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Real-time calibration and imaging of the AARTFAAC All-sky monitor for detection of fast radio transients

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Abstract. The Amsterdam-ASTRON Radio Transient Facility And Analysis Center (AARTFAAC) All-Sky monitor (ASM) will be one of the first and most sensitive image domain transient detection instruments at meter wavelengths. Based on LOFAR, it will operate 24x7 to carry out real time detection of short (∼seconds) and bright low frequency radio transients, and will trigger low latency followup at high sensitivity with LOFAR. However, the direction dependent calibration required for imaging its all-sky field of view and addressing refractive effects due to the ionosphere within a hard latency budget pose a significant calibration challenge.Here, we present our real-time wide-field calibration and imaging strategy, and discuss its performance under real observing conditions for fast transient detection. Our approach utilizes a highly efficient $O(N^2)$, model sky based multisource self calibration algorithm, with temporal tracking of solutions. In addition, a high resolution Direction of Arrival algorithm estimates model source position offsets due to the ionosphere, thereby achieving confusion noise limited imaging in real-time. Further, we utilize the difference image domain for transient detection, which has a higher sensitivity due to the cancellation of confusion noise. This allows us to generate close to thermal noise limited snapshot images in real-time.

Keywords : Radio Transients – calibration – imaging – real-time

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1. Introduction

The study of the variable and transient nature of celestial sources has lead to unique insights into both the evolution of sources as well as the nature of the intervening medium. Sources have been found to vary from a few milliseconds to years, and over a large part of the spectrum. This field has been phenomenologically driven to a large extent with new discoveries largely being a result of advances in instrumentation, now increasingly due to development of new algorithms and availability of high performance computing.

Exploration of short transients at higher energies has been extremely successful due to the emergence of wide field sky monitors, which provide low latency triggers for prompt multi wavelength follow-up. The low frequency radio domain has been relatively unexplored till now due to the absence of such dedicated sky monitors. This is due to difficulties in simultaneously optimizing field of view, sensitivity, availability and instrument latency in traditional telescopes. Thus, radio transients have been chiefly observed via beam forming, which has inherently high time, but low spatial resolutions or fields of view. Imaging searches are wide field with high resolutions, but their calibration can be time consuming. As a result, imaging searches for transients have usually been limited to long term transients only, typically via mining of archives. This trend is set to change with the recent development of several high sensitivity large field of view instruments, like LOFAR, MWA and the LWA. These are composed of a large number of low sensitivity, wide field dipole antennas. The underlying theme of digitizing incoming signals as close to the antennas as possible, with the majority of the signal processing being carried out digitally makes them extremely configurable.

An example of this flexibility is the Amsterdam-ASTRON Radio Transient Facility and Analysis Center (AARTFAAC) all-sky monitor which shares its analog elements with LOFAR but operates completely independently on a copy of the digitized data. The instrument consists of 288 dual-polarized dipoles operating between 30-90 MHz, a combined effective area of ~2000 sq. m, and a resolution of ~1deg at 60MHz. It will operate continuously, and carry out zenith pointing snapshot imaging of its all-sky field of view to detect short and bright transients. The AARTFAAC array has several advantages for detecting rapid transients. It has an almost completely filled snapshot UV coverage which results in a stable, well conditioned point spread function. It has an all-sky field of view, with a 6 dB beamwidth of 120 deg. It is extremely co-planar, allowing its full field of view to be imaged using 2D transforms, which further aids in rapid imaging. The zenith pointing, snapshot mode of observation implies correlation is simplified, with no dynamic delay compensation except the fixed cable delays. The processed bandwidth is ~13 MHz, limited by the I/O between the dipoles and processing systems. This bandwidth can be spread in subbands of 192kHz across the full 100 MHz analog bandwidth. However, the large fields of view result in direction dependent effects, both due to per element responses, as well as rapidly changing anisoplanaticity introduced by a disturbed ionosphere. These can impose severe dynamic range limitations if left untreated. Thus, calibrating such arrays is both challenging and crucial, and needs to be carried out at short cadences in order to track rapidly changing parameters.

2. Calibration approach

We employ a model sky based, direction dependent, multisource self calibration approach for array calibration, casting the problem as weighted least squares parameter estimation via model fitting. The wide field of view antennas result in the presence of several bright source in beam at any time, thus dedicated calibration observations are not required. The array is sensitive enough to allow calibration on 1 second cadences on the bright sources.

Direction dependent effects are modeled based on the apparent fluxes and positions of the model sources, (for which separate estimators are setup), resulting in solving for these effects in the direction of the model sources. We utilize the Weighted Subspace Fitting (WSF) (Viberg, Ottersten & Kailath 1991) algorithm, a standard direction of arrival estimation technique in array signal processing, for estimating the apparent positions of model sources. This is effective in countering image wander of model sources due to ionospheric distortions. The model sky is then updated with the latest direction dependent estimates. Solving for direction independent complex gain solutions per antenna is carried out via visibility model fitting based on the current model sky. We implement the StEFCal (Salvini & Wijnholds 2014) solver for estimating this set of parameters, which has a $O(N^2)$ computational complexity for N parameters, as against the $O(N^3)$ scaling of traditional solvers. This is primarily due to linearizing the cost function, allowing the solution to be computed analytically and hence avoiding the need for matrix inversions. This significantly impacts the computing cost during AARTFAAC calibration due to the large number of parameters (~590) being estimated and results in a factor 30 speedup. The process is iterative, with the calibration model being updated with more accurate estimates of one set of parameters in order to estimate another set, until the slope of the parameter estimates reaches a predefined low threshold. Due to frequent recalibration, we also initialize the solvers for one timeslice using the estimates obtained from a previous timeslice, leading to rapid convergence.

3. Results

We present some results of applying our calibration strategy on commissioning data. Figure 1 is an example of the all-sky imaging capability of the AARTFAAC. The axis are in units of direction cosines, with the zenith being the center of the image, and the visible hemisphere being projected onto the tangent plane. The circular boundary is the local horizon. The image, with an integration of 1 sec/90kHz, has a dynamic range

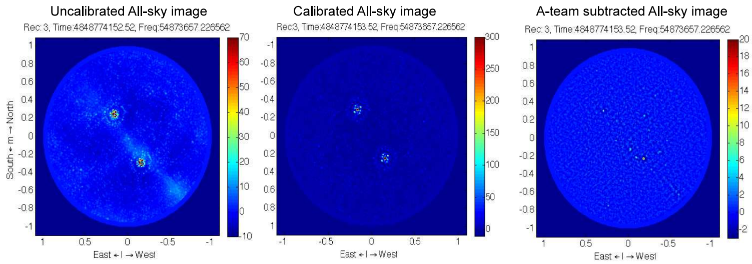

Figure 1. (left) An uncalibrated, instantaneous all sky image generated by the AARTFAAC (middle) the same timeslice after calibration (right) image after subtraction of the brightest sources reveals several bright 3C sources.

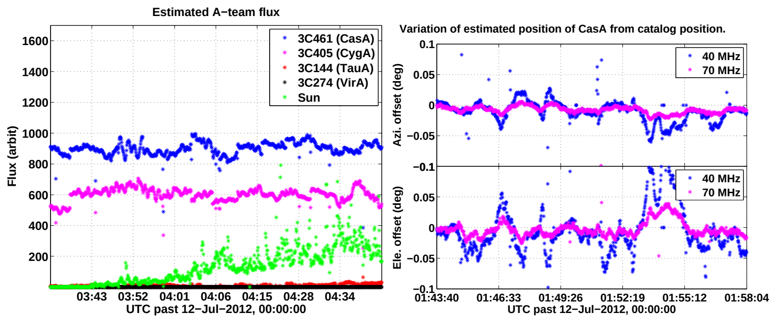

Figure 2. (left) The estimated fluxes of model sources during local dawn. (right) The position wander of CasA, estimated using WSF.

of about 2000:1, after models of the brightest sources have been subtracted from the calibrated visibilities.

Figure 2 shows the effect of the ionosphere, resulting in amplitude scintillation and image wander of model sources. On left, the visible model sources are seen scintillating, while sunrise can also be seen. The right panel shows the elevation and azimuth deviation of CasA from its cataloged position, as estimated using WSF. This wander is significant enough to cause nonconvergence. Based on this analysis, we conclude that calibration within real time latency constraints is feasible, leading to successful subtraction of bright sources, and thus high dynamic ranges. Cases leading to suboptimal calibration are due to Solar flares (hard to model in a real-time loop), and a disturbed ionosphere, which can be accounted for in certain directions only.

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