LOFAR: a Powerful and Flexible Observatory for Pulsars and Fast Transients

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Abstract

The Low-Frequency Array (LOFAR) is a sparse aperture array radio telescope that can observe from $10 - 240\,\mathrm{MHz}$ - i.e. the lowest radio frequencies observable from Earth. Construction of the LOFAR core is all but complete and regular observations of pulsars and other rapidly varying radio sources have begun. With it's huge field-of-view (FoV), flexible multi-beaming capabilities, and large collecting area, LOFAR promises to revolutionize observations of transient radio phenomena with durations of nanoseconds to years. Here we highlight a few of the most recent LOFAR pulsar observations, which demonstrate that the system is already producing science-quality data.

1 Introduction

The LOFAR radio telescope is an array of 48 multi-antenna stations, with a dense core in the Netherlands and international stations across Europe - see [1] for a detailed system description. Each station forms one or multiple "station beams", which are the coherent sum of all the station's antennas, and these can be combined to produce high-resolution interferometric images and/or high-sensitivity, high-time-resolution array beams [2]. LOFAR uses two separate antenna types in order to observe from $10 - 90\,\mathrm{MHz}$ (low-band antennas, LBAs) and $110 - 240\,\mathrm{MHz}$ (high-band antennas, HBAs). This gives almost complete spectral coverage of the lowest 4 frequency octaves observable from Earth. LOFAR will revolutionize our view of this relatively under-studied part of the electromagnetic spectrum and the scientific applications range from, e.g., detecting the Epoch of Reionization, to wide-field imaging surveys of the Galaxy and beyond, understanding Galactic magnetism, cosmic rays, mapping the transient radio sky, and monitoring the Sun and Solar System. Here we discuss LOFAR's application as an observatory for studying pulsars and "fast" (sub-second) radio transients.

Pulsar observations require microsecond to millisecond time resolution, which is currently too fast to be done with standard interferometric imaging techniques. Thus, for pulsar observations, the station beams are summed, instead of being correlated, in order to synthesize a single or multiple high-sensitivity array beams. For instance, the beam powers (square of the complex samples) can be added with the appropriate geometrical time delay in order to produce "incoherent array beams", which maintain the large single-station FoV. Alternatively, proper phase delays can be applied to the complex station signals in order to form "coherent array beams", which have a more restricted FoV but a higher raw sensitivity - see [3] for a more detailed discussion. The single station sensitivity is also high enough to be interesting for regular monitoring of bright sources, where total observing time is more important than raw sensitivity.

There is a broad science case for observing pulsars at low frequencies. These topics are described in detail in [2], and here we give just a few highlights. The wide fractional bandwidth provided by LOFAR - potentially the entire $10 - 240$-MHz range if the array is divided into sub-arrays - is interesting for studying frequency dependent properties like the flux density, pulse profile morphology, and pulse energy distribution. All of these properties impact on our general understanding of the radio pulsar emission mechanism. At low radio frequencies the intrinsic pulsar signal is strongly affected by propagation effects in the interstellar medium (ISM), such as scattering, dispersion, and scintillation. Though this poses challenges and limitations to the observation of pulsars at low frequency, it also provides an excellent opportunity to use pulsars as probes of the ISM, including polarimetric observations which can map the Galactic magnetic field. LOFAR's wide FoV, multi-beaming capabilities, and large sensitivity also make it well-suited to searching for *new* pulsars.

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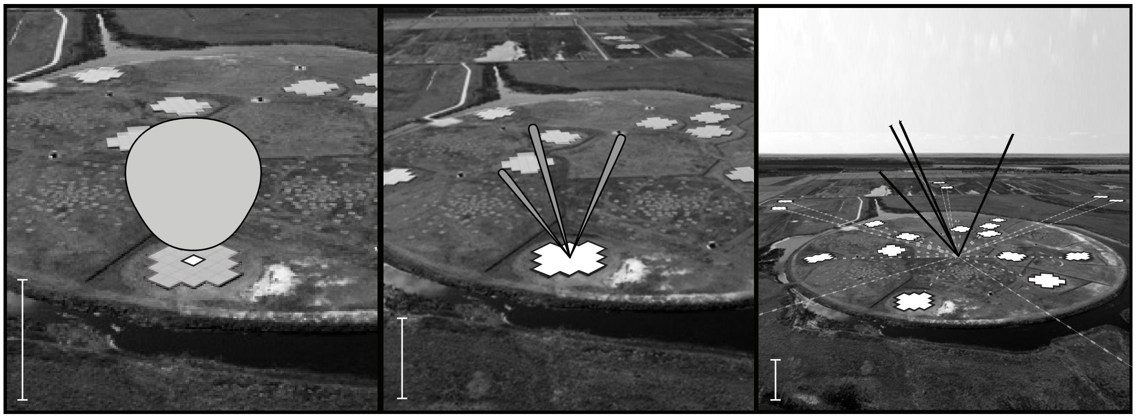

Figure 1: The LOFAR core and Superterp (circular island). The picture zooms out and, from left to right, shows the single element, single station, and tied-array (all 24 core stations combined) FoVs. The vertical bar depicts a constant spatial scale for reference.

For comparison, the LOFAR single station FoV is roughly 23 sq. deg, approximately a factor of 100 times larger than the FoV of a 100-m single-dish telescope operating at 350 MHz. This capability is being exploited to perform all-sky surveys for pulsars and other similar signals.

2 Recent LOFAR pulsar observations

Here we give a sample of some of the most noteworthy recent observations with LOFAR. Additional new results will certainly be in hand before the URSI GASS and will also be presented there.

Coherent dedispersion: For observations of very rapidly rotating pulsars, the so-called millisecond pulsars (MSPs), the LOFAR frequency resolution is insufficient to properly dedisperse the signal. Dedispersion, which causes the broad-band signal to arrive later at lower frequencies, can be corrected by shifting spectral channels in time. This "incoherent dedispersion" technique is insufficient for MSPs because the residual dispersive smearing within a channel is still too large. Furthermore, increasing the spectral resolution quickly leads to an insufficiently short sampling time (e.g. 0.7-kHz channels can be created and are adequate for dedispersion but the resulting time resolution of 1.3 ms is insufficient to resolve the typically $\sim$ 100-μs wide pulses of MSPs). Coherent dedispersion addresses this issue by also compensating for the intra-channel dispersion correction. Figure 2 (left) shows the first successful online implementation of coherent dedispersion with LOFAR.

Tied-array observations: The maximum raw sensitivity comes from adding the antennas "coherently", meaning that the differential phases between elements are corrected for. A coherent summation of numerous station beams is referred to as a "tied-array" beam. Phase differences arise from geometrical, instrumental, and environmental sources. Differential ionospheric phase delays between stations require realtime ionospheric calibration in order to form tied-array beams across the full LOFAR core (24 stations spread over an area of 2×2 km). Clock drifts between LOFAR stations are also relevant as most stations receive a separate clock signal and can drift with respect to each other by up to $\sim$ 20 ns. For the 6 stations on the LOFAR "Superterp" (the inner 300-m of the array), a single clock signal is used, eliminating the necessity for a dynamic, clock-related delay correction. This has allowed us to calibrate the remaining instrumental delays and to combine these stations coherently into a tied-array beam. This provides a great jump in sensitivity compared with the incoherent sum of these stations, as shown in Figure 2 (right).

"All-sky" multi-beaming: One of LOFAR's most powerful capabilities is the forming of multiple station beams within the single element FoV (the entire visible sky in the case of the LBAs and a 20-deg FoV in the case of the HBAs). This is done by partitioning the available observing bandwidth (up to 48 MHz)

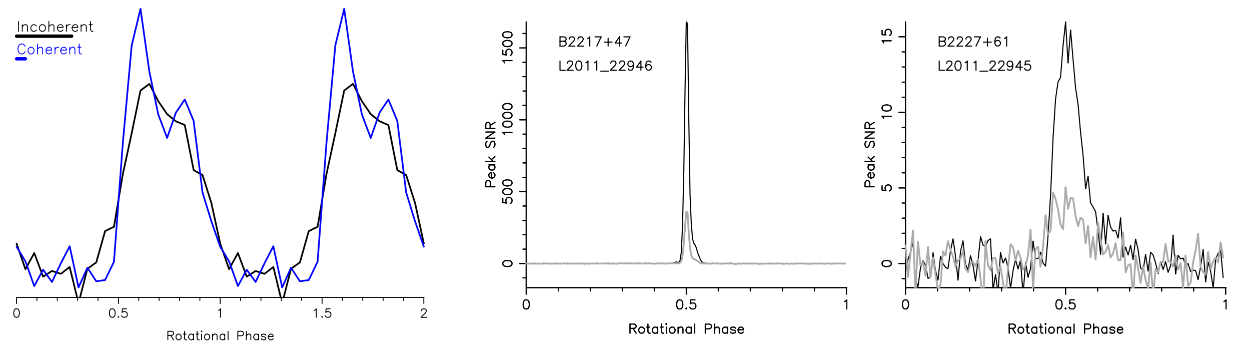

Figure 2: *Left:* Two observations of the 1.88-ms pulsar J0034-0534 are shown in order to display the difference between coherent and incoherent dedispersion. The increased effective time resolution of the coherently dedispersed data is evident from comparing the two profile morphologies (also shown schematically by the lengths of the two horizontal legend bars). *Right:* Comparison of the incoherent/coherent sum of the station beams for the 12 Superterp HBA sub-stations. Compared with the incoherent sum (grey line), the coherent sum (black line) of the stations provides an increased sensitivity proportional to roughly the square-root of the number of stations being combined (roughly 3.5 in this case).

and allows the simultaneous observation of multiple, widely separated sources which is useful for surveys, realtime calibration, monitoring transients, and in general will allow for more efficient use of the telescope. To demonstrate this, we simultaneously observed 5 pulsars spread across the observable sky (Figure 3, left). One of the many pulsar applications provided by such observations is the ability to frequently monitor numerous pulsars in order to catch rare anomalies in their rotational rate - e.g., the so-called timing “glitches”.

Wide-bandwidth observations: LOFAR stations can transfer up to 48 MHz of bandwidth back to the central processing, which combines the station signals. By dividing the array, it is possible to allocate stations in such a way to obtain near complete spectral coverage from $10-240$ MHz (the $90-110$ MHz window is filtered). Many pulsars display significant changes in their pulse profile morphology across this large fractional bandwidth range. For instance, profiles often become *intrinsically* broader towards lower frequencies (theorized to be due to radius-to-frequency mapping of the emission height in the pulsar magnetosphere), and in some cases new profile components become visible (as shown in Figure 3, right).

3 Future prospects and challenges

Here we briefly discuss a few of the observing projects that are currently underway and some of the major challenges we foresee for the coming year.

Pulsar/fast transient searches: With a large fraction of the LOFAR core complete, we have begun making a shallow survey of the sky - the LOFAR Pulsar Pilot Survey (LPPS) - for new pulsars and other fast transients. This is being done with an incoherent summation of the available stations in order to maintain a large FoV. We are also dividing the observing bandwidth into 7 beams of 7 MHz each in order to achieve a very large 160 sq. deg FoV per 1-hr pointing. This allows us to survey the entire northern hemisphere using only about 100 pointings. Processing of these data is underway.

Reaching maximum sensitivity: With properly calibrated Superterp tied-array beams, we are already within a factor of a few of the ultimate raw sensitivity that will be achievable with LOFAR in the next years. The final step is now to form tied-array beams that incorporate all 24 core stations. This will in principal provide 4 times the raw sensitivity of the 6 Superterp stations alone but comes with added challenges related to clock drifts and ionospheric calibration (see §2).

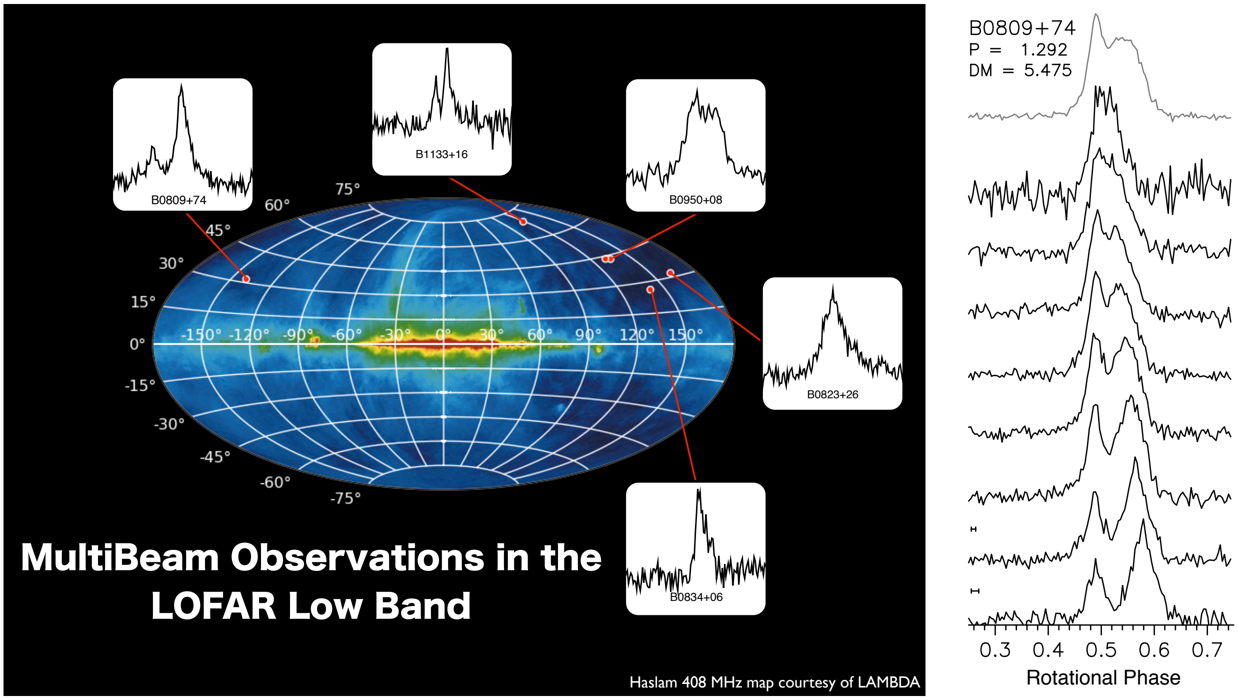

Figure 3: *Left:* An all-sky radio map showing the positions and cumulative pulse profiles of 5 pulsars simultaneously detected with the LOFAR LBAs. *Right:* Cumulative pulse profile of PSR B0809+74 as a function of frequency. The lower 8 profiles correspond to frequencies of 35, 41, 47, 53, 59, 65, 71 and 77 MHz respectively (from bottom to top). The top profile shows the summed profile from all 8 bands.

Increasing bandwidth: Each of the LOFAR antenna types has sensitivity over a ~ 100-MHz bandwidth, but only 48 MHz can currently be transferred back from the station because of limitations on the transfer rate through the 10-gbit fiber connections. In the current scheme, station data are sent as 16-bit samples in order to provide sufficient dynamic range to mitigate interference. We are currently investigating 4 and 8-bit modes that would double the available bandwidth that can be recorded from each station.

In conclusion, recent observations of pulsars with LOFAR show that the system is already capable of producing excellent, science-quality data. Many of the techniques required to make LOFAR work will also be vital for the Square Kilometer Array (SKA), and are being pioneered as part of LOFAR commissioning.

4 Acknowledgments

LOFAR, the Low Frequency Array designed and constructed by ASTRON, has facilities in several countries, that are owned by various parties (each with their own funding sources), and that are collectively operated by the International LOFAR Telescope (ILT) foundation under a joint scientific policy.

5 References

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