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Amsterdam–ASTRON radio transient facility and analysis centre: towards a 24 × 7, all-sky monitor for the low-frequency array (LOFAR)

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The Amsterdam–ASTRON Radio Transient Facility And Analysis Centre (AARTFAAC) project aims to implement an all-sky monitor (ASM), using the low-frequency array (LOFAR) telescope. It will enable real-time, 24 × 7 monitoring for low-frequency radio transients over most of the sky locally visible to the LOFAR at time scales ranging from seconds to several days, and rapid triggering of follow-up observations with the full LOFAR on detection of potential transient candidates. These requirements pose several implementation challenges: imaging of an all-sky field of view, low latencies of processing, continuous availability and autonomous operation of the ASM. The first of these has already resulted in the correlator for the ASM being the largest in the world in terms of the number of input data streams. We have carried out test observations using existing LOFAR infrastructure, in order to quantify and constrain crucial instrumental design criteria for the ASM. In this study, we present an overview of the AARTFAAC data-processing pipeline and illustrate some of the aforementioned challenges by showing all-sky images obtained from one of the test observations. These results provide quantitative estimates of the capabilities of the instrument.

1. Introduction

The recent serendipitous discoveries of several astrophysical radio transients at a variety of flux and time scales [1] have opened up a new window in the

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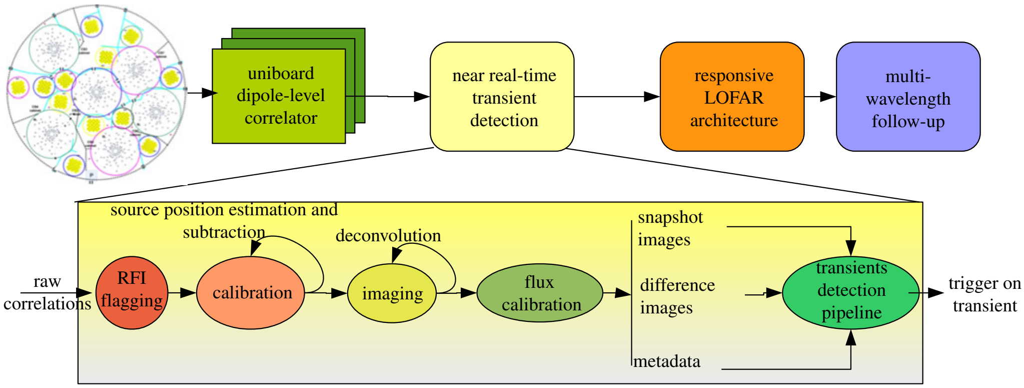

Figure 1. The main components of the AARTFAAC all-sky monitor. Signals flow from left to right. RFI, radio frequency interference. (Online version in colour.)

search for exotic objects of both known and unknown type. It is felt that the transient or dynamic radio sky, especially at low frequencies, will be rich enough to benefit from blind surveys along the lines of wide-field instruments at higher energies (X- and gamma-rays), which have been very successful at detecting transient sources. At low radio frequencies, a possible population of rare, but bright transients has been revealed, although only serendipitously. Owing to their rarity, detection of such sources can benefit from continuous sky monitoring with instruments having as wide a field of view as possible, even while trading-off sensitivity.

In this context, the Amsterdam–ASTRON Radio Transient Facility And Analysis Centre (AARTFAAC, a collaboration between the Netherlands Institute for Radio Astronomy (ASTRON), the University of Amsterdam and the Oxford e-Research Centre) aims to implement a near real-time, 24×7 all-sky monitor (ASM) for the low-frequency array (LOFAR) [2]. Such an instrument will enable detection and monitoring of low-frequency radio transients over most of the sky locally visible to the LOFAR, at time scales ranging from seconds to several days. In the following sections, we introduce the ASM in more detail, and present some initial results.

2. The AARTFAAC all-sky monitor

Each station of the LOFAR is itself a subarray composed of two kinds of receiving elements: dipoles or low-band antennas (LBAs), operating between 10 and 80 MHz, and phased array tiles of 4×4 high-band antennas (HBAs), operating between 110 and 240 MHz. The ASM will use six stations at the heart of the LOFAR and will be a zenith-pointing, transit mode instrument. This configuration makes the ASM a 288-element dual or 576-element single polarized array spread over approximately 350 m, thus providing almost full UV coverage with a well-defined point spread function which does not change with time. The ASM requires correlation between signals from all paths in order to image the full element field of view (2π sr, or the entire local celestial hemisphere for LBAs and approx. 1.5–10% of the sky for the HBAs, depending on the observing frequency). To enable continuous monitoring, the ASM will operate in a piggyback fashion simultaneously with regularly scheduled observations, sharing their observational parameters. The overall control flow and main components of the ASM are depicted in figure 1. The AARTFAAC correlator will have 576 inputs, requiring the estimation of approximately 1.65×10^5 correlations for each spectral channel. In its implementation [3], correlation is distributed on station-based hardware (built on the uniboard project), with a 24 kHz spectral and 1 s temporal resolution (to prevent time and bandwidth smearing). The 60 MHz resolution of 0.8° leads to a confusion noise of approximately 8 Jy, whereas the 0.4° resolution at 160 MHz leads to a confusion noise of approximately 1 Jy. The ASM sub-band images (approx. 200 kHz, thermal noise of approx. 8 Jy at 60 MHz, approx. 0.6 Jy at 160 MHz) are hence expected to be confusion noise, rather than

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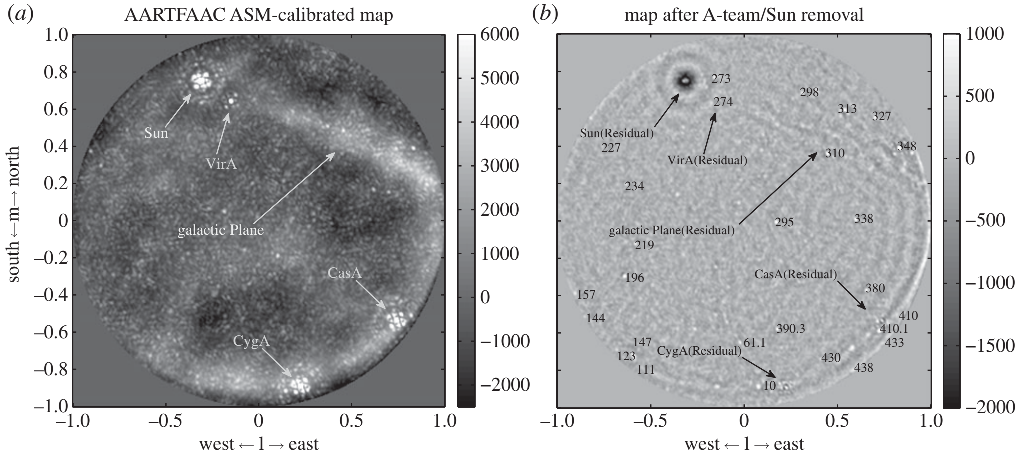

Figure 2. All-sky zenith tangent projection maps in local coordinates, intensity in arbitrary units. (*a*) Phase and gain calibrated map with flaring Sun, CasA, CygA and galactic plane visible. (*b*) Subtracting the Sun and bright sources, and filtering the galactic plane from the map in (*a*) reveals weaker sources, labelled from the third Cambridge catalogue. Maps created at 60 MHz, $\Delta\nu \sim 90$ kHz, $\Delta t \sim 10$ s.

thermal noise limited. The total available bandwidth is approximately 13 MHz, which can be arbitrarily selected from the 100 MHz total digitized band. Thus, the ASM has a very versatile instantaneous spectral coverage over two octaves in the LBAs, and one octave in HBAs.

The first-stage radio frequency interference excision is challenging because of the limited temporal and spectral baseline available, owing to the near real-time nature of the system. The compute intensive calibration and imaging can require multiple iterations, but should still have a low latency. After flux calibration, the images will be fed through the transients pipeline [4]. This carries out source extraction and association, and the generation of light curves from existing observations for transient detection. It will also generate low-latency triggers to a LOFAR architectural module termed the 'responsive LOFAR module', which can trigger multi-wavelength follow-up observations with a variety of instruments.

3. All-sky monitor calibration challenges

Calibration refers to the estimation of a complex, direction-independent gain per antenna and direction-dependent parameters per calibration source, characterizing the ASM and propagation through the ionosphere. Traditionally, calibration is carried out periodically, with the expectation that instrumental and observational parameters remain stable in the interim. However, the ionosphere can have a significant effect on the propagation of low-frequency radio waves as observed by the ASM, requiring continuous, direction-dependent calibration of each time slice. We use a weighted, alternating least-squares algorithm for multi-source self-calibration, as described in Wijnholds & van der Veen [5]. The algorithm solves for the best-fitting calibration solutions in a least-squares sense and requires an initial sky model.

Transient detection is proposed either via analysis of each source's light curve, generated by source extraction on every image time slice, or via image-level differencing. Both techniques require the minimization of calibration errors to reduce the false detection rate of transients. However, one of the contributors to calibration errors are shifts in the observed positions of the sources in the sky model owing to ionospheric refraction, leading to model visibilities differing from observed visibilities, and, hence, non-convergence of calibration. We address this by estimating source positions from data using weighted subspace fitting [6], incorporated into every calibration cycle. The dynamic range of calibrated images is then improved by the

subtraction of the visibility contribution of the brightest sources in the sky, along with their side lobes. Further, the ASM in LBA mode just resolves the Sun. This precludes its modelling as a point source, while also preventing the suppression of the solar flux by eliminating short baselines. During solar activity (e.g. flares), the Sun can be the dominant contributor of flux to visibilities, while morphing into a source containing multiple, complicated components that change with time. We have applied a sparse reconstruction-based algorithm to estimate a reasonable model of the flaring Sun in an automated manner. This was found to be effective, although compute intensive. Thus, the earlier described approaches allowed for effective removal of the Sun and the bright radio sources dominating the observed visibilities. For algorithm validation while hardware is being developed, test data from all dipoles of six stations were acquired using existing LOFAR hardware and software. Figure 2 shows images from data acquired on 21 September 2011, 12.39 h UTC, before and after the removal of the Sun and bright sources. This image at 60 MHz (10 s integration, 90 kHz bandwidth) has a dynamic range of approximately 2200 : 1. The estimated noise is approximately 10 Jy, close to the theoretical value of 4 Jy.

4. Conclusion

The AARTFAAC ASM will be one of the first ASMs at radio wavelengths. Its calibration is challenging because of the dynamic nature of the low-frequency observations owing to factors such as an active ionosphere over an extremely large field of view, or solar activity. We have shown that advanced algorithms can effectively address some factors at the cost of increased computing. The ASM's implementation is ongoing, with appropriate hardware procured and firmware in development. Appropriate calibration approaches are being developed based on experience gained via test observations.

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