Calibration of Phased Array Radio Telescopes

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1. INTRODUCTION

The dutch radio astronomy community is currently building the Low Frequency Array (LOFAR) and is involved in several design studies for the Square Kilometer Array (SKA). All these projects use phased array technology, either as aperture array with thousands of receiving elements aimed directly at the sky or as focal plane array feeds with order hundred receiving elements located in the focal plane of a classical radio telescope dish. Phased array technology is new to radio astronomy and poses a number of interesting challenges due to the large number of array elements and the wide instantaneous field-of-view. This paper briefly describes the calibration of phased array telescopes using LOFAR as an example.

2. HIERARCHICAL CALIBRATION

The primary beam, or main peak in the sensitivity pattern, of a phased array is steered by applying appropriate gain and phase corrections to the signals received by the array elements. The goal of calibration is to find the instrumental disturbances in the individual receiving paths and change the gain and phase corrections accordingly. Since the application of these corrections is a linear operation, this can be done in a hierarchical way, i.e. first the signals of a small group of antennas are combined before these aggregated signals are merged, a process which can be repeated several times. For example, LOFAR will have order 50 stations in the Netherlands, each consisting of 96 low band antennas (LBA, 10-90 MHz) and 48 high band antenna (HBA, 110-250 MHz) tiles, which is a unit of 16 HBA elements.
The calibration can exploit this hierarchy by a divide-and-conquer strategy. Applied to the HBA array, this implies that the behavior of the elements within a tile is characterized first, then the tiles within a station and finally the stations within the array. At each level, the number of receiving elements and therefore the number of signals is limited reducing the numerical complexity considerably.

3. CALIBRATION OF INDIVIDUAL ELEMENTS

Calibration of gain and phase of the individual elements is done using holographic techniques. In an anechroic chambre this is realized by reading out the complex transfer function over the probe and the antenna-under-test (AUT) from a network analyzer. In the field this can be achieved by correlating the output signals of the receiving elements.
If the individual phased array elements are directly connected to a correlator, such as the LBAs in a LOFAR station, the resulting covariance matrix can be compared directly to a data model. Mathematically this can be formulated as the least squares problem

$$\boldsymbol{\theta} = \text{argmin} \| \mathbf{R} - \mathbf{R}_0(\boldsymbol{\theta}) \|_F^2$$

where $\mathbf{R}$ is the measured array covariance matrix and $\mathbf{R}_0(\boldsymbol{\theta})$ is the data model which is a function of the parameter vector $\boldsymbol{\theta}$. As we will see in the LOFAR example, $\boldsymbol{\theta}$ may not only include the gains and phases of the individual elements but also source parameters which can not be accurately modeled due to imperfect knowledge of, e.g., the actual ionospheric conditions. A more detailed description of the data model and a solution strategy can be found in [1].

If the individual phased array elements are first combined by an analog beam former before the aggregated signal is fed to a correlator, such as with the HBAs, the gains and phases of the individual elements can be derived by correlating the beam former output with a reference signal while using the beam former to produce different superpositions of the incoming signals. This scenario is described by

$$\boldsymbol{\theta} = \text{argmin} \| \textstyle\sum_k r_k - \mathbf{w}_k^H \mathbf{R}_0(\boldsymbol{\theta}) \mathbf{w}_0 \|_F^2$$

where r_k is the correlation between the AUT with beam former settings $\mathbf{w}_k$ and the reference signal provided by the reference tile with beam former settings $\mathbf{w}_0$. $\mathbf{R}_0(\boldsymbol{\theta})$ is the data model describing the crosscorrelations between the individual elements of the reference tile and the AUT. As in the previous case, $\boldsymbol{\theta}$ may include other parameters than just the gains and phases if necessary. A more detailed description of tile calibration can be found in [2][3].

4. PRACTICAL EXAMPLE

The importance of and challenges faced by (phased) array calibration is illustrated by a 5 minute all-sky observation with a 48-element LBA station of LOFAR started on February 15, 2008 at 2:18:47 UTC. This observation consists of 300 snapshots in a single 195 kHz channel centered at 50 MHz using the station correlator with 1 s integration time. Calibration was done using a sky model consisting of two point sources, Cas A and Cyg A, which are the two dominant sources in the low frequency sky. The left panel of Fig. 1 shows the phase solutions over this 300 s period. The differences in cable lengths cause considerable phase differences between the antennas. If these instrumental effects would not be corrected, this would lead to significant loss in SNR. The standard deviation of the phase estimates is about 3° ,which is the maximum achievable accuracy after 1 s integration given that the instantaneous SNR of Cas A and Cyg A is about 0.01.

The calibration also included estimation of the apparent source powers of Cas A and Cyg A. Since the apparent source powers and the gains of the receiving elements can exchange a constant factor without altering the model of the correlations, Cas A was assigned an apparent source power of unity to solve this ambiguity. The results are shown in the right panel of Fig. 1. The results indicate that this observation was seriously affected by ionospheric scintillation. The stable phase solutions in the left panel therefore show that our calibration approach is very robust.

This robustness comes at a cost. Each snapshot requires solving for 860 free parameters (48 gains, 47 phases, the Cas A-Cyg A flux ration and 764 bias terms) from 1128 crosscorrelations and 48 autocorrelations. Using solutions from the signal processing literature all 860 free parameters of a single 1 s snapshot can be estimated in just 0.4 s on a single core of a 2.0 GHz CPU.

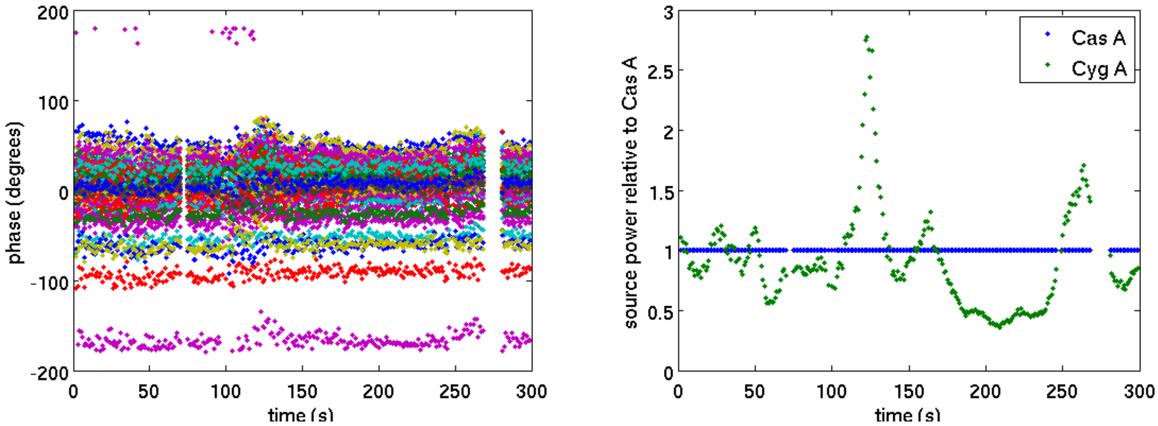

Figure 1. (left) Phase solutions for all 48 receiver paths over a 300 s period and (right) the apparent source power of Cas A and Cyg A over the same period in time.

5. CONCLUSIONS

Phased array technology starts to get a firm ground in radio astronomical applications. This poses new challenges for the calibration of future radio telescopes due to the large number of receiver elements and their wide field of view. Hierarchical calibration keeps the number of elements and therefore the amount of required computing resources at each level in the online data reduction pipeline manageable. Calibration at each level can be regarded as a least squares minimization problem. Although the details of this problem depend on the instrumental characteristics, the approach fundamentally depends on the architecture of the system: are the individual elements directly connected to a correlator or not? The importance of and challenges faced by calibration were illustrated by a LOFAR observation that was seriously affected by ionospheric scintillation.

6. REFERENCES

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