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## The Radio Sky on Short Timescales with LOFAR: Pulsars and Fast Transients

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**Abstract.** LOFAR, the “low-frequency array”, will be one of the first in a new generation of radio telescopes and Square Kilometer Array (SKA) pathfinders that are highly flexible in capability because they are largely software driven. LOFAR will not only open up a mostly unexplored spectral window, the lowest frequency radio light observable from the Earth’s surface, but it will also be an unprecedented tool with which to monitor the transient radio sky over a large field of view and down to timescales of milliseconds or less. Here we discuss LOFAR’s current and upcoming capabilities for observing fast transients and pulsars, and briefly present recent commissioning observations of known pulsars.

### 1. Monitoring the (Low-Frequency) Radio Sky at High Time Resolution

A key factor in successfully studying the dynamic and explosive events associated with compact objects is the ability to monitor a large area of the sky continuously for transient sources. This has been done for many years now, and with great success in, e.g., X-ray astronomy, where “all-sky” monitors onboard a number of space-based telescopes can alert the community to exotic transient events and trigger directed, multi-wavelength observations. The ability to do similar, sensitive all-sky monitoring in the radio regime would open up a largely unexplored domain: “the transient radio sky” (see, e.g., Cordes et al. 2004). Despite the strong scientific motivation to characterize radio transients on a wide-range of timescales, this exploration is hampered by technical challenges intrinsic to radio astronomical observations. The observational requirements are well summarized by the following simple figure of merit (FoM), which applies in general to any transient survey<sup>1</sup> (see also Cordes et al. 2004; Cordes 2008, and references therein for a deeper discussion of survey metrics):

$$FoM \propto A_{eff}^2 \frac{\Omega}{\Delta\Omega} \frac{T}{\Delta T} \quad (1)$$

To effectively probe transients over a wide range of source parameter space, including faint and rare events, one must maximize this FoM and hence also

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<sup>1</sup>Here we choose to give an extra weighting to  $A_{eff}$ . One may also consider a FoM that scales linearly with  $A_{eff}$ .

maximize:  $A_{eff}$ , the effective collecting area, i.e. raw sensitivity, of the detector;  $\Omega$ , the instantaneous field of view (FoV); and  $T$ , the total time spent observing the sky. At the same time, one should also maintain adequate spatial ( $\Delta\Omega$ ) and time ( $\Delta T$ ) resolution to provide reasonable source localization (crucial for multi-wavelength follow-up and identification) and to resolve short timescale phenomena.

Traditional “single pixel” large single dish radio telescopes and standard radio interferometers fall short of providing a good FoM because they cannot simultaneously provide high sensitivity and large FoV. One way to achieve both of these requirements is to combine the signals of many small elements, each with close to “all-sky” FoV, to produce multiple, sensitive beams on the sky. Such a telescope makes use of large computing resources to do more with the signals received by each element, and could appropriately be dubbed a “software telescope”. Such instruments are important pathfinders to the Square Kilometer Array (SKA), which will ultimately provide a monumental leap in our ability to monitor the radio sky in real time (e.g. Cordes 2008). Here we discuss specifically the low-frequency array (LOFAR), which incorporates many innovative techniques and will itself revolutionize our ability to observe the transient radio sky.

Perhaps the regime in which the transient radio sky has been least well characterized is on timescales of seconds and shorter. These timescales are too short to be probed satisfactorily by standard imaging techniques, but can be well studied with beam-formed timeseries, i.e. “pulsar-like”, data. LOFAR will provide both pulsar-like and imaging data, to a certain degree simultaneously. In addition to opening a new window on the transient radio sky, LOFAR will probe the relatively unexplored spectral window of  $\sim 30 - 240$  MHz, the lowest radio frequencies observable from the Earth’s surface.

This low observing frequency presents its own opportunities, but also difficult challenges for observing “fast” transients (timescale  $< 1$  s) and pulsars. Ultimately, the effective time resolution of observations is limited by propagation effects in the interstellar medium such as scattering and dispersion, which become very strong at low frequency. Impulsive radio frequency interference (RFI) is also a major concern for time-domain based searches, although it can be mitigated by a number of signal processing techniques and the use of a many-element interferometer.

Despite these challenges, the potential scientific rewards of probing new parameter space(s) are enticing. In addition to targeted observations of known pulsars to study, for example, their single pulse properties (Stappers et al. 2007), an all-sky survey for pulsars and fast transients will be done (see van Leeuwen & Stappers 2008, for a survey simulation). This survey will discover potentially hundreds of new pulsars, and will likely detect the majority of the nearby ( $d < 2$  kpc) radio emitting neutron stars, including those that show transient behaviour (e.g. the “rotating radio transients” McLaughlin et al. 2006). At the same time, this survey is also sensitive to other types of sources showing (dispersed) sub-second bursts, for instance nearby exoplanets and flare stars, but potentially new source classes as well. A key advantage of such a LOFAR survey is that its large FoV allows for potentially long dwell times when doing an all sky survey, which is particularly important for identifying transients, especially rare events. Coupled

with an imaging “radio sky monitor” (Fender et al. 2008), LOFAR will repeatedly cover the sky to detect even extremely rare transient events with timescales of nano-seconds to years.

## 2. LOFAR Observing Modes for Pulsars and Fast Transients

The LOFAR telescope<sup>2</sup> is actually two separate arrays, operating respectively from 30 – 80 MHz (the Low-Band Antennae, or LBAs, which consist of single dipole antennae) and 100 – 240 MHz (the High-Band Antennae, or HBAs, which consist of integrated tiles of 16 phased dipoles each). These antennae are grouped into several dozen stations of 24 – 96 elements each, and will soon be spread over the Netherlands and neighbouring countries. The core of LOFAR has the highest filling factor (i.e. antennae per unit land area) in the array and provides the best compromise between raw sensitivity and FoV for most transient and pulsar searches. The first incarnation of LOFAR will have 36 core stations of 24 HBA tiles each, roughly 50% of the total collecting area of the array. Crucial to LOFAR’s operation is the Blue Gene P super-computer (hereafter BG/P) which combines the signals from the stations to produce either visibilities for interferometric imaging or (coherent) beams from combined elements. The fact that so much of LOFAR’s low-level signal processing is handled real time in software makes it a highly flexible system. In many ways, the system is more limited by the available processing power and the amount of data that can be transported back from the stations for processing than it is by the antennae themselves. Here we summarize the LOFAR observational modes, also largely applicable to other similar telescopes, most relevant to observing transients on short timescales.

**(Multiple) Station Beams:** Independent of BG/P, each LOFAR station is capable of forming a “station beam”, which is a coherent addition of all the elements within a station. Up to 8 independently pointed station beams can be formed simultaneously within the element primary beam pattern, each having a maximum total bandwidth of  $32/n_{beams}$  MHz. An advantage is that the observing bandwidth need not be contiguous, but rather can be spread over the entire available receiver band, avoiding areas of the spectrum that are consistently contaminated by strong RFI.

This simultaneous coverage over a fractional bandwidth of roughly 1/2 also provides the exciting possibility of catching fast transients in the act: identifying these in real time, first at the top of the band, and then adjusting the system to follow the source as it appears later at lower frequency. For instance, this could happen because of interstellar dispersion, which can easily cause a delay of several minutes to an hour at these low observing frequencies, compared with higher observing frequency.

One can imagine using the LOFAR stations separately, either single stations for projects requiring less collecting area but more total observing time or as a collective, each station covering up to 8 independent regions of the sky in a mode

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<sup>2</sup>For a broader description of the LOFAR system and a status update, see also de Bruyn et al. 2009 in these proceedings and references therein.

similar to the “Fly’s Eye” experiment running on the Allen Telescope Array (Siemion et al. 2008). Since each station still has a reasonable collecting area, comparable to that of a  $\sim 35$ -m single dish telescope, this mode is interesting for achieving the maximum possible sky coverage for relatively bright, but rare, events (Table 1). Note that at 160 MHz the largest possible FoV in this mode is still only about 9% of the entire sky at any given time (nonetheless a major leap forward compared with previous radio telescopes). This increases to roughly full hemispherical coverage at 40 MHz but, at this very low frequency, propagation effects like scattering are a very severe limitation to observing fast transients.

**Incoherent Station Summation:** To increase sensitivity, the signals from individual stations must be combined. An incoherent station summation corrects for the rough time, but not the phase delays between stations when observing in a particular direction (i.e. the signals from individual stations are first converted to powers and then summed). The net gain in sensitivity over that of a single station is in theory  $\sqrt{n_{stations}}$ , but can be better than this in practice because of better robustness to RFI. This summation is computationally inexpensive and has a comparatively low data rate (Table 1). It should furthermore be possible to run this mode piggy-backing on other (imaging) observations. This provides for a potentially enormous total time  $T$  spent on the sky. The drawback is that the instantaneous sky coverage is small compared with the Fly’s Eye mode mentioned above, and the size of the beams gives relatively poor positional constraints compared with a coherent addition of stations.

**Coherent Station Summation:** The maximum raw sensitivity comes from a *coherent* addition of the stations, in which appropriate phase corrections are applied before summing individual station beams. Since the beam size is now set by the longest baseline between the stations, this results in a comparatively narrow field of view. This is highly desirable for constraining the position of a new source, but precludes monitoring large portions of sky simultaneously. To increase FoV, one may synthesize many, potentially hundreds, of these “pencil beams” in order to cover as much of the station primary beam as possible. This mode provides both the highest achievable raw sensitivity and excellent positional information (Table 1). The primary drawback is that the data rate is *extremely* high and ultimately limits how often one can observe in this mode without first reducing the data to a much smaller set of analysis products. An additional possibility is to combine only the 12 stations contained within the 300-m LOFAR inner core, referred to collectively as the “Superstation”. This mode provides a nice compromise between raw sensitivity, FoV, and spatial resolution.

Table 1 summarizes and quantitatively compares these possible modes. There is no single mode which is best for *all* conceivable types of transients - for instance a mode with large instantaneous sky coverage but comparatively low raw sensitivity will be good for rare, bright transients but not for weaker sources. The use of multiple modes, covering complementary portions of transient parameter space, is thus advisable. Furthermore, one may also prefer to consider the FoM per TB of recorded data, especially if one is more limited by available processing power for offline analysis than by observing time. In such a case, the modes with very high data rates become less desirable, despite their much larger nominal FoM.

Table 1. Comparing LOFAR Beam-Formed Observing Modes

Mode	Sensitivity (Norm.)	FoV (sq. deg.)	Resolution (deg)	Data Rate (TB/hr)	FoM (Norm.)
Single Station	1.0 / 0.4	12.5 / 100	2	0.23	1.0 / 1.3
Fly’s Eye	1.0 / 0.4	450 / 3600	2	8.3	36 / 46
Incoherent Sum	6.0 / 2.1	12.5 / 100	2	0.23	36 / 35
Superstation	12 / 4.2	9.0 / 72	0.2	23	1040 / 1020
Coherent Sum	36 / 13	0.2 / 1.6	0.03	23	1380 / 1440

Sensitivities and FoMs have been normalized to that of a single 24-tile HBA station using a single beam of bandwidth 32 MHz. FoV and resolution are at 160 MHz. Quantities are quoted assuming one beam per station (32 MHz bandwidth) and 8 beams per station (4 MHz bandwidth per beam) respectively. All modes with the exception of “Single Station” assume 36 core stations of 24 HBA tiles are being included and can be recorded separately if desired. For the “Superstation” and “Coherent Sum” modes, we assume that 100 pencil beams can be synthesized, and that the maximum baseline between stations is 300 m and 2000 m respectively. The dwell time used in each mode is assumed to be the same, though this would likely differ in practice. The data rates assume 16-bit samples, summed in polarization, and at the maximum possible spectral/time resolution, which for certain applications can be downgraded by a factor of a few in order to save on disk space and processing load.

### 3. Commissioning Observations, Current Status, & Prospects for the Near Future

The LOFAR Pulsar Working Group is part of the larger, and more all encompassing, LOFAR Transients Key Science Project (see Fender et al. 2008, for a list of collaborators and basic science case), and is actively commissioning the telescope for pulsar and fast transient observations (with of course the crucial help of several developers and support scientists). A variety of observational considerations, including dispersion, scattering, spectral turn over, and sky background, make LOFAR’s high band ( $\sim 100 - 240$  MHz) preferable for most of the observations we are planning (note however that some transient sources, like planets, may only be observable in the low band). Our current test bed for high-band observations consists primarily of 4 HBA tiles, located at the LOFAR core site between Exloo and Buinen in the Dutch province of Drenthe. A number of observational milestones have already been achieved, including:

- Detection of integrated emission from several bright known pulsars, e.g. PSRs B0329+54, B1133+16, B1919+21, and B0809+74. These are being used as test sources to commission LOFAR beam-formed modes.
- “Blind” detection of dispersed single pulses from PSR B0329+54. This same technique is sensitive to general, short timescale, dispersed bursts.
- Multi-hour tracking observations far from the zenith, using the beam formed at station level (Figure 1).
- Coherent addition of multiple “stations” - in this case the 4 HBA tiles recorded separately - into a tied-array beam. Unlike the station beams themselves, this beam is formed on the BG/P.

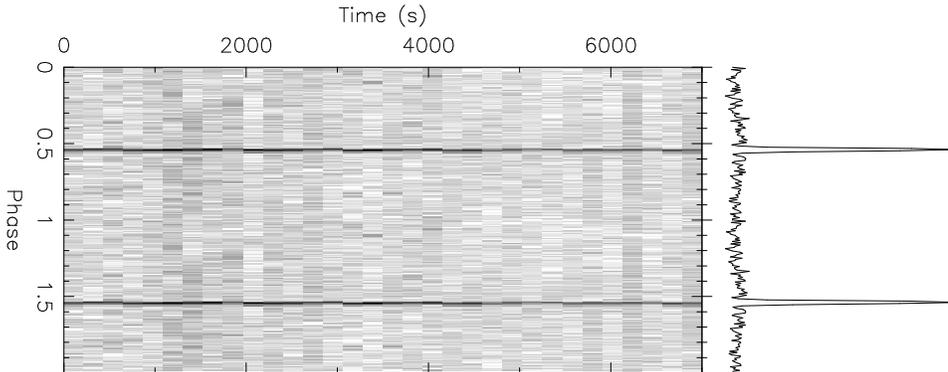


Figure 1. A roughly 2-hr LOFAR observation of PSR B1919+21 ( $P_{spin} = 1.34$  s,  $DM = 12$  pc cm $^{-3}$ ) from 2008 Nov 19. The signals from the 4 existing HBA tiles were combined at the station itself into a station beam and 46 subbands of 195.3125 kHz each were sent in real time via fibre back to the BG/P in Groningen. These subbands formed a contiguous bandwidth of 9 MHz, centred at 155 MHz. Folding and dedispersion (optionally coherent dedispersion) was performed offline on the recorded data.

We note that 4 HBA tiles constitute only 1/6 of a core station, and that the LOFAR core will, within the next two years, contain roughly 200 times as much collecting area as used in the current pulsar commissioning observations. For instance, we expect that the LOFAR core will have enough sensitivity to detect high S/N single pulses from roughly half of the known pulsars in the northern hemisphere. The functionality that is currently being implemented can be scaled relatively easily to meet this increase in collecting area. We look forward to making the first full-station observations in 2009.

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