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The LOFAR Solar Imaging Pipeline and the LOFAR Solar Data Center

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ABSTRACT

LOFAR is a new and sensitive radio interferometer that can be used for dynamic high-resolution imaging spectroscopy at low radio frequencies from 10 to 90 and 110 to 250 MHz. Here we describe its usage for observations of the Sun and in particular of solar radio bursts. We also describe the processing, archiving and accessing of solar LOFAR data, which is accomplished via the LOFAR Solar Imaging Pipeline and the LOFAR Solar Data Center.

1. Introduction

The Sun is a low to moderate activity star and because of its proximity to Earth a unique astrophysical object for studying stellar phenomena in great detail. Radio observations can make substantial contributions to such studies since the Sun is an intense radio source. Its 10^6 K hot corona emits thermal radio radiation. In addition, solar activity produces intense non-thermal radio radiation observed as radio bursts (McLean, 1985; Warmuth and Mann, 2005; Mann, 2006). They are caused by a release of energy during a reconfiguration of the Sun's magnetic field which also results in flares and eruptive events such as coronal mass ejections. The radiation is generated by plasma emission and emitted near the local plasma frequency and/or its harmonics (Melrose, 1985). For instance, type III bursts are a typical phenomenon in solar radio radiation and are signatures of energetic electrons propagating along magnetic field lines in the corona (Wild, 1950; Suzuki and Dulk, 1985; Breitling et al., 2011). Since the radio emission occurs near the local electron plasma frequency $f_{pe} = (e^2 N_e/\epsilon_0 m_e)^{1/2}/2\pi$ (e, elementary charge; ϵ_0, permittivity of free space; m_e, electron mass), and because of the gravitational density stratification of the corona, higher and lower frequencies are emitted in the lower and higher corona, respectively.

With the Low Frequency Array (LOFAR, van Haarlem et al., 2013) a sensitive high resolution radio interferometer became available for radio observations in the frequency range from 10 to 250 MHz corresponding to a radial distance between 1 and 3 solar radii ($R_\odot$) in the corona (Mann et al., 1999). Its capability for high resolution dynamic imaging spectroscopy makes it particularly useful for spatial and time resolved observations of solar radio burst. The LOFAR Key Science Project "Solar Physics and Space Weather with LOFAR" (Solar KSP, Mann et al., 2011) was formed to use LOFAR for solar observations and to address open questions. Its goals are the coordination of solar observations, the solar data processing and analysis and the provision of the resulting data products to the scientific community. These goals led to the development of the LOFAR Solar Imaging Pipeline and the LOFAR Solar Data Center described here.

2. LOFAR

LOFAR (van Haarlem et al., 2013) is a European digital radio interferometer developed under the leadership of the Netherlands Institute for Radio Astronomy (ASTRON). It currently consists of 48 antenna stations distributed over the Netherlands (40), Germany (5), United Kingdom (1), France (1) and Sweden (1) with its center near Netherlands city Groningen. Additional stations are currently under constructions in Poland (3) and Germany (1) or in the planning phase. A LOFAR station consists of high- and low-band antenna fields and an electronics container with the receiver and computer hardware. An antenna field is composed of identical antennas, which are added to a station beam (or pointing) to receive the signal from a specific sky direction. The data of the station pointings are sent to the correlator in Groningen which forms the array or sub-array pointings.

LOFAR operates in the low frequency range from 10 to 90 (low-band) and 110–250 MHz (high-band) in full polarization with high sensitivity and resolution for imaging spectroscopy. LOFAR's beam forming allows for the simultaneous observation of several different sky regions, which is important for the calibration of highly variable radio sources like the Sun. It also allows the

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Table 1
Differences between observations of the Sun and standard radio sources.

	Standard radio source	Sun
Temporal resolution [s]	$\geq 10^4$	≤ 1
Spatial resolution [arcsec]	~ 1	$\sim 10^1$
No. of stations	≥ 48	≤ 30
No. of baselines	$> 10^3$	$< 5 \times 10^2$
Field of view [deg]	$> 10^1$	~ 1
Typical flux density [Jy]	$\ll 10^3$	10^4–10^{12}
Typical noise level [Jy]	10^{-1}	10^2
Dynamic range of flux density [orders of magnitude]	0	8
Ionospheric scintillation	low	high
High res. dynamic spectroscopy	no	yes

Table 2
Differences between standard and solar data processing resulting from the differences in the observations of Table 1.

	Standard imaging	Solar imaging
Aperture synthesis	yes	no
Flagging	in frequency & time	in frequency only
uv-range [wavelengths]	0–10^6	0–10^3
Sky model source threshold	≤ 50 Jy	$\sim 10^3$ Jy
Distance calibrator - target	≤ 1 deg	≥ 5 deg
Demixing	yes	no
Imager	AWImager	CASA imager
CLEAN algorithms	Clark for point sources	multi-scale for ext. sources
Self-calibration	yes	limited to selected events
Solar Data Center	no	yes

simultaneous recording of dynamic radio spectra and images at different frequencies. These capabilities make LOFAR a very powerful instrument for imaging spectroscopy of celestial radio sources and to a radio heliograph if applied to the Sun.

3. The Solar Imaging Pipeline

The Solar Imaging Pipeline is a software package for analyzing LOFAR observations of the Sun. It was developed by the Solar KSP at the Leibniz-Institut für Astrophysik Potsdam (AIP) as an extension of the LOFAR Standard Imaging Pipeline (Heald et al., 2011) to accomplish a proper data processing for solar LOFAR data. It is necessary because of the differences between solar and standard observations and the consequences for the data processing. They are summarized in Tables 1 and 2 and explained below.

3.1. *Characteristics of solar observations*

3.1.1. *High variability of solar radio emission*

The radio emission from most radio sources that LOFAR observes such as galaxies is constant and ranges from 0.1 to 100 Jy. However, the emission from the Sun at 100 MHz is about 10^4 Jy (1 solar flux unit, sfu) during quiet periods but it can rise to 10^{12} Jy (10^8 sfu) within a few seconds in case of solar radio bursts (Mann, 2010; Dulk, 2000) which can occur anywhere near the Sun. So solar radio observations need to be able to record a dynamic range in brightness of 8 orders of magnitude with a time resolution of seconds. Consequences:

- A time resolution of seconds prevents the typical aperture synthesis which uses the Earth's rotation and observation times of hours for increasing the uv-coverage and image quality. Figs. 1 and 2 show the uv-coverage with and without aperture synthesis for comparison. Each point in the uv-plane represent a baseline.
- The short duration of some bursts prevents temporal radio frequency interference (RFI) removal also called flagging, since flagging of radio peaks could also remove the signals of solar bursts.

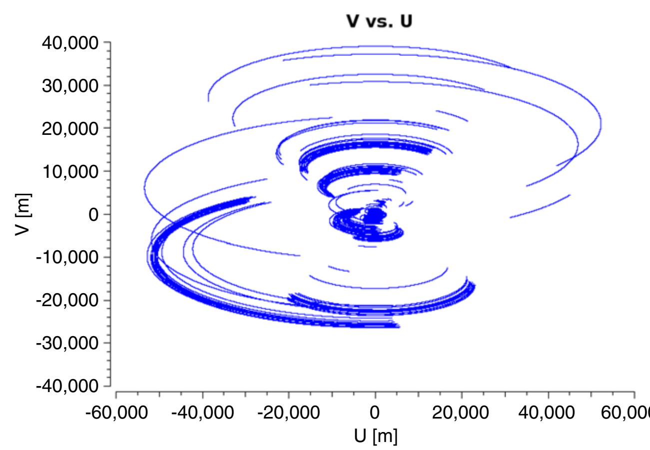

Fig. 1. uv-coverage (baselines) for 12 h of data. Because of the Earth's rotation each point in the uv-plane multiplies into an arc like point set.

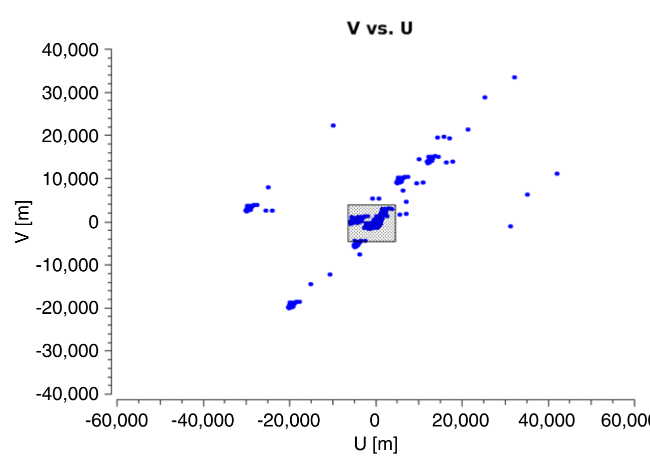

Fig. 2. uv-coverage for 1 s of data. The box indicates the approximate region of points (baselines) that remain if the uv-range is limited to ≤ 1000 wavelengths.