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LOFAR: The potential for solar and space weather studies

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Abstract

The Low Frequency array (LOFAR) will be a next generation digital aperture synthesis radio telescope covering the frequency range from 10 to 240 MHz. The instrument will feature full polarisation and multi-beaming capability, and is currently in its design phase. This work highlights the solar, heliospheric and space weather applications where LOFAR, with its unique and unprecedented capabilities, can provide useful information inaccessible by any other means. The relevant aspects of the LOFAR baseline design are described, and the most promising techniques of interest are enumerated. These include tracking coronal mass ejections (CMEs) out to large distances using interplanetary scintillation (IPS) methods, tomographic reconstruction of the solar wind in the inner heliosphere using IPS, direct imaging of the radio emission from CMEs and finally possible Faraday rotation studies of the magnetic field structure of the heliosphere and the CMEs. This work is a part of an effort directed towards ensuring the compatibility of LOFAR design with solar and space weather applications, in collaboration with the wider community.

Keywords: Faraday rotation; Interferometry; Interplanetary scintillation; Remote sensing; Solar wind

1. Introduction

The Sun affects the Earth via the turbulent and magnetised plasma of the solar wind that perpetually flows out of the Sun. The surface features on the Sun modify the energy and magnetic field content of this plasma, and its coupling to the Earth's magnetosphere leads to an impact on the space weather and geomagnetic conditions on the Earth. Coronal mass ejections (CMEs) are the most dramatic transients from the Sun. They are now recognised as the primary source of disturbances in the interplanetary medium (e.g. Manoharan, 1997). A study of their origin, evolution and propagation has been an active discipline in solar physics since their discovery about three decades ago.

Most existing dedicated solar instruments and facilities either observe the solar disc or make satellite borne in situ measurements of the solar wind plasma. This leads to a wealth of information about the solar transients and the quiescent Sun on or close to the solar surface, spanning an impressive range of the electromagnetic spectrum from gamma-rays to low radio frequencies. The in-situ studies provide the only direct measurements of the solar wind plasma but most of this information is limited to the ecliptic plane and at 1 AU, simply because that is where most of the spacecraft have been concentrated. This leaves the large volume of space from close to the solar surface out to 1 AU practically unsampled. In order to understand how the observations close to the Sun relate to those close to the Earth and improve our understanding of the evolution of the solar wind and space weather, it is essential to learn about the solar wind in this vast intervening space. Remote sensing techniques offer the means to study the solar wind in the entire inner heliosphere. Some of these techniques are not new and are already routinely in use for space weather applications (Jackson et al., 2001). However, the returns from these techniques are expected to be greatly enhanced when applied using the next

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generation radio telescopes like the Low Frequency array (LOFAR), which is expected to become available in near future.

We investigate the potential of LOFAR for remote sensing of both solar transients and the quiescent Sun and the heliosphere. The techniques considered include interplanetary scintillation (IPS) studies of the solar wind in the inner heliosphere and direct imaging of CMEs. The exciting possibility of monitoring background sources and measuring the change in Faraday rotation due to the CME magnetoionic plasma is also considered.

2. LOFAR: a capable instrument on the horizon

The LOFAR is a next generation digital aperture synthesis radio interferometer based on the concept of phased array interferometric stations (Bregman, 2000). It is being designed to cover the 10–240 MHz range, in order to explore the last remaining part of the radio spectrum accessible from the Earth with high sensitivity and resolution. Low-frequency aperture synthesis imaging has been a difficult challenge, primarily because of the corruptions of the incoming celestial signal by the terrestrial ionosphere and the large fields-of-view associated with the large wavelengths of observation. LOFAR will exploit the recent and continuing advances in computing capabilities and algorithmic development to compensate for ionospheric distortions and cope with radio frequency interference (RFI). The conversion of signal to the digital domain at the earliest available opportunity makes it possible to form multiple independent beams simultaneously. A possible design allows up to 8 beams using the entire collecting area of the array and 256 beams per polarisation using only the part of the array lying within the central 2 km of the array (core). The instrument will also feature an *All Sky Monitor*, which will use the array core and will provide an image the entire field-of-view about every second.

While the detailed design effort is in progress, a preliminary design for LOFAR is in place. It is hence an appropriate time for examining the proposed design to ascertain its compatibility with the space weather objectives. It will be timely to assess the potential of LOFAR for space weather studies and suggest design modifications, if needed, to improve the returns from space weather studies.

3. IPS studies

The phenomenon of IPS is the radio analogue of the optical twinkling of stars when seen through the Earth's atmosphere. The solar wind acts as a medium with a fluctuating refractive index to the incident plane wavefront from the distant compact radio source. The emergent wavefront carries an imprint of these fluctuations as phase corrugations. By the time the emergent wavefront travels to the observing plane, the phase corrugations develop into an interference pattern. The motion of the solar wind causes this interference pattern to sweep past the radio telescope. A cut across the interference pattern is observed as a time series of intensity fluctuations by a radio telescope, referred to as IPS.

IPS data can be modelled based on the mathematically rigorous theory of weak scattering and can yield information about the physical properties of the solar wind through which the radio wave has traveled. In the weak scattering regime, the medium can be represented by a collection of independent thin screens. The measured IPS observable, the power spectrum of intensity fluctuations, can be treated as a weighted sum of the power spectra of intensity fluctuations due to each of the thin screens. For a rigorous modelling of IPS data, the physical properties of each thin screen like velocity, fluctuations in the electron number density and inner scale, etc., form the free parameters in the problem. A few isolated observations do not have sufficient information to determine the distribution of the properties of solar wind along the line-of-sight and hence cannot constraint the large number of free parameters involved. For this reason, most IPS studies involving a few observations have largely concentrated on situations where either the entire heliosphere can be described using solar wind models with a few free parameters, like the uniform solar wind velocity models, or the plasma along a small part of the line-of-sight dominates the IPS measurables.

In the high-frequency part of LOFAR band, we expect to be in the weak scattering regime beyond solar elongations of $\sim 32^\circ$ at 110 MHz and $\sim 19^\circ$ at 240 MHz. A very large fraction of the inner heliosphere will hence be simultaneously accessible to IPS studies from LOFAR. The full field-of-view data streams from each of the primary receptors in the core will be used to form a large number of simultaneous independent beams. A possible design for the core beam-former aims to provide 256 beams for each polarisation. These beams will independently track astronomical sources lying within the wide fields-of-view of primary receptors. This key capability, to form a large number of independent simultaneous beams, will bring enormous benefit to IPS studies by allowing a much denser sampling of the inner heliosphere. In addition, the larger collecting area, as compared to currently operational IPS observatories, will provide data with significantly improved sensitivity.

4. IPS tracking of CMEs

Coronographs provide the most effective means for observing CMEs close to the solar surface. As the CMEs travel away from the Sun, they move out of the field-of-view of the coronographs. The Cambridge IPS group proposed a means of tracking the CMEs through the inner heliosphere using IPS measurements (Gapper et al., 1982). The technique required regular daily observations of all the available sources, suitable for IPS, as they crossed the local meridian, and plotting the results suitably to build up daily sky maps of normalised scintillation levels. The IPS events, for instance the interplanetary disturbances (IPDs) associated with the CMEs, would appear as regions of correlated excess scintillation levels and could be tracked from one day to the next. This simple application of the technique with potentially significant returns, fell short of expectations. The various factors which contributed to this were contamination of the data due to ionospheric scintillation at the frequency of operation of the Cambridge array (81.5 MHz), its high latitude (52°) which allowed rather limited coverage south of the Sun and being a transit instrument, it could sample a source only once a day (Duffett-Smith et al., 1980). LOFAR's ability to observe at higher frequencies where ionospheric contamination is more manageable and the improvement in the sampling of the heliosphere by more than two orders of magnitude by allowing hundreds of sources to be observed simultaneously makes the use of this technique very viable (Fig. 1). In place of having a daily map of relative scintillation strengths with each source observed once a day, LOFAR will be able to provide continuous monitoring of a few hundred sources distributed over a large fraction of the visible sky. This information can provide a movie of the variations in the relative scintillation strengths. IPS tracking will routinely allow the study of radial evolution of some of CME physical properties like velocity, density and turbulence characteristics (Manoharan et al., 2000).

It should be pointed out that IPS observations have the potential to be used for predicting geomagnetic activity. Though the performance of the technique has usually remained below expectations, the reasons for this are now fairly well understood (Hapgood and Lucek, 1998). The LOFAR design addresses many of the issues which lead to the sub-optimal performance. However, independent measurements of the orientation of the interplanetary magnetic field, especially the B_z component, which controls the flow of energy and momentum from the solar wind into the terrestrial magnetosphere, are required to utilise the technique to its full potential.

5. IPS tomography

IPS observations can sample a very large fraction of the inner heliosphere at any given time. IPS observables are sensitive to line-of-sight integrated properties of the solar wind and hence are suitable for tomographic inversion techniques. Solar rotation and the near radial outflow of the solar wind allow Earth-based observers to view the same stable features in the solar wind from a variety of different perspectives. It is conceptually simple to realise that if IPS measurements are made such that they sample a large volume of the heliosphere adequately, such a data set must contain the information of the global three-dimensional structure of the solar wind (Fig. 2). The process of extracting this information from such a data set is analogous to *tomography* where one tries to reconstruct the N-dimensional structure of an object from a set of its projections in $N-1$ dimensions.

Heliospheric tomography has been demonstrated with varying degrees of success (Jackson et al., 1998; Kojima et al., 1998; Asai et al., 1998; Oberoi, 2000) and is now routinely performed in near real time using data from Solar Terrestrial Laboratory in Japan.[1] The most constraining limitations of the tomographic inversion arise from the sparse sampling of the heliosphere available from the current instruments. The much denser sampling and the better signal-to-noise promised by LOFAR will enormously benefit heliospheric tomography.

It is worthwhile to note the considerable synergy between tomography using IPS and that using Thomson scattering data (Jackson and Hick, 2002). While IPS measurements constraint primarily the velocity of the solar wind and the fluctuations in the number density of electrons in the solar wind, Thomson scattering is sensitive to the total electron column density along a line-of-sight. As these measurements constraint different physical properties of the same medium, the simultaneous use of both these data sets can lead to significantly better constrained tomographic reconstructions. A space-based experiment, the Solar Mass Ejection Imager (SMEI), designed to detect and measure transient plasma features in the heliosphere using Thompson scattering data was launched in January, 2003 (Jackson et al., 1991) and a more ambitious mission incorporating a heliospheric imager, the Solar Terrestrial Relations Observatory (STEREO) is currently scheduled for launch in February, 2006.

6. Direct imaging of CMEs

CMEs have routinely been observed at visible wavelength with coronographs, though their counterparts at other wavelengths have remained elusive. There is significant interest in radio imaging of the CMEs as it provides many advantages over optical and soft X-ray

[1]The real time heliospheric tomography results are available at `http://stesun5.stelab.nagoya-u.ac.jpips_datae.html`.

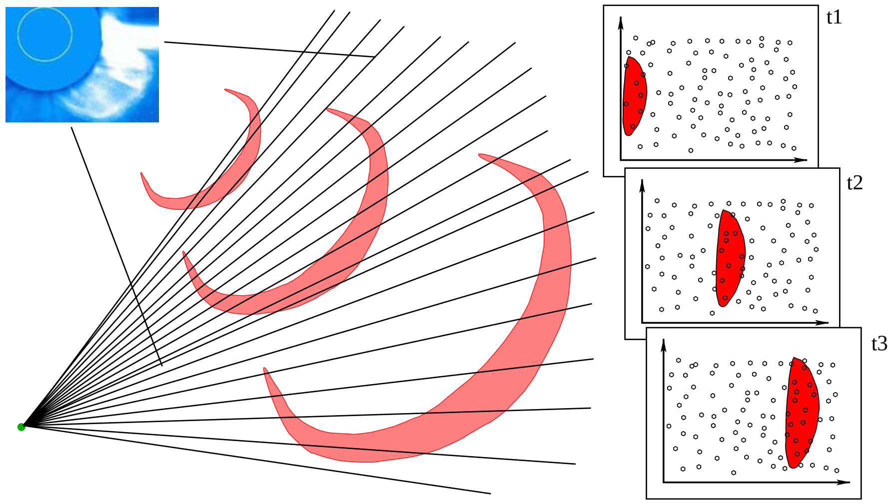

Fig. 1. The cartoon shows the lift off of a CME from the solar surface at some time $t0$ and the position of the IPD it gives rise to at three subsequent times, $t1$, $t2$ and $t3$. The lines-of-sight to a grid of IPS sources are also shown. The panel on the right shows a projection of the directions of the lines-of-sight to the IPS sources projected on the sky plane at $t1$, $t2$ and $t3$. The shaded areas show the location of the sources which will be seen "lit-up" as the CME crosses the lines-of-sight to these sources. The multi-beaming capability of LOFAR will allow simultaneous multi-frequency monitoring of an extensive grid of IPS sources making, it a very capable instrument for such studies.

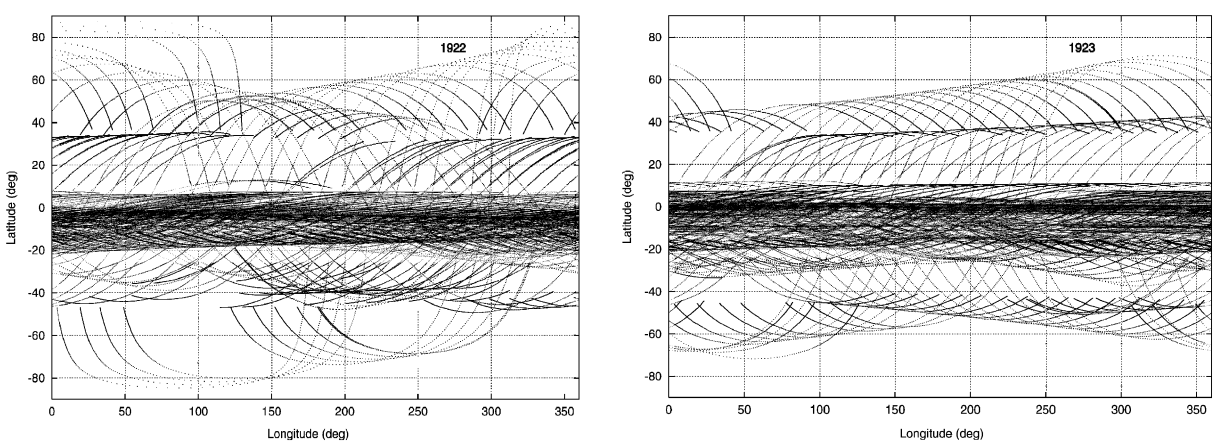

Fig. 2. The plots above show the actual coverage of solar surface obtained for Carrington rotations 1922 and 1923 in a heliospheric tomography attempt (Oberoi, 2000) which concentrated on the solar equatorial belt. The X and Y axes are the heliographic longitude and latitude, respectively. Each line represents the geometric projection of the line-of-sight to a source on to the solar surface. About 750 observations were made in each of the Carrington rotation periods. The multi-beaming capability of the LOFAR central core will allow us to observe a few hundred times as many sources, each of them with better sensitivity than the current instruments. This will make LOFAR a very promising instrument for conducting IPS tomography studies.

observations (Bastian and Gary, 1997). For instance, since radio observations do not require an occulting disk, CMEs can, in principle, be imaged against the disk of the Sun. Radio observations are useful for detecting emission from both thermal and non-thermal electrons. For the thermal plasma, radio observations are sensitive to a broader range of temperatures as compared to soft X-ray and the measurements can provide temperature and emission measure. For non-thermal emission radio observations can provide the parameters of the non-thermal electron distribution and the strength of the CME magnetic field. In addition, radio measurements can be carried out by ground-based observatories, which are significantly less expensive than space-based observatories.

Bastian and Gary (1997) also concluded that the meter and decimeter wavelengths are the most promising regions of the electromagnetic spectrum in which to look for CMEs. Only a handful of direct detections have been reported in the literature, all of them at meter wavelengths or longer. The most spectacular of these was observed with the Nançay radioheliograph, France at 164–421 MHz (Bastian et al., 2001). Imaging of CMEs requires good sensitivity to emissions of the angular size of $\sim 1^\circ$, good snapshot imaging capability and high dynamic range imaging, all of which are met by the LOFAR design. A large fraction of the collecting area of LOFAR is concentrated in a compact part of the array, making it very sensitive to large scale emission. The large number of LOFAR stations will provide unprecedented snapshot imaging capability with a dynamic range of 10^5 or more. The rapid steepening of the CME emission spectra with increasing distance from the Sun further enhances the potential of LOFAR for direct radio imaging of CMEs. As the CMEs move further out from the Sun, their emission will shift to frequencies below LOFAR's observing range and space-based radio imaging can provide complimentary observations.

7. Faraday rotation studies

LOFAR will be able to exploit another radio remote sensing technique to probe the structures in the inner heliosphere. The apparent changes in the position angle of the linearly polarised flux from distant background radio source can be related to the variations in the magnetised solar wind plasma. A linearly polarised radio wave propagating along a magnetic field line may be represented as a combination of two components with right- and left-hand circular polarisations. In a magnetised plasma, like the solar wind, these two circular polarisations experience different indices of refraction, leading to a phase lag between the two components. This phase lag results in an overall rotation of the plane of the linear polarisation of the incident wave and is referred to as Faraday rotation (FR) whose magnitude is given by

$$\Omega = 2.62 \times 10^{-13} \lambda^2 \int N_e(s) \vec{B}(s).\hat{s}\, \mathrm{d}s, \quad (1)$$

where Ω is the observed FR, in rad, λ the wavelength of observation in m, $N_e(s)$ the electron number density along the line of sight in m^{-3}, $\vec{B}$ the magnetic field along the line-of-sight in T, s a dummy variable running along the line-of-sight in m and $\hat{s}$ the unit vector along it. The observed FR is thus an integral along the line-of-sight and depends on the distributions of the magnetic field and electron density along the line-of-sight.

Faraday rotation may be used to probe the three-dimensional electron number density and magnetic field topology of both the background heliosphere and the transients, such as CMEs. It is particularly interesting to note that the FR measurements are sensitive to the product of the total electron number density and the magnetic field along the line-of-sight, IPS measurements to the electron density fluctuations and Thomson scattering measurements to the total electron density. It is anticipated that simultaneous availability of these measurements will significantly complement one another providing a more complete picture of the magnetoionic structures in the inner heliosphere.

Prior work on this subject has involved monitoring the variation of polarised extragalactic sources and the telemetry streams from spacecraft as they are occulted by the solar corona. The signals from spacecraft such as Helios (Pätzold et al., 1987) and Pioneer 6 (Pätzold and Bird, 1998) have been used to determine the radial variation of the spectrum of turbulent fluctuations in the corona (Bird et al., 2002). More recently, tracking of polarised extragalactic objects using VLBI (Spangler et al., 2002) and the VLA (Mancuso and Spangler, 2000) over periods of tens of days have been used to test models of the structure of quiet streamer belts. Typically these studies have all been conducted at high frequencies, a few GHz and higher, and have remained confined to the inner corona though a few measurements as far out as elongation of $\sim 16^\circ$ have also been made.

LOFAR could make a significant contribution to the study of the global density and magnetic field structure of the heliosphere through FR measurements. By observing at much lower frequencies, LOFAR is expected to be able to make FR measurements at larger distances from the Sun. Additionally, the large field-of-view of LOFAR presents the possibility that a large number of objects could simultaneously be monitored, providing better spatial and temporal sampling than possible with any of the available instruments.

The results from the recent Canadian Galactic Plane Survey (CGPS) at 1.42 GHz (Brown et al., 2003), which identified approximately one compact polarised extragalactic object, suitable for FR studies, per square degree in the sky are especially encouraging. To estimate the size of the effect and the region of the inner heliosphere which could be remotely probed through FR we constructed a simple model of heliospheric field and density structure during solar minimum. We used solar wind observations by the SWOOPS instrument on the Ulysses spacecraft (Bame et al., 1992) to construct an axially symmetric profile of the average speed and density as a function of heliographic latitude. Data were selected from the entirety of the first Ulysses polar passages from June 26, 1994 through September 29, 1995. Measurements of the photospheric magnetic field by the Wilcox Solar Observatory during Carrington rotation 1895, which started on April 19, 1995, were used to construct the radial field on a source surface at 2.5 R_s through a force-free potential model. The field and plasma measurements were then combined with a simple Parker field model for the evolution of the magnetic field throughout the inner heliosphere (Parker, 1960). The resulting structure is essentially one of high-speed, low-density solar wind at the poles and low-speed, high-density wind in the equatorial region with higher winding of field lines and a field reversal at the

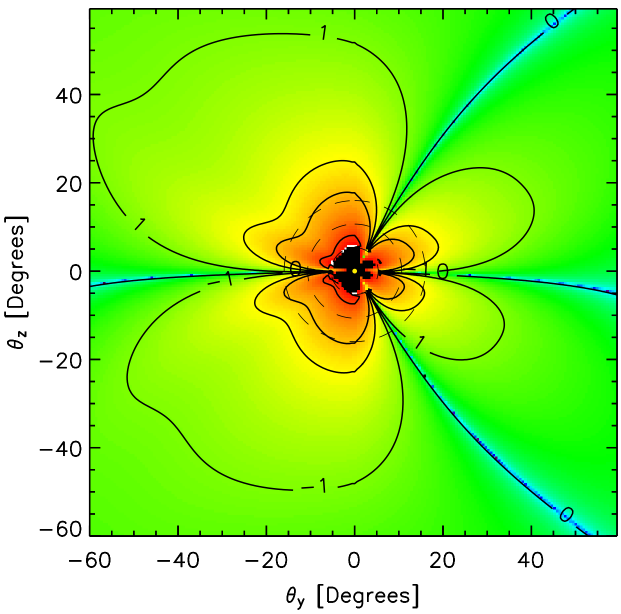

Fig. 3. The expected Faraday rotation due to the quiescent heliosphere at 110 MHz is shown projected on the sky at a resolution of one degree. The Sun lies at the origin, the θ_x and θ_z axes are the elongations measured along the ecliptic plane and perpendicular to it, respectively. The grey scale indicates the absolute value of the FR, and the contours mark Faraday rotations of 0°, ±1°, ±5°, ±10°, ±50°, ±100° and ±500°. A simple model which combines axially symmetric density and velocity profiles with Parker-spiral magnetic fields extrapolated from photospheric field measurements has been used for these calculations. See text for details.

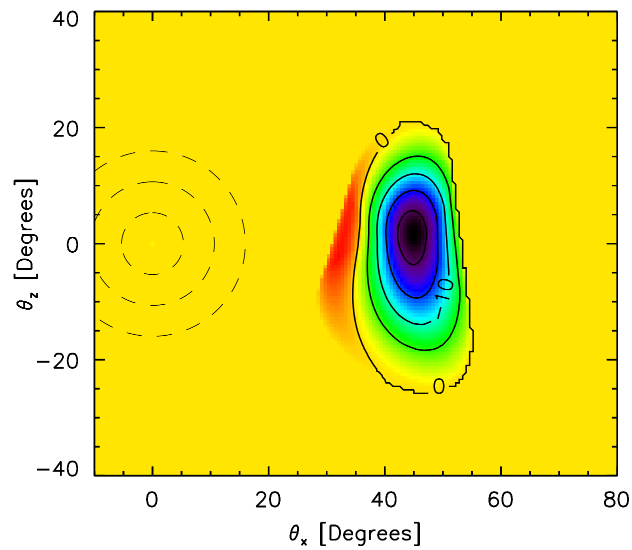

Fig. 4. The figure shows the Faraday rotation at an observing frequency of 110 MHz for a simple magnetic flux rope of radius = 0.25 AU, length = 0.7 AU, $B_{\max} = 30\,\mathrm{nT}$ and $n_e = 90\,\mathrm{cm}^{-3}$. The contours are in increments of ±5°. The axes are the same as for Fig. 3. The Sun is at the origin, the Earth at coordinates of (0, −1) and the flux rope is located at (0.9,0).

equator. Fig. 3 shows the expected Faraday rotation due to the quiescent heliosphere at 110 MHz at a resolution of one degree. Clearly, combining maps of the Faraday Rotation with IPS and Thomson scattering measurements would greatly enhance our ability to understand the structure of the inner heliosphere.

Faraday rotation measurements with LOFAR will also allow us to remotely characterise the properties of the CME ejecta. The FR expected due to a simple magnetic flux rope at 110 MHz is shown in Fig. 4. It is evident that the FR signal due to the flux rope will be easily discernible using LOFAR. This suggests the exciting possibility that the high sensitivity and full polarisation capability of LOFAR may provide the first ever opportunity to investigate the magnetic field structure of CMEs by observing background polarised sources, viewed through the CME plasma.

8. Conclusions

Information about the large scale physical properties of the inner heliosphere plasma is the much needed missing link for improving our understanding of the evolution of the solar wind as it flows from close to the solar surface to 1 AU and is also sought for space weather applications. This information can only be obtained by remote sensing techniques. LOFAR will, in principle, have the capability to serve as a powerful tool for making this information available. The large field-of-view and multi-beaming features of LOFAR are very well suited for IPS tomography studies. Being a sensitive and a high dynamic range imaging instrument, LOFAR has all the necessary features for efficient direct imaging of CMEs. The full polarisation capability of LOFAR presents the possibility of routine large field-of-view Faraday rotation studies of the quiescent and transient features in the inner heliosphere. The simultaneous availability of IPS and Faraday rotation observations and the likelihood of availability of independent Thomson scattering measurements, all of which provide complimentary information, will enable the most detailed characterisation of the inner heliosphere yet.

LOFAR is currently in its design phase. It is hence an appropriate time to assess the potential of LOFAR for solar and space weather studies, examine the proposed design for its compatibility with solar and space weather studies and, if required, suggest modifications to maximise the returns from this powerful new instrument.

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