Overview of SKA Calibration Challenges and Impact of Design Decisions

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Abstract

The Square Kilometre Array (SKA), a future radio telescope envisaged to be an order of magnitude more sensitive than current instruments, poses significant calibration challenges. We provide an overview of calibration challenges and discuss current insights in the interplay between calibration and system design. Although further research is required to make quantitative statements on the imaging dynamic range limitations imposed by calibration, we illustrate this interplay by deriving specific requirements on the size and filling factor of SKA aperture array stations.

1 Introduction

The radio astronomy community is making detailed plans for the Square Kilometre Array (SKA), a future radio telescope envisaged to be an order of magnitude more sensitive than current radio telescopes and to produce images with at least 70 dB dynamic range [1]. The latter requirement poses significant calibration challenges. In this paper, we provide an overview of calibration challenges for the SKA system and raise a number of questions regarding system design decisions that may facilitate the calibration. We also show, that we are already able to derive specific requirements on the size and filling factor of SKA aperture array stations based on current insights regarding calibratability.

2 Calibration scenarios

In this section we provide a compact overview of the calibration challenges in the SKA system, for a more extended overview with proper literature references, the reader is referred to [2].

To keep the data volumes manageable, the SKA will exploit a hierarchical signal processing scheme. In each level of this hierarchy, signals are combined and only the combined signal is passed on to the next level. The Low Frequency Array (LOFAR) [3] is an example of such a hierarchical scheme. The signals from sixteen droopy dipoles in a high band antenna tile are combined in an analog tile beamformer to form a tile beam. The tile beam signals from all tiles within a station are beamformed in the station backend to produce the station beam. Finally, at the central processing level, the station beam signals from all stations are correlated with each other or (in)coherently added. Calibration is required at each level in this signal processing hierarchy to ensure proper beam control and prevent signal losses. It will be clear, that each level differs in the type of hardware involved, available field-of-view (FoV), achievable sensitivity, etc. and therefore requires a distinct calibration approach. The signal processing challenges associated with these calibration problems can be categorized in four scenarios:

element-based corrections only If no direction dependent corrections are required, a single gain correction per element is sufficient. This can be treated using the classical self-calibration assumption. This scenario typically holds if the elements have a small FoV since possible propagation effects are constant over the FoV of each element.

identical direction dependent corrections for each element If the elements have a large FoV, distinct directions within the FoV may be affected by different propagation effects. These propagation effects are the same for each element if the elements are sufficiently close to each other. This scenario requires a direction independent gain correction for each element and a direction dependent correction that is the same for all elements.

distinct direction dependent correction for each element This is the most general scenario and it is intractable in its general form. Additional constraints, imposed for example by an ionospheric model, are therefore required to calibrate the system.

compound elements In the aforementioned scenarios, it was assumed that we can measure the visibilities between the elements of the array. If compound elements are used, for example phased array feeds or tiles, we can no longer measure the visibilities between individual elements, but only the superposition of a number of element signals. Calibration of such systems is typically done via holographic measurements. This normally requires dedicated calibration time and puts demands on the stability of the electronics in the compound element.

3 Open questions regarding the Impact of design decisions

The SKA developers are in the favorable position that many calibration issues have already been identified and are under study in the SKA pathfinder projects. Ideally, this situation should be exploited by weighting the impact of a given design decision on the calibratability of the SKA against other costs and benefits of that decision. In this context, calibratability does not only mean whether there are no fundamental reasons why the telescope cannot be calibrated, but it also refers to the accuracy with which the telescope can actually be calibrated. Unfortunately, it appears to be very hard to quantify the required beam shape accuracy and stability of the station and dish beam patterns that determine the imaging FoV of the SKA telescope. These values are required to derive requirements on the setting accuracy in lower levels of the beamforming hierarchy and on the accuracy and stability of the antenna hardware by means of an error propagation analysis. Due to their pivotal importance, we therefore raise the questions:

What station or dish beam shape accuracy is required to achieve 70 dB dynamic range in the SKA synthesis images?
What station or dish beam stability is required to achieve 70 dB dynamic range in the SKA synthesis images?

Ultimately, the dynamic range of the system, defined as the flux ratio of the strongest source in a synthesized image and the noise per pixel, will be limited by the effective noise floor as determined by the actual imaging approach. The effective noise consists of three components, thermal noise, estimation noise and source confusion [4]. Estimation noise is the contribution to the noise floor caused by the fact that estimation of calibration parameters extracts information from the data that can no longer be used to reconstruct the source structure in the image. This implies that the effective noise in an image will increase with the number of calibration parameters as illustrated in [4]. At some point, too much information is lost to achieve the desired dynamic range. The question

How accurate do we have to calibrate the system to ensure that calibration is not limiting its performance?

thus boils down to reducing the degeneracy between calibration and imaging parameters, which imposes stability requirements on the system and to the question whether astronomical sources provide sufficient SNR to estimate the calibration parameters with sufficient accuracy. Depending on the answers to these questions, we may have to design calibration mechanisms into the system. The latter may require addition of specific calibration hardware to the system or subsystem designs that include a dedicated calibration mode.

From an imaging (deconvolution) perspective, the point spread function of an ideal array would consist of a main beam without side lobes. This cannot be achieved in practice, since an area with a given diameter has to be covered with a limited number of stations or dishes and the distribution of stations or dishes within this area is restricted by practical constraints. In complicated fields, having redundant baselines within the array may be a great asset from a calibration perspective, but too many redundant baselines will degrade the (u, v)-coverage. This simple example begs the following questions:

Can we derive guidelines for the design of the array configuration from the calibration (and imaging) requirements and methodologies?
Are there features in the array configuration that should definitely be avoided or definitely be exploited to achieve the desired imaging performance?
Is there a relatively easy way to assess the potential image quality achievable with a proposed configuration, such that proposals may be compared?

All these questions indicate that we need to take a few additional steps to assess the calibratability of the SKA at a quantitative level.

4 Example deriving requirements from calibratability considerations

Fortunately, we can already set a number of hard limits on station or dish size and the minimum filling factor of the stations based on the design considerations of the LOFAR project [5]. We illustrate this by applying these arguments to the envisaged SKA aperture array system for low frequencies (AA-lo), currently expected to cover the 70 – 450 MHz frequency range with possible extension to 50 MHz.

Ionospheric calibration is a challenging task at the low frequency end. The variability of the ionosphere enforces an update interval of about 10 s. If a station can detect 3 sources within such short integration, we can calibrate a 2-D phase screen, if it can detect 5 sources, we can calibrate for a curved phase screen. We will assume that the beam width is reasonably well matched to the ionospheric coherence size. The latter scales proportional with frequency while the station beam width scales with wavelength. This means that the lowest frequency that needs to be observed, defines the minimum station size. LOFAR uses 40-m stations that have a sufficiently narrow beam at 120 MHz, but uses 55-m stations at distances larger than 300 km from the center of the array to provide more sensitivity for the partially resolved calibration sources.

Here, we assume that this station size requirement has been met, such that 3 – 5 calibration sources are sufficient to characterize the ionospheric phase screen and beam errors. Based on the source statistics given in [6], we can find a requirement on the filling factor of the array. In this analysis, we define the filling factor as the ratio of the effective area of all elements in the station and the physical area, which we assume to be 10^4 m^2. We take a typical fractional bandwidth of 20% and the aforementioned 10 s integration time enforced by the ionospheric variability. We assume a reasonable 50 K for the contribution of the antenna and receive electronics to the system temperature, which is dominated by the sky noise temperature at the lowest frequencies.

Figure 1 shows the estimated number of detected 5σ sources as function of the filling factor for a number of frequencies in the 50 – 450 MHz range. The curves for 50 and 100 MHz almost overlap, because the system is sky noise limited. This causes the decrease in FoV to be compensated by an increase in sensitivity making the number of 5σ sources within the FoV almost constant over this range. In this range, a filling factor as small as 0.1 would just do. At higher frequencies, the calibration becomes more challenging, because the system is no longer sky noise dominated and, as a result, higher filling factors are required. In a practical sparse aperture array consisting of dipoles above a ground plane, the effective area per dipole scales with frequency as $\lambda^2/3$, which implies that the sparsity of the station becomes a function of frequency for a given number of dipoles. The filling factor requirement can potentially be relaxed if a larger contiguous FoV is created by multi-beaming. However, such an approach needs further investigation and will reduce the multi-beaming flexibility of the instrument.

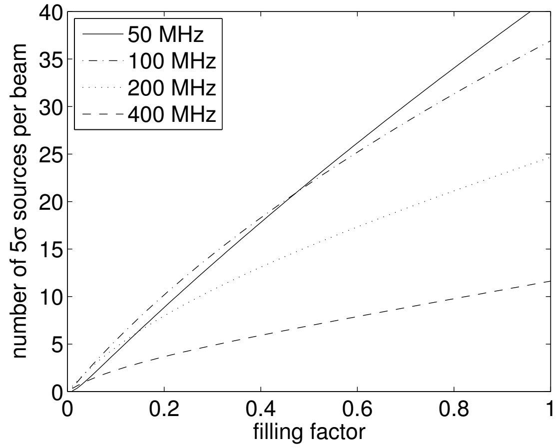

Figure 1: Estimated number of 5σ sources per beam versus the filling factor of the array for the indicated frequencies assuming a physical area of 10^4 m^2, 10 s integration, 20% fractional bandwidth and $T_{\mathrm{sys}} = T_{\mathrm{sky}} + 50$ K.

5 Conclusions

In this paper we presented an overview of the SKA calibration scenarios and open issues with a specific focus on the interplay between calibration and system design. We showed that based on calibratability arguments alone, we can already set the following requirements on the station lay-out based on current calibration schemes:

- The size of the AA-lo stations should be such that the beam size is matched to the ionospheric coherence length at the lowest frequency to allow proper calibration.
- The AA-lo stations should have a filling factor of at least 0.1 over the 50 − 100 MHz range increasing to at least 0.2 and preferably 0.4 at 400 MHz.
- At higher frequencies, a filling factor close to unity is required, which can, for example, be realized in the form of a dense aperture array.

References

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