A renaissance in low-frequency pulsar studies with LOFAR

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Abstract. A new generation of sparse, digital aperture arrays is revitaliz- ing interest in radio astronomy at the lowest frequencies visible from Earth (10–300 MHz). Together, the Long-Wavelength Array (LWA), Murchi- son Widefield Array (MWA), and Low-Frequency Array (LOFAR) cover a broad range of science, including observations of cosmic magnetic fields, the Sun and (exo)planets, cosmic-ray air showers, transients, and the epoch of reionization. Here I focus on LOFAR observations of pulsars and fast transients. LOFAR’s large fractional bandwidth and wide-field, flexible multi-beaming capabilities present many advantages over past low-frequency instruments. We are exploiting these capabilities to study pulsar magneto- spheres, the interstellar medium (using pulsars as probes), and to perform an all-sky search for nearby pulsars and other ‘fast transient’ signals.

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1. Introduction

Modern super-computing and high-speed, Gb/s fiber networks together enable low-frequency, sparse aperture array radio telescopes that are more flexible and more ‘information rich’ than their predecessors. The ability to transfer, record, and process
much larger data volumes gives the opportunity to use a significantly larger fraction of the information available from each individual antenna. Practically speaking, this means recording much broader bandwidths, and having the ability to form very wide fields-of-view, which can be carefully tailored to the specific scientific goals of a given project.

The Low-Frequency Array (LOFAR) started official scientific operations in December 2012. LOFAR is the largest of the new generation of low-frequency aperture array telescopes, providing both a large total collecting area and long baselines for high-resolution imaging (van Haarlem et al. 2013). The 10–240 MHz band is covered using two sets of antennas: the low-band antennas (LBAs) can instantaneously observe from 10–90 MHz, while the high-band antennas (HBAs) can optionally observe either the entire 110–190 MHz or 160–240 MHz band.

While interferometric imaging is the main technique employed, a substantial fraction of LOFAR science (currently ~ 30% of the requested observing time) relies on the use of high-time-resolution, ‘beam-formed’ modes (Stappers et al. 2011). Instead of providing cross-correlations between LOFAR stations, the beam-formed modes either coherently or incoherently add these station signals to form array beams that can be recorded with microsecond to millisecond time resolution. These modes are used, e.g., for observations of the Sun, (exo)planets, interplanetary or ionospheric scintillation, flare stars, radio recombination lines, fast transients, and pulsars.

Here we focus on LOFAR pulsar observations made by the LOFAR Pulsar Working Group (part of the LOFAR Transients Key Science Project). Though pulsars were originally discovered at 82 MHz using the Cambridge Interplanetary Scintillation Array, most recent pulsar studies and surveys have moved to higher observing frequencies (300–3000 MHz) in order to mitigate the deleterious effects of sky temperature and propagation effects in the interstellar medium (ISM), such as dispersion and scattering. LOFAR provides high time/frequency resolution and, optionally, coherent dedispersion which allow us to mitigate propagation effects and to study their properties in very fine detail — thus providing a powerful probe of dispersion measure (DM) and scattering variations as well as their time/frequency evolution. Searching for new pulsars below 200 MHz remains very challenging, especially because of the large number of required DM trials. Nonetheless, LOFAR is showing that it can find new faint, nearby pulsars missed by previous surveys (see §4). In the following sections we give a taste of some of these ongoing studies.

2. Characterizing known pulsars with LOFAR

Despite the challenges of observing in the 10–240 MHz range, there are several advantages. For studying pulsar magnetospheres, the 4 octaves of frequency coverage provided by LOFAR probe a relatively large range of emission heights and can constrain (or detect) aberration and retardation of the signal. For example, in Hassall et al.
For Figure 1. Left: LOFAR HBA observation of PSR B0943+10, clearly showing the Bright (B) and Quiet (Q) modes (adapted from Hermsen et al. 2013). The white stripe is data excised because of interference. Right: LOFAR HBA/LBA profiles of PSR B0943+10 spanning 20–200 MHz (Bilous et al., in prep.).

(2012) we compared LOFAR LBA and HBA data of four bright pulsars with simultaneously acquired data at 1.4 and 8 GHz from the Lovell and Effelsberg telescopes, respectively. By modeling the profile evolution over this combined 8-octave range in frequency, it was possible to constrain both the accuracy of the $v^{-2}$ dispersive delay law for the ISM as well as the maximum emission height at these radio frequencies.

We are also studying the well-known, steep spectrum pulsar B0943+10. This source shows two distinct modes of radio emission, termed ‘Bright’ (B) and ‘Quiet’ (Q) — see Figure 1, left. Using a combination of simultaneous LOFAR (150 MHz), GMRT (350 MHz), and XMM-Newton (X-ray) data it was possible to show that the X-ray spectrum and timing properties change in concert with the radio mode switches — thus illustrating a rapid and global magnetospheric change (Hermsen et al. 2013). Follow-up LOFAR LBA observations can further illuminate the nature of the modal change. For instance, modeling of the 20–200 MHz profile evolution in the B/Q-modes indicates that the obvious switch in profile morphology does not necessarily indicate a large shift in the magnetospheric origin of the emission (Bilous et al., in prep.; Figure 1, right). This work also identified a more gradual profile evolution during the B-mode, which appears to reset at the beginning of each mode instance.

3. Interstellar weather and millisecond pulsars with LOFAR

Propagation effects in the ionized ISM become very strong towards low frequencies: dispersive delays and scattering times go as $v^{-2}$ and $\sim v^{-4}$, respectively. Though this can seriously hamper the detectability of a pulsar signal at LOFAR frequencies, it also gives a strong lever arm for studying subtle and/or dynamic effects. We are preparing a sample of LOFAR scattering measurements to test the frequency power-law of the
delay (Zagkouris et al., in prep.). For some sources we can do this using a single, wide-band HBA observation (e.g. Figure 2).

For millisecond pulsars (MSPs), better characterizing the dynamic effects of interstellar propagation takes on a practical importance: to maximize the precision with which an ensemble of MSPs can be used as a pulsar timing array requires careful correction for DM variations (e.g. Keith et al. 2013). Low-frequency MSP observations thus have the potential to better characterize the effects that the ISM has on limiting timing precision; such observations could also in principle provide an ISM weather report to correct high-frequency timing data. In a LOFAR census of 55 MSPs, we have successfully detected 38 pulsars in the high-band and 3 in the low-band (Kondratiev et al., in prep.). Some example detections are shown in Figure 3. In the case of non-detections, scattering likely plays a role in many cases, though spectral turnover may also be relevant for some sources (Hassall et al., in prep.). Regular monitoring of DM can be done for a large fraction of the detected sources, with single epoch DM uncertainties on the order of $10^{-4} - 10^{-5}$ pc cm$^{-3}$ in many cases. The importance of variable scattering delays also remains an open question. This is being investigated in detail using cyclic spectroscopy to measure the very fine frequency width of the scintles in the LOFAR band (Stinebring, Archibald et al., in prep.).
4. LOTAAS: the LOFAR Tied-Array All-Sky Survey

Capitalizing on LOFAR’s large field-of-view, we are performing LOTAAS, the LOFAR Tied-Array All-Sky Survey. LOTAAS uses both a coherent and incoherent sum of LOFAR’s 12 ‘Superterp’ HBA sub-stations (see van Haarlem et al. 2013, for an explanation of this terminology) to produce a combined field-of-view of 9 and 30 square degrees, respectively (Figure 4). The 183 coherent beams per pointing are densely clustered to give roughly uniform sky coverage. The 3 large incoherent beams provide a larger field-of-view, but at $\sqrt{12}$ reduced sensitivity. An additional 36 coherent beams are manually pointed at known pulsars within the field, in order to provide useful data in parallel. The survey records from 119–151 MHz with 2592 12-kHz channels and 492 $\mu$s sampling. The resulting data rate to disk is an amazing 36 Gb/s, resulting in 4 TB per pointing once the data are converted to 8-bit samples.
Figure 5. From left to right LOFAR pulsar discoveries #1–4: PSRs J0140+56, J0607+37, J1529+40, and J0935+33. These plots are all from 30-min confirmation observations using the Full Core, which provides better S/N and localization than the discovery observations that use only the Superterp. An up-to-date list of LOFAR pulsar discoveries, as well as localization plots for new discoveries, is available here: http://www.astron.nl/lotaas/.

A unique aspect of LOTAAS is the large on-sky time: 1 hr per pointing. This pushes into a new parameter space for highly intermittent pulsars as well as fast radio transients like those reported by Thornton et al. (2013). Though scattering and sky temperature will severely limit the survey at low Galactic latitudes, well above the Galactic plane it will be possible to see sources to a much larger distance. Indeed, LOTAAS is partly conceived as a survey for nearby, low-luminosity pulsars which can be used for extrapolating to the entire Galactic population and which can serve as excellent multi-wavelength follow-up sources (though they may be faint in radio, they could be good X-ray or γ-ray targets).

Thus far we have acquired 225 survey pointings (Figure 4). Processing of the data is a major challenge because of the large data volume (900 TB collected so far), large number of required DM trials, and long dwell times. Searching, both via Fourier-based and single-pulse techniques, is currently being tackled with the Dutch national super-computer Cartesius, which provides thousands of cores. The search effort is only beginning to ramp up, and the next challenge will be to sift through the millions of candidates that will ultimately be generated. This will require machine learning and artificial intelligence techniques developed for other pulsar surveys. Nonetheless, the first discoveries are being made, with 2 recent LOTAAS discoveries as well as 2 new pulsars found as part of commissioning surveys (Coenen 2013). LOFAR’s first 4 pulsar discoveries are shown in Figure 5. Three of these pulsars are at distances of only 600–700 pc (according to the NE2001 model of Cordes & Lazio 2002), placing them amongst the closest 10% of pulsars.
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References

Coenen T., 2013, PhDT, ‘Searching for Pulsars with LOFAR’, University of Amsterdam
Hermsen W., et al., 2013, Sci, 339, 436
Thornton D., et al., 2013, Sci, 341, 53