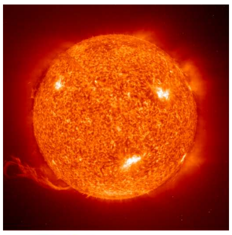

Key Science Project

Solar Physics and Space Weather with LOFAR

Leibniz Gemeinschaft

AIP

Abstract

The Low Frequency Array (LOFAR) is a novel radio telescope that operates in the frequency range of 30 – 240 MHz. It is a radio interferometer consisting of about 50 stations that are distributed in a central core at Exloo in the Netherlands and remote stations across central Europe. LOFAR's basic working principle is digitizing the antenna signals at each station and sending them to the Central Processing System (CPS) at Groningen. This novel approach provides LOFAR with a high flexibility, and the possibility of directing up to eight beams at different sources in the sky so that it can be used by a corresponding number of concurrent users. A remote station is planned by the AIP at Bornim near Potsdam. Solar radio radiation in LOFAR's frequency range emanates from the upper corona. The solar activity manifests itself in flares and coronal mass ejections (CMEs) that are strong radio sources. These phenomena of the active Sun can have a strong impact on the terrestrial environment, that is commonly referred to as Space Weather. LOFAR observations of CMEs as they are launched into interplanetary space enable predictions whether they might hit Earth. Different solar observation modes are proposed in this paper which include continuous monitoring of solar activity, the identification and flexible responses to radio bursts, as well as joint observation campaigns with other instruments. The tasks of the Solar Science Data Center that is to be established at the AIP will additionally be introduced.

05.12.2007

1 LOFAR — The LOw Frequency ARray

1.1 Introduction

LOFAR, the LOw Frequency ARray, is a new interferometric radio telescope that covers the frequency range of 30 – 240 MHz. It is currently being constructed by ASTRON at Exloo in the Netherlands. In its first construction phase, LOFAR consists of sensor fields that are arranged in a 2 km diameter compact core located at Exloo with about 20 stations, and 20 remote stations that provide baselines of up to 100 km.

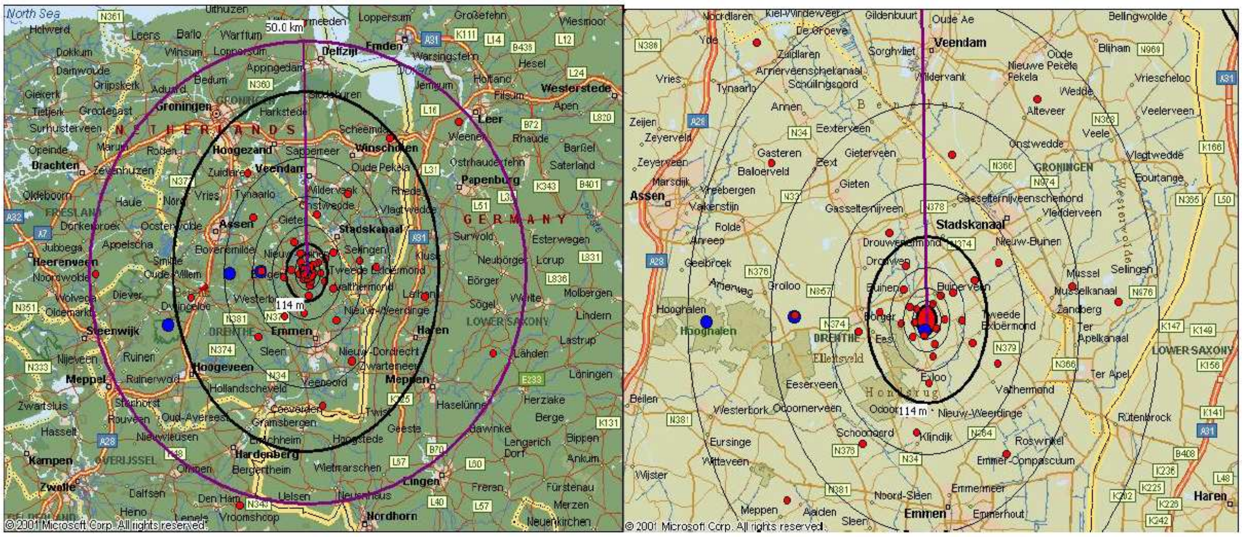

Figure 1: LOFAR central core and remote station configuration.

Figure 1 shows the configuration of LOFAR's central core and remote stations. Additionally to these remote stations that are planned by ASTRON, LOFAR is open towards further remote stations all over central Europe. Such remote stations provide longer baselines, e.g. Exloo – Potsdam = 450 km, and thus increase the angular resolution of the radio telescope.

1.2 Interferometry with LOFAR

In "classical" interferometry (Kraus, 1986) an array of radio dish antennae is oriented towards the observed source in the sky. The antenna signals are correlated with well-defined delays, and an image is synthesized. With this setup, only a single source can be observed at a certain frequency at the same time. LOFAR pursues a different approach that offers an unprecedented flexibility and versatility. LOFAR uses arrays of simple dipole antennae that essentially cover the whole sky. At each LOFAR station, the antenna signals are digitized, preprocessed and sent to the Central Processing System (CPS) at Groningen where the signal correlation and further data processing, e.g. image synthesis, is done. The results ("data products") are sent to the LOFAR users and their respective Science Data Centers.

Thus, the radio interferometer LOFAR is basically realized in software. The price for this approach is demanding computing resources at the CPS and the necessity of fast data connections from the antennae fields. Since these are available today, the LOFAR setup offers multiple advantages. First, it is possible to correlate the signals with different phase delays at the same time and to form multiple beams that point towards different sources in the sky. Thus, LOFAR can be used by different observers simultaneously. Furthermore, LOFAR is highly flexible. Observing programs can be changed quickly by readjusting data processing parameters and the programming of the CPS. Finally, buffering of the raw data enables LOFAR to "look back" in time and point one of its beams e.g. towards a transient event, and study its nascent stage after the burst has been detected by LOFAR or another instrument.

1.3 Sensitivity and angular resolution

The large number of LOFAR antennae results in a large collecting area of up to 1 km^2 and yields an unprecedented sensitivity. The remote stations in Europe provide long baselines that are necessary for a good angular resolution of the interferometer.

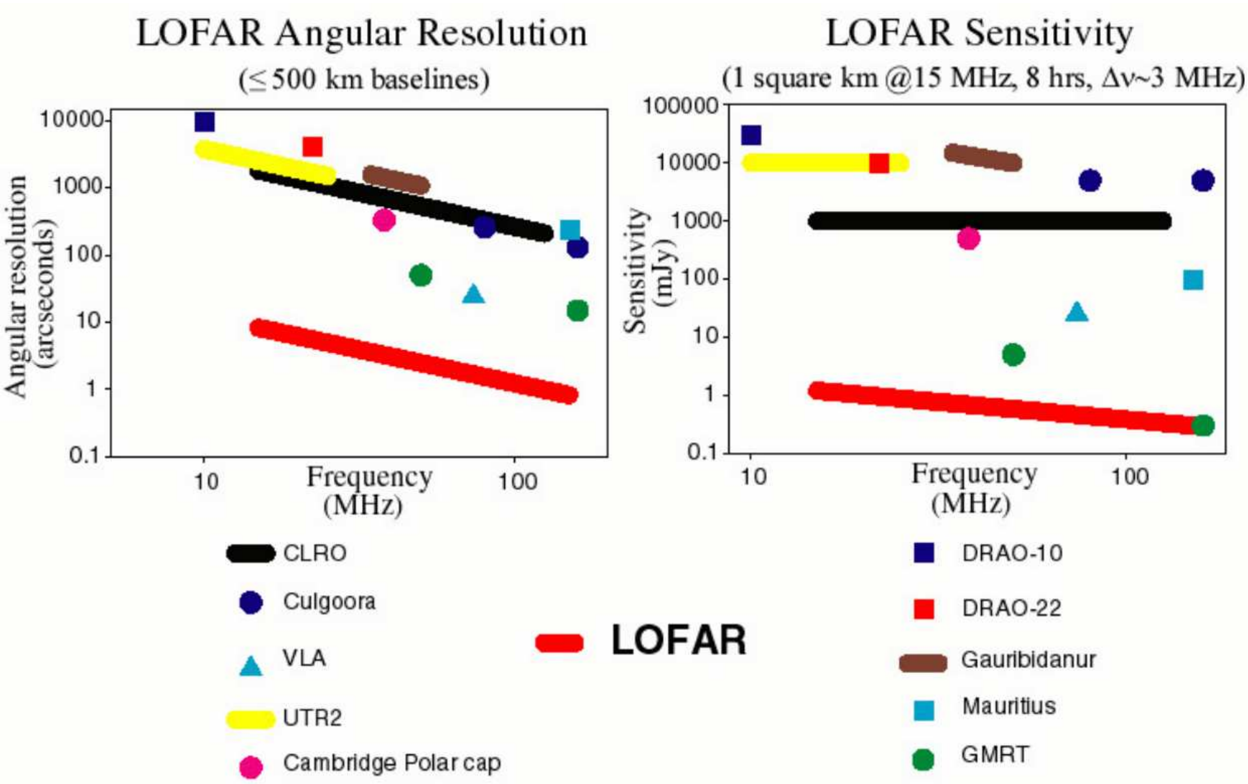

Figure 2: Comparison of LOFAR capabilities with those of previous facilities as a function of frequency. The angular resolution (left) and the sensitivity (right) of LOFAR are shown in red together with those of previous low frequency radio survey facilities. From de Bruyn et al. (2002).

Figure 2 displays LOFAR's angular resolution and sensitivity in comparison with those of existing low frequency radio telescopes. It is evident that LOFAR will improve both quantities by more than two order of magnitudes in the frequency of 30 – 240 MHz and thus paves the way for new discoveries in radio astronomy.

1.4 LOFAR remote station at Bornim near Potsdam

LOFAR remote stations are to be set up at isolated locations sufficiently far away from RFI (radio frequency interference) sources like trains, highways, high voltage lines, industrial plants etc.. A remote station consists of two fields of dipole antennae for high (120 – 240 MHz) and low (30 – 80 MHz) frequencies, respectively. The antennae are spread out over an area of 60 m x 60 m for the low and 50 m x 50 m for the high frequencies. The gap in the frequency coverage avoids the troublesome FM radio range.

Figure 3: LOFAR low (left) and high (right) band antennae.

Figure 3 shows a typical LOFAR low-band antenna field, and a high-band antenna tile. For the low frequency band, dual polarization antennae are used with dipole arm lengths of 1 m and a total height of 1.4 m. For the high band antennae, 4 x 4 dipoles with arm lengths of 0.7 m and a height of 0.60 m are arranged as “tiles”. A remote station contains about 100 antennae of each type. The antenna signals are preprocessed at the station and sent to the CPS. The required data rate is about 2 Gbit/s, thus a fast data link must be provided to the station despite its isolated location. The system of remote stations in the Netherlands that is planned for the first construction phase is shown in Fig. 1.

German institutes interested in LOFAR like the AIP or the MPI for Radioastronomy at Bonn have recently founded the GLOW (German LOng Wavelength) consortium. Figure 4 shows the planned sites of LOFAR remote stations in Germany. The AIP’s site next to the Leibnitz Institute for Agricultural Engineering Potsdam-Bornim is a promising location that meets the requirements set up by ASTRON for a LOFAR remote station, like minimum distances from man-made radio noise sources, size and topography of the area, accessibility, and unobstructed sky view.

Figure 5 shows an aerial view of the AIP’s site at Potsdam-Bornim together with the locations of the antennae fields of the LOFAR station. First talks to local authorities about the permission to set up a LOFAR station have been conducted successfully. Electrical power and a fast data link are provided through the neighboring Institute for Agricultural Engineering.

Figure 4: Sites of planned LOFAR remote stations in Germany.

Figure 5: Aerial view of the planned antennae fields of a LOFAR remote station at Bornim near Potsdam. The buildings left of the station belong to the Leibnitz Institute for Agricultural Engineering Potsdam-Bornim.

2 LOFAR observations

This section provides an overview of the LOFAR data processing and transport system from the remote stations to the Central Processing System (CPS), especially the necessary reduction of the data to a bandwidth of about 2 Gbit/s that can be handled with today's technologies. This data reduction has implications on LOFAR users that have to be considered when planning LOFAR observations.

2.1 Remote station data processing

The basic principle of LOFAR measurements is to digitize the signals of all station antennae and to send the data to the Central Processing System (CPS). There, the data are further processed. The observed sources in the sky are selected through beamforming, i.e. correlation with proper phase delays between the signals of different antennae. A variety of observation modes can be employed to study the beams, e.g. obtaining time series or image synthesis. The principle of performing all data processing and analysis in a computer offers LOFAR great flexibility. Changing the observed frequencies or moving an observation beam to another source in the sky only requires the change of some parameters for the data processing that can be quickly done, and even the introduction of new observation modes is possible through adjustments of the software running on the CPS. Any LOFAR observer could use his beam independently from the other concurrent users.

However, if LOFAR had the digitized information from all antennae at all stations available, each remote station would produce a data rate of several tens of Gbit/s. This neither can be transmitted from most locations to the CPS, nor can the CPS handle the combined data flow from all stations. Thus, some data processing and reduction has to be performed on the station level. The following processing steps are foreseen for each LOFAR remote station:

- Each receiver unit is connected to a low (30 – 80 MHz) and a high band (120 – 240 MHz) antenna. The receiver can only process the signals from one of these antennae.
- The antenna signal is digitized and Fourier-transformed with a bandwidth of 100 MHz, that covers the low band completely and most of the high band. This 100 MHz wide frequency band is subdivided into 195 kHz bands.
- Only a total bandwidth of 32 MHz, i.e. 160 of the 195 kHz bands, can be further processed. The rest of the information is lost. These 32 MHz can be distributed among up to 8 different beams. Thus, it is possible to define a single beam with a total bandwidth of 32 MHz, or 8 beams with a total bandwidth of 4 MHz each, or any combination in between.
- Now up to 8 station beams are formed by correlating the signals of all antennae on the station with phase delays that correspond to the specified direction in the sky.
- The station beam information is finally sent to the CPS

The result of this data processing is up to 8 dual polarization station beams with a total bandwidth of 32 MHz. The required data rate towards the CPS is about 2 Gbit/s and thus well within the range of today's possibilities, e.g. through optical fibers or a radio link from the station.

At the CPS, the data from all stations are collected and further processed according to the needs of the different LOFAR users. An important step is the data calibration that is also done at the CPS by regularly pointing towards a set of reference sources, e.g. quasars, and adjusting an ionospheric model in order to yield agreement between the calibrated data and the reference sky model.

2.2 Implications for LOFAR users

The necessity of a station data processing has important implications for the users of LOFAR. If the LOFAR data processing was as simple as outlined in the beginning of the previous subsection, each users could select observation objects, frequencies, and observing modes according to his needs and entirely independent from other users, except for the limitations of total computing power and data bandwidth. But since the data flow from the remote stations is limited to 2 Gbit/s, some information necessarily is lost. This leads to some limitations for LOFAR users, and to some dependencies between concurrent observing programs:

- The formation of station beams limits the field of view of each beam. For a station with a size of $L = 200$ m and a wave frequency of 150 MHz (wavelength $\lambda = 2$ m), the diameter of the station beam can be estimated as $2 \cdot \lambda/L = 2 \cdot 10^{-2}\,\text{rad} = 2.2^\circ$. This is not a strong limitation, e.g. it is shown below that this does not limit solar applications. All sky surveys that need large fields of view will mainly use the central core of LOFAR that is not subject to station beam limitations.
- Since the antenna receivers are connected to either the low or the high band antennae, observations in either frequency range have to be coordinated with other LOFAR users. This has to be considered in LOFAR's observation planning.
- A user that operates one of 8 observation beams is limited to a total bandwidth of 4 MHz, i.e. 20 subbands of 195 kHz width each. But since this selection is performed by the station data processing and realized in software, flexible and fast changes of the subbands are possible.

At the CPS, the 195 kHz bands are further subdivided into 1 kHz subbands, that define LOFAR's spectral resolution. The temporal resolution is consequently limited to 1 ms. The integration times are also noteworthy. For sensitivities of the order 1 mJy as displayed in Fig. 2, an integration time of 1 hour is necessary. For the Sun as a bright radio source, much smaller integration times are sufficient. The intensity of the quiet Sun's thermal radiation at 40 MHz is about 200 Jy, and it increases with increasing frequency. Thus, even under quiet solar conditions the minimum integration times are not much longer than LOFAR's temporal resolution.

To summarize, the necessary station data processing imposes on LOFAR users the restriction to a 4 MHz section of the total spectrum that is available at the same time, and it requires a coordination with other observers on the choice of the high or low frequency band.

2.3 LOFAR Key Science Projects

The new radiotelescope LOFAR has a wide range of applications that cover many scientific objectives. Science with LOFAR is organized in "Key Science Projects" that address certain topics. In the Netherlands, the following Key Science Projects currently are defined:

- Epoch of Reionization of the Universe
  - Determination of the epoch of reionization
  - Information on the sources of reionization (UV radiation of hot stars or X-rays from black holes)
  - Measure the power spectrum of fluctuations as a function of redshift
- All-sky surveys
  - Observations with large field of view
  - Star forming galaxies, AGN, clusters, etc.
  - More than 100 m. new sources expected to be found
- Detection of transient events
  - Multiple station beams cover a significant part of the sky
  - Daily monitoring of a large fraction of the sky
  - Flare stars, X-ray binaries, supernovae, gamma ray bursts, etc.
- Cosmic ray showers
  - Detection of cosmic rays through gyrosynchrotron emission of electrons and protons in Earth's atmosphere
  - Derivation of air shower properties
- Solar Physics and Space Weather with LOFAR
  - Monitoring of the solar activity
  - Quick response to solar radio bursts
  - Observations of coronal mass ejections as they are launched into space, and estimates of their potential impact on Earth: **Space Weather**

But these key science projects are not exclusive. LOFAR science covers the early universe, the structure and evolution of galaxies, galactic astronomy and supernova remnants, as well as solar and stellar physics, stellar-planetary systems, especially the Sun-Earth system, and ionospheric physics.

3 Solar radio astronomy with LOFAR

The flexible and versatile radio telescope LOFAR is very well suited for solar radio astronomy. The Sun as our closest star is an intense source of radio waves. The already strong thermal radiation of the quiet Sun is superimposed with intense radio bursts that are associated with phenomena of the solar activity like flares and coronal mass ejections (CMEs).

The theory of space plasmas provides the tools for investigating the physics of the source regions of solar radio emission as it is observed on Earth, e.g. by LOFAR. Thus, radio waves can be used to investigate the physical parameters within flares and CMEs, and to gain insight into their mechanisms. Radio waves can be generated by manifold processes in these manifestations of solar activity. Basically, energetic electrons are needed for non-thermal radio emission. The energetic electrons excite high frequency plasma waves, e.g. Langmuir or upper-hybrid waves, which convert into electromagnetic (radio) waves. Thus, the radio waves are emitted at the local electron plasma frequency

$$f_{pe} = \frac{1}{2\pi}\sqrt{\frac{N_e e^2}{m_e \epsilon_0}} \qquad (1)$$

and/or its harmonics (Melrose, 1985). N_e is the electron number density of the plasma, and m_e the electron mass. For instance, electrons can directly be accelerated in a flare and then be injected into magnetic field geometries that are open towards the higher corona or interplanetary space, leading to the formation of type III radio bursts, see (Suzuki & Dulk, 1985) for a review.

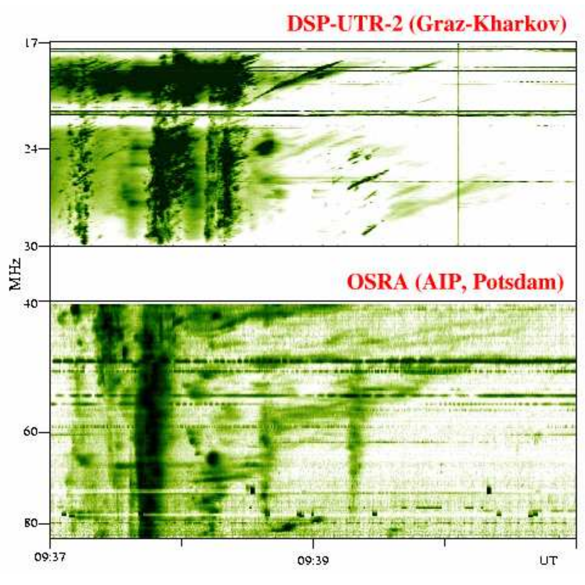

Figure 6: Joint observation of UTR-2 and the Tremsdorf solar radioobservatory of the solar radio event of 6 July 2002 (Mel'nik et al., 2004).

Figure 6 presents an example for a joint radio observation of the solar event of 6 July 2002 by the DSP in Kharkov, Ukraine, and the radio observatory in Tremsdorf (Mel'nik et al., 2004). The frequency range covers LOFAR's low band (30 – 80 MHz). The figure clearly shows type III bursts as features with very high frequency drift rates, i.e. nearly vertical lines. Another source of radio radiation are shock waves, which are produced either by a flare or a CME. If such a shock wave is able to accelerate electrons up to supra-thermal velocities, it can emit radio waves via the mechanism described above (Mann, 1994). These radio waves manifest themselves as a type II radio burst in dynamic radio spectra with lower frequency drift rates than the type III bursts. Type II bursts can also be identified in Fig. 6.

3.1 Analysis of solar low frequency radio radiation

It has already been noted that the frequency of solar radio radiation corresponds to the local plasma frequency, Eq. (1) or its harmonic at the source region. It is noteworthy that the plasma frequency only depends on the electron number density and natural constants. It is independent of the magnetic field and electron or ion temperatures. Due to this connection, the electron density at the source is immediately known whenever solar radio radiation is received.

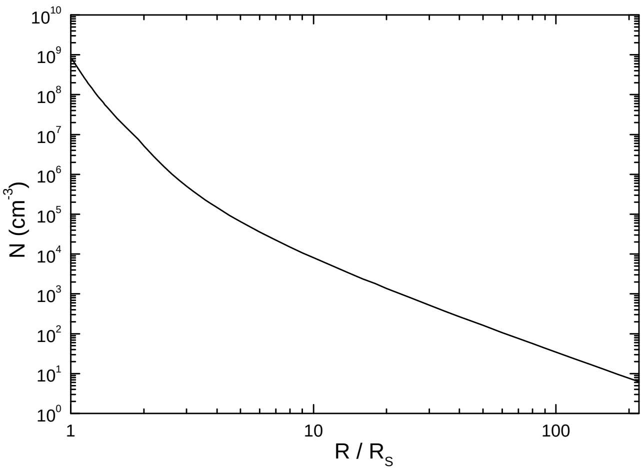

Figure 7: Heliospheric density model of Mann et al. (1999)

In order to determine the source's height in the solar corona, a heliospheric density model is needed that provides information on the variation of the electron density with distance from the Sun. Figure 7 shows the heliospheric density model of Mann et al. (1999). R is the distance from the solar center. With this model, frequencies can now be converted into solar distances. The model covers the whole corona, the transition into the solar wind and the interplanetary space up to 1 AU. With the density model, the plasma frequency can now be calculated as function of the solar distance:

f [MHz]	30	40	70	100	170	240
$R/R_\odot$	1.80	1.68	1.48	1.37	1.24	1.17

Table 1: Frequencies in the LOFAR range and corresponding solar distances according to the density model from Fig. 7

Table 1 clearly shows that the source regions of radio waves in LOFAR's frequency range of 30 – 240 MHz are located in the upper corona with a minimum value of $R = 1.17\,R_\odot$ for the highest frequencies, that approximately corresponds to a height of 120,000 km above the photosphere.

With the density model at hand, it is also possible to transform the frequency drift rates of solar radio bursts into source velocities. From the definition of the plasma frequency, Eq. (1), it follows that:

$$\frac{df}{dt} = \frac{f}{2N_e}\frac{dN_e}{dr}V_{Source} \tag{2}$$

With this relation it is possible to investigate the speed and thus energy of electron beams from type III burst drift rates, or shock velocities from type II bursts. Generally, it is now possible to transform dynamic radio spectrograms into coronal height-time diagrams, see e.g. (Warmuth & Mann, 2004) as a review.

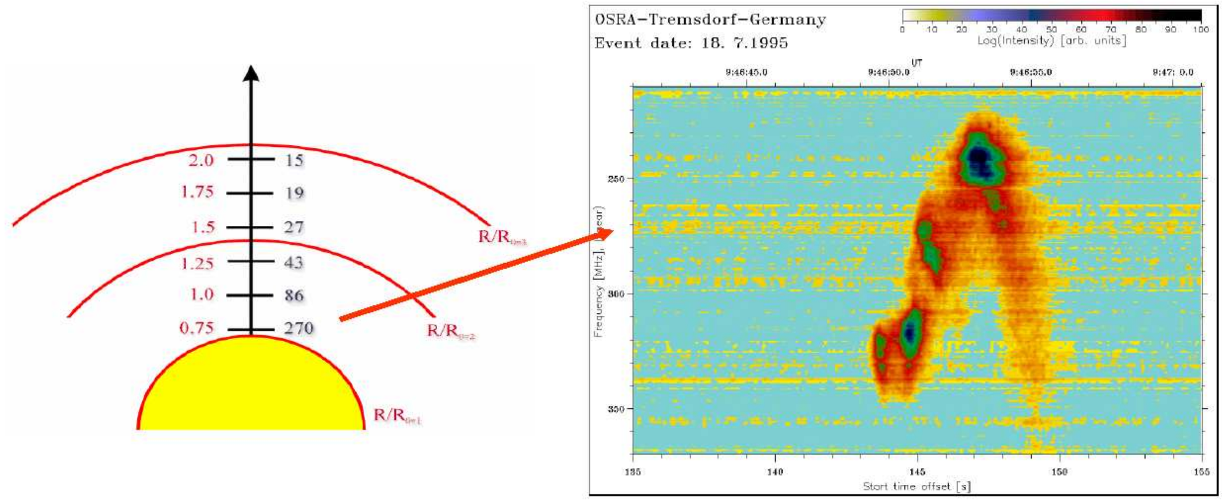

Figure 8: Connection between dynamic radio spectrograms and height-time diagrams in the solar corona.

Figure 8 displays the dynamic radio spectrum of a so-called type U-burst that is characterized by a decrease and a subsequent increase of the emitted frequency. Note that the frequency scale is upside down, since lower frequencies correspond to larger heights in the corona. Within 3 s, the emitted frequency shifts from 340 MHz to 240 MHz, and then increases back to 340 MHz within 2 s. From the coronal density model (Mann et al., 1999) it follows that 340 MHz corresponds to a height of $8.9 \cdot 10^4$ km above the coronal base, and 240 MHz to $1.56 \cdot 10^5$ km. Thus the radio source first moves with a vertical velocity component of $22.3 \cdot 10^3$ km/s upwards and then with $33.5 \cdot 10^3$ km/s downwards. Therefore, this type U burst is regarded as the radio signature of an electron beam traveling along a closed magnetic field line in the corona.

U-bursts are the signatures of energetic electrons that have been injected into a magnetic loop by a solar flare near a loop footpoint. The electrons propagate upwards along the loop, reach the loop top, and return back to the low corona at the other footpoint. The above source velocities correspond to electron energies of several keV, and the velocity difference between both sides of the loop is due to a skewness of the loop, i.e. different angles of the magnetic field towards the normal to the solar surface on both sides of the loop.

3.2 Solar observations with LOFAR

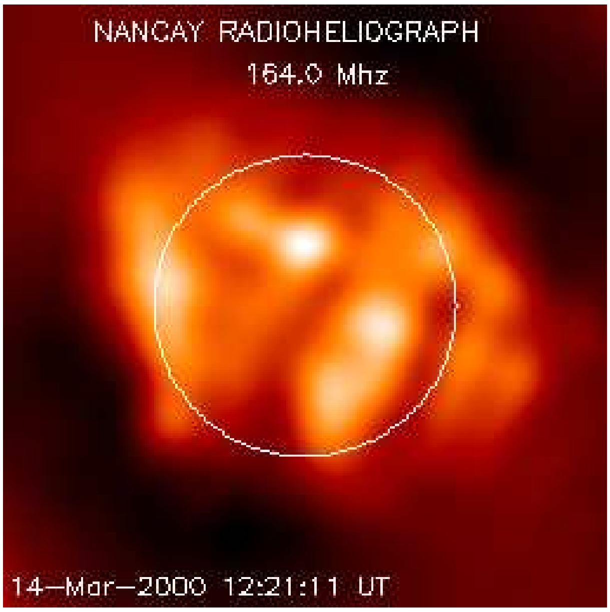

Figure 9: Nançay radio heliograph image of of 14 March 2000.

The solar radio data presented so far have been recorded with radio telescopes like Tremsdorf or UTR that do not have a sufficient spatial resolution to observe any details of the Sun. The Sun is just a point source to them. At low frequencies, only a few instruments observe the Sun with relatively coarse resolution, e.g. the radioheliograph at Nançay, France, (Kerdraon & Delouis, 1997) is operated on selected frequencies ranging from 150 – 432 MHz and yields an image resolution of up to 1', see Fig. 9. LOFAR will dramatically improve the situation with routine observations, and will expand the frequency range down to 30 MHz.

Figure 10 shows an EUV image of the solar corona that was recorded by the EIT instrument onboard the SOHO spacecraft on 11 September 1997. The resolution of the image is approximately 2". Although LOFAR comprises baselines long enough for a similar resolution in the meter wavelength range, scattering of the radio waves in the solar corona limits the image resolution to a few 10". But with simultaneous observations at several frequencies, it will be possible to probe different heights in the corona. These heights reach up to the transition from the corona into the solar wind due to LOFAR's low-frequency coverage. Thus, LOFAR will reveal structures in coronal radio sources that are yet unexplored.

When planning LOFAR full Sun imaging, the limited field of view that is available to a each user has to be taken into account. In Section 2.2 it has been noted that the preprocessing of the data at the LOFAR remote stations limits the station beams to a diameter of $2 \cdot \lambda/L$, with λ being the wavelength and $L = 200$ m the station size. For LOFAR's low frequency limit of 30 MHz, i.e. $\lambda = 10$ m, the beam diameter is 5.7°. From Table 1 it follows that this corresponds to a largest accessible height of $r = 1.8\,R_\odot$ in the corona. Since $1\,R_\odot$ appears from the Earth under an viewing angle of about 0.5°, this radio Sun has an angular diameter of 1.8° and thus fits well into the 5.7° beam. For LOFAR's high frequency limit of 240 MHz ($\lambda = 1.25$ m), the corresponding numbers are a station beam diameter of 0.72° and a coronal height of $r = 1.17\,R_\odot$ that corresponds to an

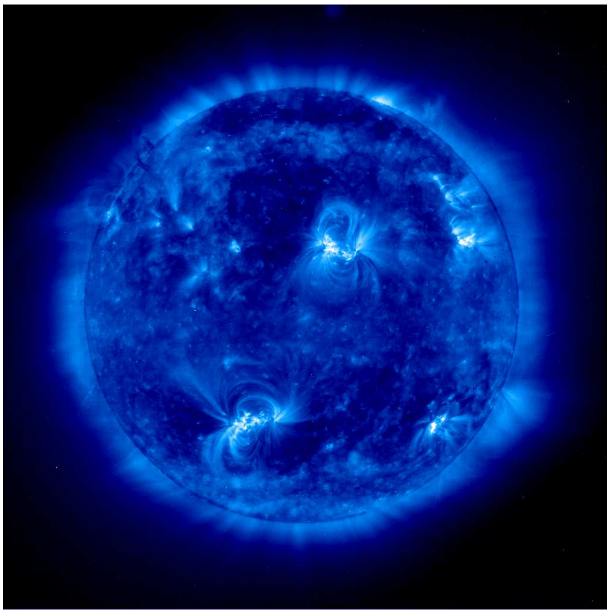

Figure 10: The Sun in the light of the resonance lines of eight and nine times ionized iron (Fe IX/X) at 171Å that is emitted at a temperature of 10^6 K. The image was recorded on 11 September 1997 by the EIT instrument onboard the SOHO spacecraft.

angular diameter of the radio Sun of 0.59°. So it can be concluded that the field of view limit is not critical for LOFAR solar observations.

It is also important to assess the memory demand for LOFAR full Sun images. For station beams with diameters of up to 5° and a spatial resolution of a few 10", it follows that image sizes of 1000×1000 pixels are a reasonable estimate. A 16 bit sampling results in 2 Byte/pixel, and if the polarization is characterized by the 4 Stokes vectors, the total image size will result in:

$$10^6 \,\text{pixel} \times 2 \,\text{Byte/pixel} \times 4 = 8 \,\text{MByte per image}$$

But this assessment does not include any kind of data compression. Generally, image compression algorithms can reduce file sizes by an order of magnitude without (e.g. GIF) or with minimal (e.g. JPEG) loss of information. Thus, image sizes of less than 1 MByte are reasonable.

3.2.1 Monitoring with LOFAR

The high flexibility of the LOFAR instrument offers several different modes for solar observations. Some examples are presented in the next subsections. A standard mode will be continuous monitoring of the Sun. This mode will allow for studies of the long-term evolution of solar active regions and provides information on the precursors of solar radio bursts, flares, and CMEs. Optical solar observatories routinely monitor the Sun, e.g. the Kanzelhöhe Solar Observatory (KSO), Austria, with an image cadence of 1 image per minute.

With LOFAR it will be possible to produce solar images at different selected frequencies in regular intervals and to archive the images. Since either the low (30 – 80) MHz or the high band (120 – 240) MHz is available at the same time, see Sect. 2.2, two sets of frequencies for the two bands have to be defined. The resulting data volume can be easily estimated. It has been found in the previous subsection that a LOFAR image of the Sun requires 8 MByte uncompressed. One LOFAR beam will be available to solar observations for 8 hours per day. If the Sun is observed in 5 different frequencies with an image cadence of 1 minute, the daily data require:

$$8\,\mathrm{h} \times 60\,\mathrm{images/h} \times 5 \times 8\,\mathrm{MByte/image} = 19.2\,\mathrm{GByte/day}$$

Again, this number only refers to uncompressed data, and it can be reduced by an order of magnitude easily. Thus, after compression the data rate produced by such a monitoring mode corresponds to 1 CD/day, or one state-of-the-art harddisc per year. Thus, archiving the data and making them accessible to the scientific community through the Solar Science Data Center is not a problem.

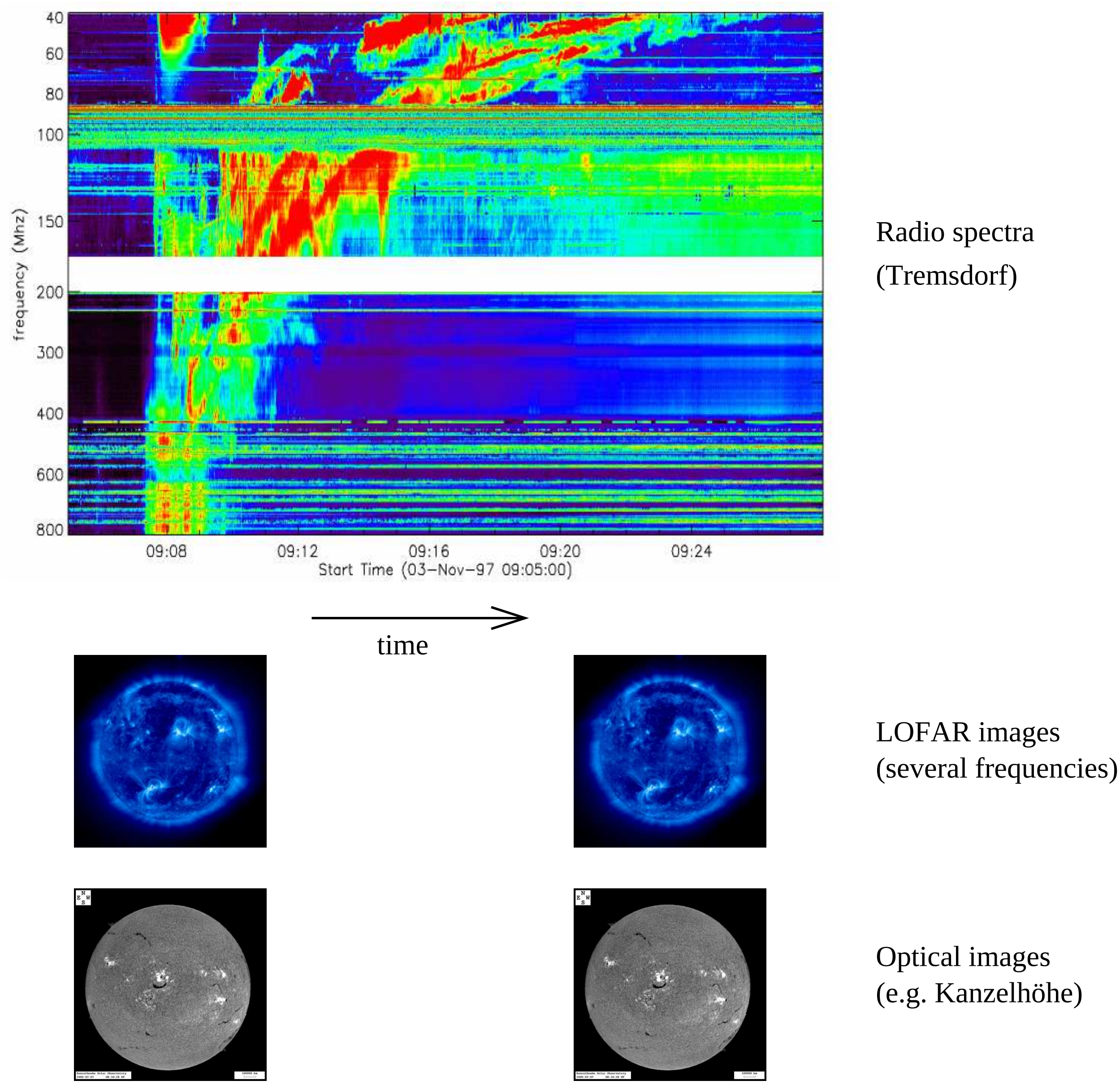

Figure 11: Sketch of a solar monitoring data analysis interface that combines the sequence of LOFAR images with solar images in other wavelengths, e.g. optical, and dynamic radio spectra e.g. from the Tremsdorf observatory.

These sequences of solar radio images can be ideally combined with images in other wavelengths, e.g. optical, and solar radiospectrometer data that provide no spatial resolution but cover a wide frequency range. Figure 11 shows a sketch of such an analysis interface. With such analyses it is possible to investigate solar active regions in different layers of the atmosphere and to study the source regions of solar radio bursts with high spatial resolution (from LOFAR images) and high frequency coverage (from radiospectrometer data).

3.2.2 Response to solar radio bursts

Apart from routine monitoring of the Sun, LOFAR's flexibility can be used to trigger automatic responses to transient phenomena like solar radio bursts. This first leads to the task of identifying a burst in the radio data. Such a trigger mechanism is called 'burst bell". A method analogous to the burst trigger mode of the Burst and Transient Source Experiment (BATSE), see (Aschwanden et al., 1995), can be implemented. The method is based on calculating the standard deviation σ of the count rates recorded by BATSE within a previous time window. If the count rate increases by more than $5.5\,\sigma$ in two energy channels, this is considered as a burst.

For LOFAR, a "burst bell" can work in a similar way. Depending on the current availability of the low or high band, the total power on the frequencies 40 MHz and 70 MHz or 150 MHz and 200 MHz can be monitored. The power is averaged over a time window of e.g. three minutes that is sufficiently long compared to the growth times of solar radio bursts, and the standard deviation σ is calculated. If the power exceeds the average by more than e.g. $5.5\,\sigma$ on both frequencies, this is considered as a solar radio burst. Once a burst is identified, the "burst bell" serves to purposes:

- Alert other working groups and other instruments in order to trigger follow-up observations in different wavelength ranges.
- Perform a pre-defined series of follow-up observations with LOFAR in order to study the evolution of the radio source both in frequency and space.

An example of LOFAR observations triggered by the detection of a solar radio burst is a sequence of solar images with high cadence, and with different frequencies that are adapted to the frequency drift of the burst. From the technical description of the LOFAR data processing in Sect. 2.1 follows that this requires a continuous readjustment of the selected frequencies out of the available band. This is controlled by the Central Processing System and can be pre-programmed. Thus, LOFAR's flexibility due the realization of much of the interferometry in software makes it ideal for this task.

Since the source region of radio waves in the LOFAR frequency range between 30 MHz and 240 MHz is located in the upper corona, the observation of solar radio bursts is especially important in the context of studying the release mechanism of CMEs. As soon as a CME reaches supersonic/superalfvénic speed, it drives a shock wave (Mann, 1994) that is capable of accelerating electrons to high energies. These electrons lead to the emission of type II radio bursts (Aurass, 1996). LOFAR observations of nascent CMEs provide spatial information that helps determining the direction of the CME as it heads towards interplanetary space. This helps assessing the potential impact of a CME on Earth. The study of CMEs connects LOFAR observations of solar radio bursts closely with Space Weather research.

3.2.3 Space Weather studies

It has already been mentioned that the phenomena of the active Sun, like flares and CMEs, can have a severe impact on the terrestrial environment. This relationship is usually referred to as

Space Weather. Solar flares accelerate eletrons and protons to high energies. These particles can disturb electronic equipment onboard satellites, and they pose a threat to astronauts in space. Furthermore, flares are strong X-ray sources that influence the ionosphere, and lead to a heating and subsequent expansion of the upper atmosphere that endangers satellites in low orbits due to enhanced aerodynamic drag.

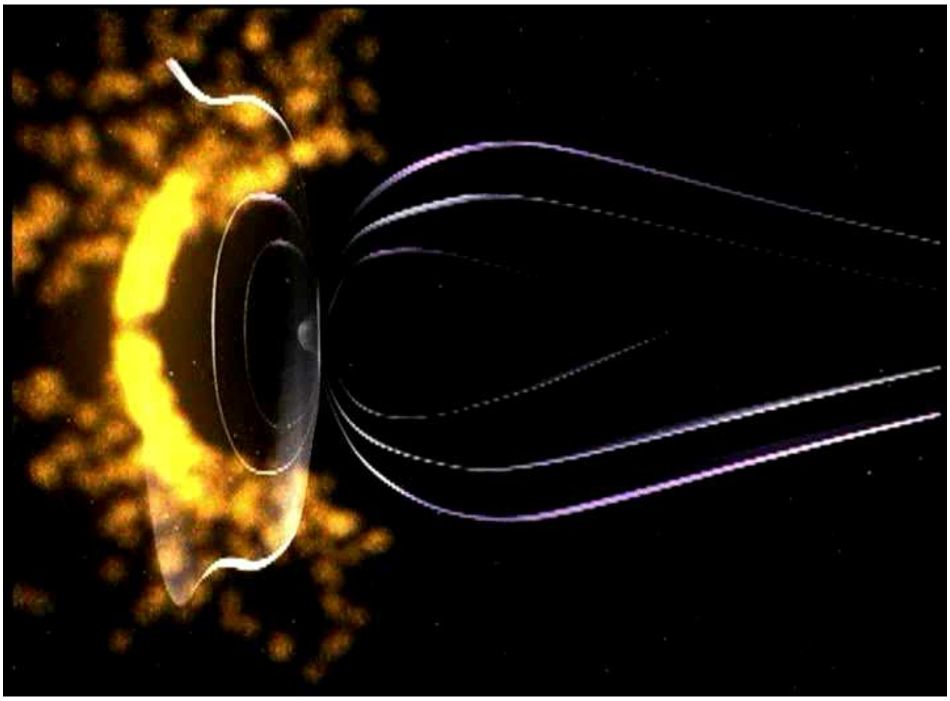

Figure 12: Artist's impression of the impact of a CME on the Earth's magnetosphere.

Figure 12 shows a sketch of the impact of a CME on the Earth's magnetosphere. Such events lead to a significant deformation of the magnetosphere, and cause magnetic storms that can induce strong currents in power lines and pipelines, and disturb navigation systems. So it is of high relevance for our technological civilization to monitor the solar activity, and to be able to quickly determine the geoeffectiveness of a nascent CME. LOFAR's frequency range corresponds to radio source locations in the upper corona, as can be seen in Table 1. Thus, LOFAR is the ideal instrument for observing the onset of a CME and its launch into interplanetary space. LOFAR observations of the Sun go beyond the scope of astrophysics, and will provide valuable information on whether a CME will hit Earth or not.

3.2.4 Observation campaigns

In the previous subsections the continuous task of monitoring the radio Sun has been described. In case of the detection of solar radio bursts the monitoring is interrupted and a predefined follow-up observation program is performed that provides a detailed investigation of the burst. Apart from these basic observational activities, LOFAR can be used for specific observation campaigns that target special aspects of the solar activity.

An example is the acceleration of energetic electrons in solar flares. These electrons do not only produce radio waves that can be observed by LOFAR, but also X-rays as they interact with the solar atmosphere. Thus, joint observations with X-ray instruments like the NASA's RHESSI (*http://hessi.ssl.berkeley.edu*) are well suited for studying the production and propagation of energetic particles. The strong heating of the solar atmosphere results in intense EUV and soft X-ray radiation that is studied by the Japanese Hinode (*http://solar-b.nao.ac.jp/index_e.shtml*) and the upcoming NASA's Solar Dynamics Observatory (SDO, *http://sdo.gsfc.nasa.gov*). Additional images in optical wavelengths with GREGOR or the Kanzelhöhe observatory provide further information on the connection of the acceleration site with the photosphere and chromosphere, and mm-wave data, e.g. from the Atacama Large Millimeter Array (ALMA, *http://www.eso.org/projects/alma*), reveal the response of the chromosphere.

Another example is the study of CMEs at they travel through the interplanetary space. NASA's STEREO mission (*http://stereo.gsfc.nasa.gov/mission/mission.shtml*) and the upcoming ESA's Solar Orbiter (*http://sci.esa.int/home/solarorbiter*) will collect radio and in-situ plasma data on CMEs, while LOFAR provides images of the nascent CME as it accelerates in the upper solar corona. STEREO has the special advantage that the mission consists of two nearly identical spacecraft, one ahead of Earth in its orbit, the other trailing behind. Thus, it provides a stereoscopic, 3-dimensional view of CMEs heading towards Earth, and it covers the frequency range of 16 MHz – 30 kHz that is not accessible from Earth. Together with the LOFAR images, this will enable unprecedented studies of the spatial structure of the CME release mechanism. These joint observations also benefit from LOFAR's "burst bell" that was introduced above.

3.2.5 LOIS/LOFAR

LOIS, the LOFAR Outrigger In Scandinavia (*http://www.lois-space.net*), is the Scandinavian Earth and space observing extension to LOFAR, currently under construction in northwestern Europe.

LOIS aims at enhancing the atmospheric and space physics capabilities of LOFAR by providing a software configurable sensor and emitter infrastructure distributed in southern Sweden. Primary target areas for LOIS are solar physics, ionospheric physics, and space weather as well as large-scale sensor, radio, antenna, telecom, and IT research. LOIS will enable an active probing of the solar corona and CMEs as they propagate through interplanetary space and potentially head towards Earth.

4 Solar Science Data Center

The LOFAR data are not analyzed at each station, but are sent to the Central Processing System at Groningen as it has been discussed in Sect. 2.1. Only the combination of the data from all stations yield LOFAR's sensitivity and angular resolution. At the CPS, the incoming data are processed and "data products" are produced according to the needs of the different observers. Examples of such data products are radio images or time series of radio fluxes of a certain source.

But these data are not routinely archived at the CPS for a long time, and a scientific data analysis is also not done there. Instead, the data products are sent to different Science Data Centers (SDCs) that are dedicated to special research interests. Fast network connections of 1 Gbit/s are envisaged between the CPS and the SDCs that enable a quick transfer of observational data toward each SDC. The Science Data Centers are responsible for LOFAR's Key Science Programs. They are centers of scientific expertise in low frequency radio observations in the relevant field, and they perform the following tasks:

- Development of observational modes needed to address the scientific questions.
- Planning of observations, under consideration of the availability of the required frequency range, that depends on the requests of concurrent users.
- Running observational programs, either automatically or interactively.
- Archiving of the data.
- Dissemination of the data to the scientific community.

4.1 LOFAR and Grid technology

Archiving the data from all solar observation modes described in Sect. 3.2 and the operation of a Science Data Center (SDC) require the storage of large amounts of data of the order of many hundred TByte or even a PByte. Furthermore, the processing of these data by users who are not physically located at the Science Data Center makes distributed computing resources essential.

With the concept of SDCs, the tier model, that has been developed by the High Energy Physics (HEP) Community at the European Organization for Nuclear Research (CERN), is adapted to the needs of the LOFAR instrument. At CERN, this model has been used for the Large Hadron Collider (LHC) data. The first tier, the Central Processing System (CPS), generates the data products of the instrument. The second tier, formed by the SDCs, receive and store part of the data product for further processing and analysis.

To manage distributed data storage for LOFAR data products, Grid technology, e.g. the dCache (*http://www.dcache.org*), is available to ensure the integrity and transparent accessibility across different SDCs. The SDCs are connected within a Grid framework that provides facilities for running data analysis tools on LOFAR products remotely. Furthermore, the Grid framework enables access to distributed computing resources for such tasks. Science Data Centers will provide portals for scientific users accessing the LOFAR grid. The Grid includes security mechanisms that will ensure the protection of the resources and the users. The concept of a Virtual Organization, which builds on the grid security, facilitates the formation of collaborations. Thus, the Grid is an important component of the development of **E-Science**.

4.2 The Solar Science Data Center

A Solar Science Data Center is planned to be established at the AIP. This SDC will organize the LOFAR solar observations and archive the data. Figure 13 summarizes the tasks of the Solar SDC. The observational duties comprise the development of observational programs and data analysis tools that are necessary to derive quantitative information on the state of the solar corona from the LOFAR data, as well as the performance of the observations itself. The different observation programs have been introduced in Sect. 3.2 above. At the SDC, the observations are planned, and the required observation programs and parameters, e.g. frequencies, are sent to the CPS. It is noteworthy that the “burst bell” from Sect.3.2.2 can not only be used to interrupt the routine

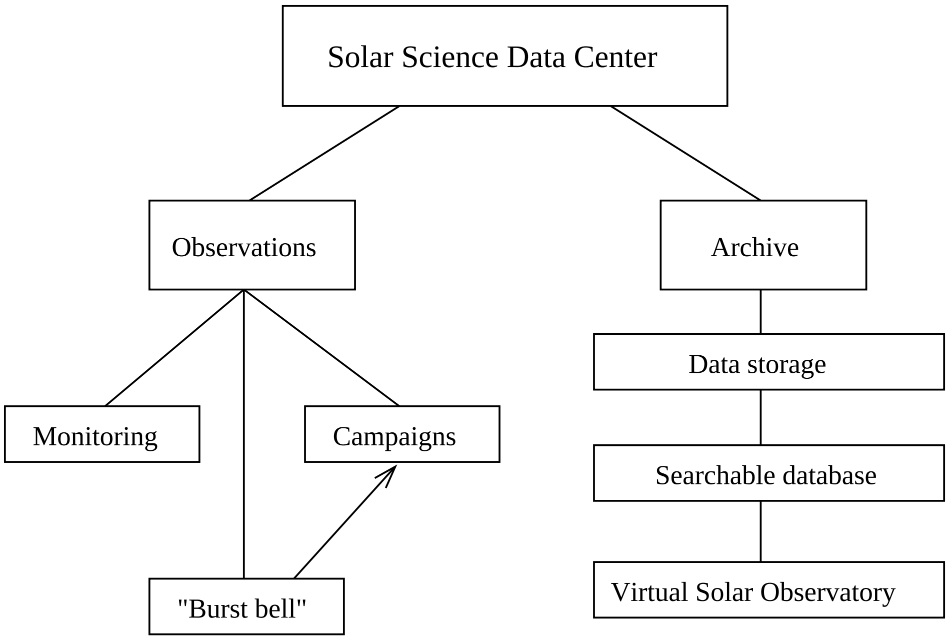

Figure 13: Diagram of the tasks of the Solar Science Data Center.

monitoring for fast responses to solar radio bursts, but is also useful for triggering special observing programs of cooperating instruments during joint observations in specialized campaigns. Alerting them is a task of the Solar SDC, as well as starting follow-up observations at the CPS as part of LOFAR's response.

The other main task of the Solar SDC is archiving the observations once the data products have been sent from the CPS. This includes the storage of the data, but also making them available to the scientific community. Since the routine monitoring and specialized campaigns generate a multitude of different observations, a searchable database is necessary in order to let a scientist find the relevant information. Thus, the SDC fulfills the task of a **Virtual Solar Observatory**.

5 Key Science Project management plan

The partners who are collaborating within a Key Science Project (KSP) are grouped into core members, ordinary members, and associated members. The management plan of the KSP "Solar Physics and Space Weather with LOFAR" is shown in Table 2 below.

6 Summary

LOFAR opens a new spectral window for high-sensitivity and high-resolution observations in the meter wave range. The telescope consists of a central core and remote stations that are spread over central Europe. A remote station is planned by the AIP at Bornim near Potsdam.

LOFAR follows the approach of digitizing the antenna signals at each station, sending the data to the Central Processing System (CPS) at Groningen, and doing the radio interferometry there in software. This offers LOFAR a high flexibility and allows fast changes of observation programs

	Name	Affiliation	Country
PI	Prof. Dr. Gottfried Mann	AIP	Germany
Core members	Dr. Alain Kerdraon	Obs. de Paris-Meudon	France
	Dr. Joe Khan	Univ. Glasgow	UK
(project manager)	Dr. Christian Vocks	AIP	Germany
Ordinary memb.	Dr. Henry Aurass	AIP	Germany
	Dr. Andy Breen	Univ. Aberystwyth	UK
	Dr. Alexander Warmuth	AIP	Germany
	Dr. Jürgen Rendtel	AIP	Germany
	Dr. Matthias Hoeft	Jacobs Univ.	Germany
	Dr. Harry Enke	AIP	Germany
Associated memb.	Prof. Dr. Carsten Denker	AIP	Germany
	Dr. Karl-Ludwig Klein	Obs. de Paris-Meudon	France
	Mag. Wolfgang Otruba	Sonnenobs. Kanzelhöhe	Austria
	Prof. Dr. Helmut Rucker	IWF	Austria
	Prof. Dr. Bo Thide	Univ. Uppsala	Sweden
	Prof. Dr. Joachim Vogt	Jacobs Univ.	Germany

Table 2: Managment structure of the KSP “Solar Physics and Space Weather with LOFAR”

and thus responses to transient events. However, the sheer volume of raw data requires station data processing and reduction that results in some loss of information. As a consequence, this leads to some restriction for the users as compared to an ideal instrument where each user can do his observations without any interference with concurrent users. These limits are the selection of either the low (30 – 80 MHz) or high (120 – 240 MHz) frequency band at a time and a limited bandwidth of 4 MHz out of this band that is available to each of 8 observation beams. But the latter restriction is alleviated by the possibility of fast changes of the observed frequency.

The Sun is a strong radio source, and solar activity leads to intense radio bursts that accompany flares and Coronal Mass Ejections (CMEs). The source regions of LOFAR frequencies are located in the upper solar corona, and thus provide information on the nascent phase of CMEs as they head towards interplanetary space. Thus, LOFAR contributes to estimates of their impact on Earth, especially in combination with data from current and upcoming satellite missions like RHESSI, STEREO, SDO, Hinode, and Solar Orbiter.

For LOFAR observations of the Sun different modes are proposed. The basic mode is routine monitoring with full Sun images that are taken, e.g., with a cadence of 1 min and on 5 different frequencies. The estimated data rate of such a mode is 19.2 GByte/day. Image compression can reduce this by one order of magnitude with no or minimal loss of information, and thus yield manageable data volumes. Such observations allow studies of the long-term evolution of active regions and the precursor phase of solar flares. The combination with other solar monitors, e.g. optical (Hα) images from the Kanzelhöhe Solar Observatory, Austria (*http://www.kso.ac.at/*).

During such a monitoring mode, the signals can also be checked for solar radio bursts. Once a burst is identified, a fast response with follow-up observations can be triggered. Such a “burst bell” is also useful for other working groups operating different ground- or space-based instruments. Beside of such routine tasks, specialized campaigns can be undertaken, e.g. for more detailed studies of selected active regions by joint observations with other instruments.

For planning and running observation programs, as well as data analysis and archiving, a **Solar Science Data Center** (SSDC) will be established at the AIP. The SSDC will concentrate the expertise in solar low frequency radio astronomy and will be responsible for all aspects of solar radioastronomy with LOFAR. The observational methods will be developed there, and the observations will be planned and performed by sending the requirements to the CPS and receiving the data products from it. At the SSDC the data will be analyzed, archived, and disseminated to the scientific community.

Contact information

PI: Prof. Dr. Gottfied Mann
Tel.: +49-331-7499-292, E-Mail: gmann@aip.de

Project manager: Dr. Christian Vocks
Tel.: +49-331-7499-327, E-Mail: cvocks@aip.de

Both at:
Astrophysikalisches Institut Potsdam
An der Sternwarte 16
14482 Potsdam, Germany
Fax: +49-331-7499-352

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