *ALMA Regional Centre*, building and supporting instrumentation for near-infrared interferometry at the LBT (the NIR beam combiner LINC/NIRVANA) and the VLTI. The institute is also performing scientific observations using local and global cm- to mm-interferometry arrays (VLBI, EVN, VLBA, Merlin, BIMA, Plateau de Bure). These activities are supported by complementary measurements using HERSCHEL and SOFIA. Central scientific interests that will be linked to LOFAR would be nearby active galactic nuclei (AGNs) and large-scale structures of radio galaxies and their interaction with the galactic and intergalactic medium.

The I. Physikalisches Institut of the University of Cologne plans to invest one scientific position (PhD or Postdoc).

The MPIfR and the I. Physikalisches Institut are going to collaborate closely on LOFAR issues.

7.2.3 Bremen: Large-scale radio structures & Technology

The International University Bremen (IUB) is committed to contribute to the LOFAR project, both scientifically as well as operationally. The astrophysics group has a strong interest in non-thermal radio sources, such as relics and halos, in radio observations of coronal mass ejections from the Sun and in ionospheric studies. The astrophysics group has pioneered cosmological
simulations of radio relics and is investigating the origin of cluster magnetic fields. An ongoing project aims at characterising radio signatures from coronal mass ejections in terms of macroscopic source region parameters and microphysical processes.

Magnetohydrodynamic simulation codes will generate synthetic radio maps to help defining LOFAR observation strategies and identifying key physical processes and parameters in future LOFAR observations. The electrical engineering group is involved in antenna
design and signal processing. The IUB is also willing to establish and maintain a LOFAR station in its vicinity.

The IUB plans to invest:

- 2 scientists on LOFAR-related science
- 2 PhD positions on LOFAR
- computational infrastructure of the Computational Laboratory for Analysis, Modelling and Visualisation (CLAMV)
- organisational infrastructure and support for GLOW

7.2.4 Garching: Cosmology & Software Infrastructure

The Max-Planck-Institut für Astrophysik (MPA) in Garching will provide expertise in theoretical and observational cosmology and will also contribute software infrastructure designed to process and administrate large quantities of data using distributed pipelines.

The MPA is a world-leader in cosmological structure formation and emphasizes its imprint on the radio sky, in particular, the spatial distribution of radio galaxies, and the appearance of radio halos and relics associated with the violent shock waves induced by structure formation. The institute participates in the ongoing Sloan Digital Sky Survey, and this wide-angle mapping of the large-scale structure of the galaxy distribution will be cross-correlated with the radio counterpart delivered by LOFAR. MPA is also a major European centre for the physics of the Epoch of Reionization and of the Cosmic Microwave Background. The latter is represented by the large PLANCK group at the MPA, which also will provide software infrastructure for the GLOW data centres.

The MPA plans to invest:

- 4 scientists on LOFAR-related science
- Software infrastructure and related expertise and support (Process coordinator, data management component)
- The MPA will propose for DFG or MPG funding for a dedicated software support person.

The MPA is also discussing to establish a LOFAR station.

7.2.5 Hamburg: Surveys

The Hamburger Sternwarte offers to host a centre for surveys and to host a LOFAR station. The Hamburger Sternwarte has run two objective prism surveys using Schmidt telescopes: The northern *Hamburg Quasar Survey* (HQS) and the southern *Hamburg/ESO Survey* (HES). Both surveys have taken about 1700 spectral plates, which are completely digitized and provide about 5 10^7 spectra. The archive will become part of the *German Virtual Observatory* (GAVO). The expertise to handle a large-scale survey will go into the proposed LOFAR Survey Science Centre. The observatory is currently running several parallel computers, including the first Apple Xserve G5 cluster in Europe (52 CPUs, 78GB RAM, 2TB disc space) and an AMD Opteron cluster (50 CPUs, 52GB RAM, 3TB disk space). Another 5 Terabyte disk space is provided by RAID servers. Parallel computers and local workstations are connected in the frame of a heterogeneous grid. The expertise available in parallel computing will be used for the Survey Centre.

The Hamburger Sternwarte plans to invest one scientific position and 0.5 technical positions (computer and electronic lab) for LOFAR.

7.2.6 Jülich: Blue Gene Supercomputer & GRID

The mission of the John von Neumann Institute for Computing (NIC) at the Forschungszentrum Jülich (FZJ) is the provision of state-of-the-art supercomputer capacity and GRID services for the computational science communities in Germany and Europe.

In July 2005, the NIC has installed a Blue Gene/L test system with 2048 processors and a peak performance of 5.6 Teraflop/s. Its main areas of application lie in the field of highly scalable problems in (astro)physics, chemistry, biology, and environmental sciences. Furthermore, Blue Gene is a highly efficient data processing system. The FZJ plans to extend the machine in 2006 by a factor of six followed by an upgrade to Blue Gene/P in 2007, aiming at a peak performance of several hundred Teraflop/s (leadership-class). Recently, the NIC became part of a NRW-Dutch cooperation agreement in the field of high performance computing. Furthermore, the NIC strives to become the European supercomputing centre for Germany.

In Germany, the NIC is a leading research institute for Grid middleware technology (15 research positions). NIC coordinates the development of the state-of-the-art Grid middleware UNICORE which is used to access supercomputer resources worldwide; examples are the European DEISA project or the Japanese NAREGI project. The NIC leads the *Kerngrid* activities within the D-Grid integration project, with the aim to set up a flexible and universal prototype Grid infrastructure for computational science and engineering in Germany. Within this project NIC supports the ILDG with a dCache System which is connected to a tape archive with more then 2 PetaByte capacity.

NIC is central to the BMBF-funded *VIOLA* project, enabling 10 Gigabit wide area network technology for computational science.

The NIC plans to invest:

- 1 scientist supporting LOFAR supercomputer applications on Blue Gene
- Grid software and capability computing expertise through the NIC support team
- Supercomputer Capacity on Blue Gene/L and Blue Gene/P.

7.2.7 Karlsruhe: GRID

The Forschungszentrum Karlsruhe aims to support scientific research activities with the GRID computing technologies:
GridKA at the Forschungszentrum establishes a regional data and computing centre to serve as a Tier 1 centre for the four *Large Hadron Collider* (LHC) experiments with approximately 4000 computing nodes and 1 PByte online memory until 2007. While *GridKA* is reserved for the LHC experiments, *CampusGrid* provides a seamless IT environment supporting the research activities in astronomy, physics, bioinformatics, nanotechnology and meteorology. Currently it consists of a heterogenous environment with several vector computers, computing clusters (e.g. a cluster with 32-64 Opteron working nodes) with fast memory systems, high–speed networks (*InfiniBand*) and the middleware for efficient and comfortable usage. In future the extension up to 512 working nodes and the installation of an experimental cell processor system with new parallel processor architecture and broadband communication on a chip is expected.

Grid resources provided by the Forschungszentrum Karlsruhe valuable for LOFAR:

	Value [k€]
64 nodes Opteron cluster with high-speed InfiniBand interconnections	240
Extension to 512 nodes until 2008	1920
Scaleable Oracle Reap Application Cluster	200

The Forschungszentrum Karlsruhe plans to invest one scientific, one PhD student and one engineering position into LOFAR.

7.2.8 Potsdam: Solar physics, GRID, & Virtual Observatory

The Astrophysikalisches Institut Potsdam (AIP) (http://www.aip.de) has a strong interest in many science aspects of LOFAR. In the framework of the GLOW consortium, the AIP is the only German partner with expertise in the area of solar radio physics. The AIP thus intends to establish a centre for coordinating activities concerning solar physics in terms of a *Virtual Solar Radio Observatory*. Furthermore, the AIP offers the infrastructure and area (200 m x 200 m) at the observatory in Tremsdorf to host a LOFAR station. This area represents an excellent topographical location.

The AIP is coordinating the GRID activities of the German astronomical community and is one of the initiators of the *German Astrophysical Virtual Observatory* (GAVO). The AIP runs a vigorous program in computational astrophysics, cosmology, AGN physics, galactic dynamics and star formation. Owing to this broad expertise, the AIP can provide some important synergetic input to LOFAR.

The Land Brandenburg supports researchers in the Berlin-Brandenburg area to establish a *Cluster of Excellence in Geo- and Space Sciences*. Furthermore, it supports activities to provide the infrastructure for an *E-Science Centre for Astrophysics*. LOFAR will be embedded as a key component in this program.

The AIP plans to invest two scientific and 2/2 engineering positions into LOFAR.

7.3 Synergy with other projects

7.3.1 The *Forschungsverbund Astro-Interferometrie*

The following four institutions located in Nordrhein-Westfalen (NRW) have recently formed a *competence cluster* (“*Forschungsverbund*”) *for interferometry*: the I. Physikalisches Institut at the University of Cologne, the Astronomical Institute at the University of Bochum, the Astronomical Institute at the University of Bonn, and Max-Planck-Institut für Radioastronomie Bonn. This cluster combines and coordinates the potential of these institutes in optical, near-infrared, millimeter and cm-radio interferometry. As one of its activities the cluster has formed an *ALMA Regional Centre* (ARC) which is recognized and supported by the *European Southern Observatory*. Instrumentation and scientific observations using cm- and mm-VLBI networks, ALMA, the VLTI and the LBT are the core activities of the competence cluster. Special interest lies in the combination of scientific results at different wavelengths and angular resolutions. The gained experience will have an important impact for the German participations at LOFAR and SKA, the next steps of radio interferometry.

7.3.2 The *D-Grid Program*

The D-Grid program is an initiative of the “Bundesministerium für Bildung und Forschung (BMBF)” to support the development of e-science and Grid middleware for scientific applications in Germany. Starting in autumn 2005 the *D-Grid Integrations Project* managed by the Forschungszentrum Karlsruhe aims:

1. to build a robust, flexible and sustainable technical Grid infrastructure for e-science applications
2. to develop e-science services for scientific communities and
3. to enhance the scientific efficiency.

7.3.3 The *EISCAT_3D* FP6 Program

EISCAT stands for European Incoherent Scatter Scientific Association. It was established more than 25 years ago for studies of the Earth's ionosphere and upper atmosphere in polar regions. The EISCAT observatories, located in northern Scandinavia and on Spitzbergen/Svalbard, operate high power radars with high-gain dish antennas and sophisticated digital radar control, data acquisition and analysis systems.

EISCAT is presently in the stage of preparing a new generation radar system that will apply interferometry, imaging and digital beam forming techniques. A close collaboration on technology and digital signal processing between the communities of LOFAR/GLOW and EISCAT is planned.

8 Estimated Costs of a German LOFAR Engagement

The German contribution should consist of

(i) about six early LOFAR remote stations (planned locations: Bremen, Effelsberg-Bonn, Garching, Hamburg, Jülich, Tremsdorf-Potsdam, and possibly Göttingen) in the first stage ("Phase I") from 2006-2009

(ii) six more stations in "Phase II" (2009-2012)

(iii) a Science Network starting with six network nodes (Bochum, Bonn/Cologne, Bremen, Garching, Hamburg, Potsdam).

While the cost estimates for these contributions are subject to uncertainties, we will attempt to list the costs for each of these positions below.

8.1 Early Remote Stations (Phase I)

Early LOFAR stations are essential for gaining the necessary experience with LOFAR observations and to conduct tests over long baselines with the stations in the Netherlands. Single stations will also allow new kinds of experiments, like all-sky surveys for transients. Furthermore, student education and training has to establish the knowledge for future science with LOFAR and finally the SKA.

Figure 15: Locations of the LOFAR core near Dwingeloo and the proposed early remote stations. Another station in Garching is under consideration. Plans for a station near Göttingen depend on the future fields of research of the Universitätssternwarte.

The cost of a ***Remote Station*** (estimate by ASTRON from March 2005, see Table 3) consists of the antennas and station electronics (~€ 460k). The station infrastructure (housing, power supplies, etc.) are estimated as ~€ 80k. The manpower needed for test and integration forms part of the station costs (~€ 50k). Local storage and processing costs should be added to this (~€ 30k). The total cost to budget for a Remote Station excluding land and external connections is ~€ 620k. Important subsystems (receiver unit, high band antenna) still have large cost uncertainties.

For that reason a contingency of 10% is used, giving a total of ~€ 686k per station. The cost of land, connection to the power grid and the Wide Area fibre connection are not specified here, since they heavily depend on the local situation. We assume that the land for the station will be provided by the host institutes – some have already allocated land for this.

	unit cost	units	cost (€)	**Total (€)**
Remote Station Subsystems (ASTRON)				
Low Band Antenna (incl. cables)	110	96	10,560	
High Band Antenna (incl. cables)	994	96	95,424	
Receiver Unit	731	192	140,352	
Station Processing	8,057	24	193,368	
Clock and Control	22,156	1	22,156	
Total			**461,860**	**461,860**
Station Infrastructure				
Housing, Power (ASTRON)	77,710	1	77,710	
Network interface	4,000	1	4,000	
Test and integration	50,000	1	50,000	
Local storage and processing	30,000	1	30,000	
Total			**161,710**	**623,570**
Contingency (~10%)				**62,430**
Total Remote Station				***686,000***
Site etc				
Mains supply	p.m.	1	**p.m.**	**p.m.**
Acquisition of land	p.m.	1		
WAN connectivity	p.m.	1		
Total				**p.m.**

Table 3: Cost estimate for a remote station.

Costs for 2006-2009 (Phase I):

Initial investment per station (Table 3): **€ 686,000**

Two engineers to be in charge of the six stations (after 2007): **€ 100,000/year**

Excluding the costs for the data connection and land we envisage for a period of 3 years a total investment of ~ € 5 Million.

Applications for partial funding have already been submitted to different organizations.

8.2 Further development for 2009-2012 (Phase II)

The final aim to reach LOFAR's full sensitivity and resolution is 12 stations in Germany. The costs are another ~€ 5 Million plus € 200k/year for maintenance.

The total investment for the 12 German stations will be of order € 10 Million.

The estimated total costs of the German LOFAR project will be of order € 17 Million.

8.3 Science Network

In order to harness LOFAR observations most effectively and to provide an organisational framework for LOFAR science, it is envisaged to establish a *LOFAR Science Network*. This network should be a highly versatile institution that is distributed over various university institutions and Max-Planck institutes. Regular workshops, a vibrant exchange programme and the use of modern communication will ensure that this network leads to a concerted effort. This structure is not unlike the D-GRID organisation that serves a somewhat similar purpose. The LOFAR science institute will consist of the contributions (personnel and infrastructure) from the participating institutions. As of May 2005 the contributions that could be committed to this project are as follows:

Node	Scientists (full/half)		Technical positions
Bochum	1	-	-
Bonn	1	1	1
Bremen	2	2	-
Cologne	1	-	-
Garching	4	-	-
Hamburg	1	-	0.5
Jülich	1	-	-
Karlsruhe	1	1	1
Potsdam	2	-	1
Total	**14**	**4**	**3.5**

This contribution will be supplemented by the following, centrally financed resources:

6 astronomers (BAT IIa)	6 x 75,000 €
Full-time computer administrator	75,000 €
Central computing facility+ data storage (investment/life time + running costs)	200,000 €
Total costs per year	**725,000 €**

Based on the existing expertise in Germany, the foci of the science network could be, but are not restricted to, the following areas:

- Galaxies
- Polarization, Galactic astronomy, AGNs
- Large-scale structures
- Cosmology & Epoch of Reionisation
- Surveys
- Solar physics

The total costs for the Science Network will be of order € 725,000 per year.

8.4 Long-term development

A low-frequency telescope on the backside of the Moon, concentrating on frequencies around and below 10 MHz where LOFAR stops, would be an ideal choice and a perfect extension of LOFAR. At very low frequencies (<10 MHz) the Earth ionosphere makes astronomical observations impossible and man-made interference is particularly bad below 20 MHz. On the other hand, a low-frequency telescope requires a large area and a ground-based installation. Hence the backside of the Moon - shielded from any artificial interference and with essentially no ionosphere - is the only sensible place where to put such an observatory. The idea has teamed up by the LOFAR team at ASTRON with EADS, Europe's biggest aerospace company. The feasibility of a low-frequency telescope on the backside of the moon has been demonstrated already by past ESA studies. The German LOFAR activities could become the seed for major space initiatives together with the German space industry.

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