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The Low Frequency Array (LOFAR): A Comprehensive Tool for Space Weather Observation

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1. Extended Abstract

The Low Frequency Array (LOFAR) is a radio astronomy array consisting of a dense core of 24 stations within an area of diameter ~4km, 14 stations spread further afield across the north-east of the Netherlands, and a further twelve stations internationally (six across Germany, three in northern Poland, and one each in France, Sweden and the UK). Each station is capable of observing over a wide bandwidth across the frequency range 10-250 MHz, at high time and frequency resolutions, and forming multiple beams to point in any direction on the sky. Any number of the stations can be combined as an interferometer for radio imaging of the sky, and/or the core stations combined to form up to ~200 narrow pencil beams ("tied-array beams"). The latter enables raster imaging techniques to be used or, with some limitations, multiple radio sources to be observed simultaneously. These capabilities make LOFAR one of the world's most flexible radio instruments and enable studies of several aspects of space weather to be advanced beyond the current state-of-the-art.

Solar dynamic spectra and imaging: Raster imaging of the Sun and lower corona with multiple, simultaneous, narrow beams offers a number of advantages over current interferometric imaging. Data for each beam are recorded as dynamic spectra covering, currently, 80MHz of bandwidth with, typically, 0.01s time resolution and 12.2kHz frequency resolution (higher resolutions are also possible). Although spatial resolution is naturally limited by beam diameter, this technique offers much faster imaging than is currently possible with traditional techniques, and determination of the type of radio burst from the dynamic spectrum of each beam. Results so far have shown Type III bursts on the flanks of a CME, short-duration "S"-bursts associated with the top of a coronal loop, and "J"-bursts propagating along the path of a coronal loop from the lower corona upwards.

The solar wind: Interplanetary scintillation (IPS – the scintillation of compact radio sources due to density variations in the solar wind) enables the determination of solar wind speed and estimates of solar wind density throughout the inner heliosphere. Observations of many radio sources can be combined via tomography to form 3-D maps of these quantities and obtain a global picture of the solar wind from inside the orbit of Mercury to beyond the orbit of Earth. A month-long campaign in October 2016 provided data to demonstrate LOFAR's capabilities in providing the many observations necessary for visualising the inner heliosphere, in addition to the improvements which could be made to the 3-D tomography maps when these data are combined with those of other facilities worldwide. These data can also be used to compare several standard IPS analysis techniques in single observations to establish their relative accuracy and limitations, a comparison which is not currently fully possible with other instruments.

The interplanetary magnetic field (IMF): Global determination of the IMF remains something of a "holy grail" for space-weather forecasting, with current efforts for predicting the likely IMF strength and direction upon arrival at Earth dependent on extrapolation from solar surface measurements to the direct spacecraft measurements from instruments at the L1 Lagrangian point. One of the only methods by which this could be achieved is via the observation of heliospheric Faraday rotation in the polarised signal from either a polarised radio source or a Galactic polarised background. This is a challenging measurement which is only remotely possible using a LOFAR-type instrument. Efforts are underway to attempt to extract information on the IMF from such observations.

Ionospheric scintillation: Observations of strong natural radio sources such as Cassiopeia A and Cygnus A taken using LOFAR show almost continual ionospheric scintillation. Dynamic spectra of these observations show scintillation progressing through the weak and strong scattering regimes and sometimes the effects of refraction due to large-scale structure in the ionosphere. For single observing frequencies, the normalised intensities received by each station can be plotted as images where each intensity pixel corresponds to the spatial location of the station. This results in a series of images where the scintillation intensity can be seen 'flowing' across the stations in movies created from them. Such movies demonstrate how the scintillation appears to flow across the compact core area of LOFAR in waves at highly-variable speeds, and the small-scale structure which exists well within single pixels of even high-resolution GNSS TEC maps.

In this paper, we summarise the latest efforts and results using LOFAR to study all these phenomena.