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Searching for Low Frequency Radio Transients with LOFAR CS1

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The Low-Frequency Array (LOFAR) promises to revolutionize the study of transient radio phenomena. The first prototype station of LOFAR, Core Station 1 (CS1), is being commissioned in the northeast of the Netherlands. As a part of this commissioning, we have conducted a search for radio transients in the area of Cygnus A. This paper describes some of the physical processes expected to create low-frequency radio transients and the methods we will employ in the search for them. No clear celestial events were detected, so we give an upper limit to the rate of bright transient events near 60 MHz and describe what a similar survey may find in one year's time.

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1. Introduction

Transient and variable astronomical sources potentially hold a great deal of information about the physics of the Universe. Transient astronomical sources include stars, accreting compact objects, pulsars, supernovae, and more. With such a wide range of objects, the range of physical processes is also broad. Normal stars may vary due to a restructuring of their magnetic field, while clumpy or irregular accretion onto a compact object results in an uneven energy output by their radiation or jets. And although something as simple as rotation leads to the repeating pulse of a pulsar, related objects such as rotating radio transients (RRATs; [10]) and soft gamma repeaters (SGRs; [5]) are clear indications of more complex physics.

While many types of transient sources are already known, it is important to note that many others may remain undetected. Figure 1 shows one representation (courtesy of [2]) of the physical distribution of transient radio phenomena. The parameters plotted in the figure are related to luminosity and the duration of the event relative to its wavelength[1]. Guided by the idea that nature abhors a vacuum, one can argue that the empty parts of Figure 1 may be home to new types of transient astrophysical phenomena.

A goal of the LOFAR Transients Key Project is to search further and more sensitively through the transient parameter space at radio wavelengths [4]. By searching more sensitively, we hope to find new examples of variability caused by known radio transients, such as accreting compact objects, Gamma-ray bursts, and propagation effects of the ISM and IGM [3, 13, 7]. Expanding the known population of radio transients will drastically improve our understanding of how they operate. On the other hand, the systematic searches capable with LOFAR will reach into the unexplored regions of radio transients parameter space and, hopefully, uncover new and unusual objects.

The methods for searching for radio transients can be divided into two broad categories: imaging and nonimaging. Katz et al. [8] used the coincidence of signals in three, widely-separated radiometers to conduct an all-sky search for radio transients at 611 MHz. The distance between their radiometers acted as a filter against interference from terrestrial sources, which is a major source of confusion in nonimaging surveys, especially at low frequencies. Using this technique, they found a few thousand transient events that were all associated with solar radio bursts; they put an upper limit of 27 kJy on other transient events during their 18-month survey. Matsumura et al. [9] used the Nasu Observatory, a transit interferometer, to survey the sky for transients at 1.4 GHz. Their survey seems to have found a class of 1-3 Jy radio transients. An interesting example of an imaging survey for transients was conducted by Bower et al. [1] using archival VLA data at 5 and 8.4 GHz. They detected ten events with fluxes around 1 mJy. These studies represent some of the best measurements of the transient radio sky, but they seem to raise more questions than they answer. LOFAR's transient search technique takes the best of imaging and nonimaging approaches by searching images covering a large fraction of the sky at high cadence.

While this paper is focused on the search for exotic, or as-yet-unknown transients, one of the most active radio transients is our own host star. Figure 2 shows the correlated amplitude along one CS1 baseline during an early commissioning observation. During this observation there was a Type-III solar burst that reached a brightness of about 1 GJy (for 60 second integrations and 1 kHz

[1]One merit of using these axes is that it is easy to separate coherent ($T_B \gtrsim 10^{12}$K) from incoherent ($T_B \lesssim 10^{12}$K) emission.

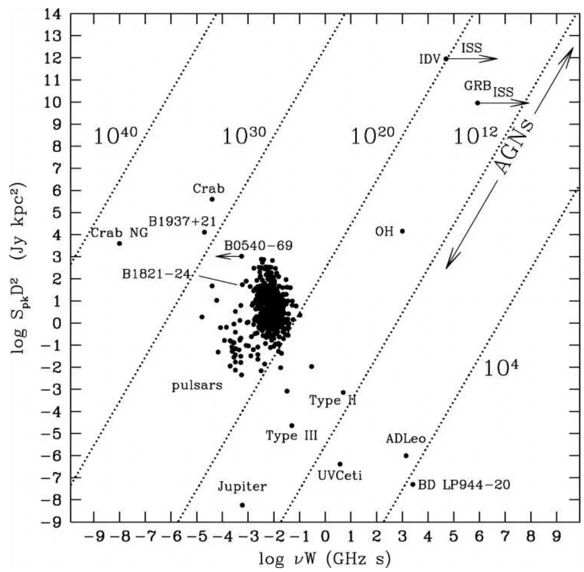

Figure 1: A figure from [2] showing the effective luminosity of transient events versus the product of its timescale and emission frequency. Diagonal lines show constant brightness temperature. Transient events shown on the plot include a wide range of physical systems, including pulsars, AGN, and radio-active stars. While parts of this parameter space are occupied, many new types of sources may lurk in the unexplored regions.

channels). During that burst, the sun was by far the brightest radio source in the sky. However, the focus of our project is finding more unusual objects, objects that can only be observed by next-generation telescopes like LOFAR.

This paper describes the first step in commissioning LOFAR in the search for radio transients. We have observed a region near Cygnus-A with the first station of LOFAR, "Core Station 1" (CS1). Section 2 describes the observatory in more detail and how the observations were done, §3 gives the results of our survey, and §4 concludes with an optimistic prediction for a future search for transients with LOFAR.

2. Observations and Analysis

CS1 is the first station of LOFAR and is located in the northeast of the Netherlands. CS1 was constructed with prototype hardware as a test of the design of a full LOFAR station. It consists of 96 pairs of dipoles with a maximum baseline of 200 m. Dipoles are distributed into a central group of 48 and three outer groups of 16. The arrangement of dipoles in CS1 reflects the distribution of stations in full LOFAR, which will have a dense core with multiple, irregularly-spaced arms.

At the time of this survey for transient sources, only sixteen signals could be correlated. We chose to conduct our observation with fifteen dipoles from the outer part of CS1 plus the coherent sum of the central 48 dipoles. The "beam" formed by the coherent sum of the central 48 dipoles has a FWHM of roughly 5°, while the individual dipoles are essentially sensitive to the entire sky. The signals from the central 48 dipoles were summed with a phase delay that points to J2000 coordinates (20h10m00s,+40°30′). This location is roughly two degrees from Cygnus A

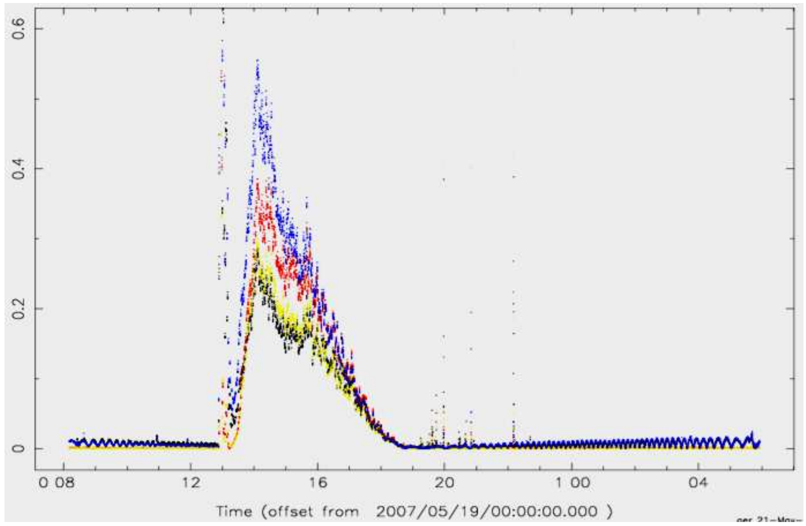

Figure 2: A plot of the correlated amplitude (with units of relative intensity) as a function of time (in hours) from a CS1 baseline during a Type-III solar burst. The initial spike near 13h had a flux of roughly a GJy, while the broad activity was several hundred kJy. The fringe seen at later times is from what are normally the brightest sources in the sky: Cas A and Cyg A.

(19h57m42,+40°35′54), one of the two brightest sources in the sky at frequencies below 1 GHz. The location was chosen partly because the self-calibration solutions from Cygnus A are most accurate for the region near Cygnus A; phase errors across the 200-m array introduced by the ionosphere reduce sensitivity for angular separations larger than a few tens of degrees. A second reason to study this field is that the Cygnus region is a rich star-forming region with known x-ray and radio transients (e.g., [11]).

Our survey consisted of four, 12-hour observations during the transit of Cygnus A. The frequency coverage of the data used in this survey was centered near 60 MHz and had a bandwidth of about 1 MHz. The data were self-calibrated by assuming that the sky is dominated by Cassiopeia A and Cygnus A, each with a flux density of 20 kJy [6]. All baselines shorter than 100 meters were ignored, which effectively removes any Galactic plane contribution to the visibilities and mostly validates the assumed sky model. The calibration solutions toward Cassiopeia A and Cygnus A were used to subtract their respective contributions to the visibilities; the residuals were corrected with the calibration solution of Cygnus A. This entire process was performed with the MeqTrees system [12].

The data were imaged with the aips++ imager. We made all-sky images from the data with a pixel size of 120″. This significantly over-resolves the FWHM of CS1 at 60 MHz, which is about 0.°7. All images used for this study are produced by an inverse fourier transform of the visibilities and no cleaning algorithm is used; this is possible since the distribution of dipoles in CS1 gives a psf with relatively weak sidelobes. An example of one of the best images produced by the MeqTrees calibration system in mid-2007 is shown in Figure 3. This dataset has Cassiopeia A at the center, although it has been subtracted from the data prior to imaging (Cygnus A is visible, since it was not calibrated as well). Improvements to the calibration system can now produce much

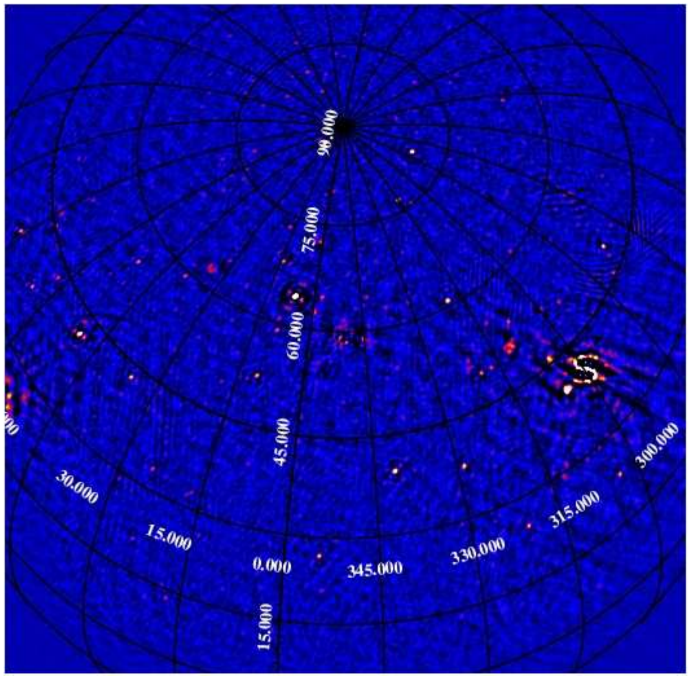

Figure 3: The best calibrated all-sky image from CS1, as of mid-2007. The field is centered on Cas A, which has been subtracted from the data; the "S"-shaped source on the bottom right is a remnant from the imperfectly-subtracted Cyg A. A few dozen sources with brightness up to about 300 Jy are visible in this image, which was made with a 24-hour integration and 4 MHz bandwidth. At the time of this writing, images have been produced with several *hundred* sources.

higher quality maps, but this image is shown to indicate the quality of calibration possible at the time of the survey.

The large volumes of data to be searched for transients makes it important to develop an automated system. We refer to this as the "transient detection pipeline" and it is one of the main software developments of the LOFAR Transient Key Project. The basic idea is to image the data on a range of time scales and difference neighboring snapshot images to find sources in the field that change with time. If a source changes on a time scale that we are studying, it should appear in the differenced image as a positive or negative source, depending on whether the flux increased or decreased. The shortest time scale probed in this study is 0.5 hours, since the computational time required to make the images becomes very large on shorter time scales. The longest time scale probed is 8 hours, which is the amount of time that the Cygnus A region spends at an elevation higher than $\sim 40^{\circ}$, where calibration is most trustworthy.

3. Results

Figure 4 shows a typical, 8-hour, all-sky image made from our calibrated data. The brightest source in the center of the image is the imperfectly-subtracted residual of Cygnus A. The second, elongated feature seen left of Cygnus A was a candidate transient. Imaging the data on smaller time scales showed that the source did indeed vary in brightness, but also that it seemed to move on

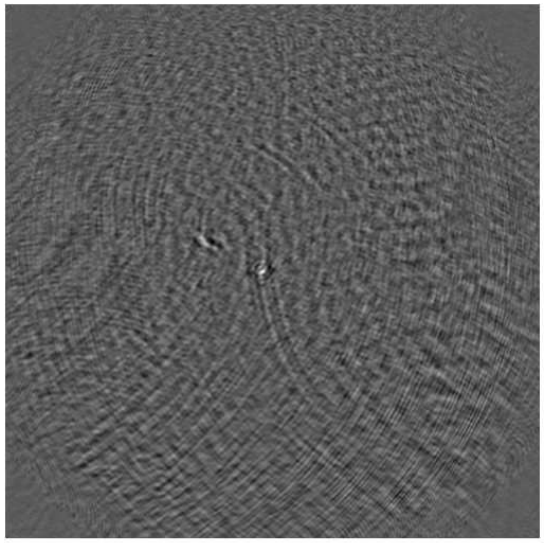

Figure 4: An example of an all-sky image produced by CS1. This image was generated from calibrated data with the brightest sources removed from the *uv* data.

the sky by a few degrees (giving the elongated shape in the 8-hour integration). Furthermore, the source seemed to appear near the horizon, where interference is most likely. For these reasons, we rejected this and two other candidate transients. After differencing images from the four, 12-hour data sets on time scales from 0.5–8 hours, we found no transient events that were clearly celestial.

At a given time scale, the number of images gives us an upper limit to the duty cycle of bright transients. Assuming the number of transients detected follows a Poisson distribution, we can use nondetection to constrain the rate of events at a given sensitivity. The probability of zero events is $P(N_{\rm det} = 0) = e^{-f*N}$, where f is the event rate and N as the number of samples of the distribution. In the context of our observations, we can think of f as the duty cycle of the event (i.e., the fraction of time the event is on) and N is number of observations; this assumes the transient has a time scale similar to those probed by the images. Solving for a 95% upper limit, we find $f < 3/N$. This relation allows us to connect the number of images at a given time scale to an upper limit on the duty cycle.

Figure 5 shows the limits imposed by our survey on the the flux and duty cycle of transient events near the Cygnus A region. Transients with brightness at 60 MHz of 100 Jy and duty cycles of greater than several percent are excluded. Note that at the highest duty cycles, the flux limit goes down because the images have longer integrations and lower noise levels. The names of well-known transients are shown (with approximate positions) in the plot, with a particular focus on bright transients that vary on hour time scales. At the highest duty cycles, our assumptions of break down, since individual events from a source are more likely to overlap, reducing the apparent variability.

Although our survey with CS1 only gives rough upper limits to transient event rates, the future for LOFAR holds great promise. In the middle of 2008, LOFAR plans to have twenty stations built. Considering a factor of twenty improvement in collecting area and an additional gain from

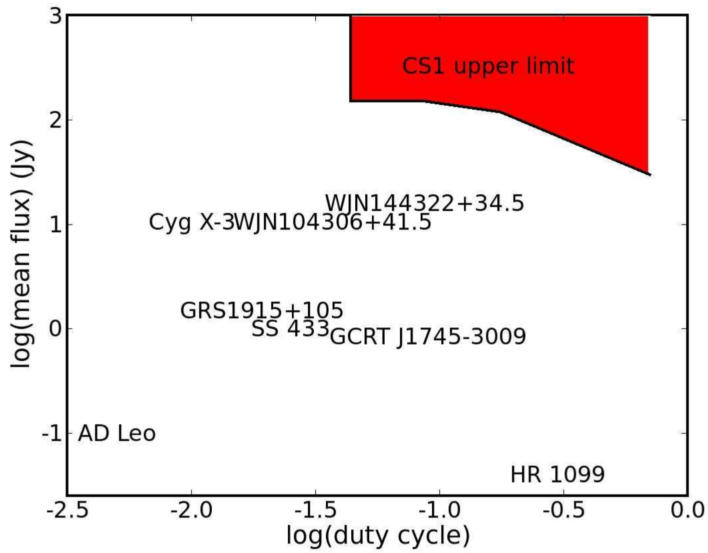

Figure 5: A plot of the limits on the flux and duty cycle of transient radio events during the CS1 observations. The number of maps made at a given sensitivity give a constraint on the duty cycle of events, assuming they follow a Poisson distribution. The locations of known transient radio events are also shown based on a rough estimate of low-frequency radio activity (e.g., [11, 9]).

improved calibration and source analysis pipelines, a similar survey in mid-2008 is likely to have more exciting results. Figure 6 shows the 95% upper limit on the transient events for a similar (4 12-hour observations, 1 MHz bandwidth) survey in mid-2008. This kind of survey will have a good chance of detecting bursts from Cyg X-3 or the type detected by the Nasu Observatory.

4. Conclusions

We report on the results from a commissioning project for LOFAR CS1 to survey for transients near Cygnus A. The calibration and transient search pipelines are described, giving a view of some of the challenges of working with a next-generation, low-frequency radio observatory. We searched our 4, 12-hour observations for transients with time scales from 0.5–8 hours, but found none. Assuming the number of transients detected follows a Poisson distribution, we give upper limits to the duty cycle and flux of transients near Cygnus A. We project that a similar survey in the middle of 2008 will likely find bright transients such as Cyg X-3.

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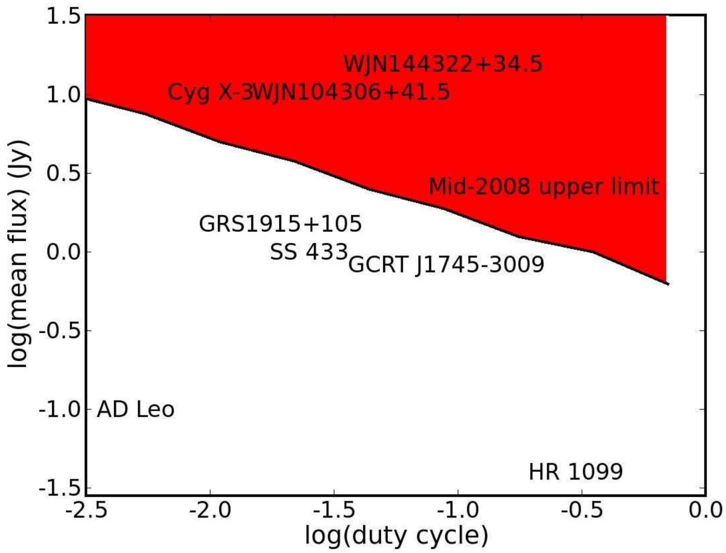

Figure 6: A plot similar to Figure 5, but showing the expected limits for a similar survey by LOFAR in the summer of 2008.

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