Notes on the calibration and simulation strategy

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1 Introduction

This memo identifies the effects specific for the xNTD and KAT, as well as for multi-feed interferometers in general. The approaches to calibration of these effects are outlined along with the role, which can be played by computer simulations in the future study. The content of this memo is a subject of ongoing research and is expected to be updated as we learn more. The simulations can be split into two groups depending on the purpose they pursuit. The first group is done to assess the performance of an imaging or calibration algorithm. These simulations can be done with a "realistic" model of the sky brightness and the full scale data reduction. The main outcome of such simulations is an estimate of how long the data reduction takes place and how good the quality of the final image or calibration is. For this type of simulations we need a more accurate sky model, than that which is currently available, to reproduce such effects like confusion. The second group is done to investigate the influence of any particular effects on imaging and test the algorithms under development. In most cases, a sky model consisting of a single point source or a few of them is sufficient for this type of simulations. In addition, using a simple sky model avoids burying the signatures of the studied effect in the signal from the complex sky. Various individual problems are discussed below.

2 Feed-dependent gains

In contrast to the conventional interferometers, where the calibration procedure produces antenna-based gains, interferometers with multi-feed receptors require an independent gain solution for each feed. The major factor behind feed to feed variations is the difference in LNA gains. Computing implications are relatively minor: **VisJones** has to be modified to accommodate additional free parameters. The required calibration procedure seems to be similar to that used for single-beam interferometers, with the exception that one has to accumulate a sufficient flux in each beam to be able to solve for individual gains. The most straight forward way to do this is to observe a calibrator sequentially with each beam. This however would significantly increase the overheads. The LNA gain stability and the stability of the phase transfer system limit the maximum duration between required calibrator observations (calibrator cycle time). With the existing single-feed interferometers this cycle time is of the order of 30 min - 1 hour. It may be possible to calibrate the KAT this way, but the overheads are prohibitive for xNTD. If one had a good model of the gains behavior, which is able to predict the evolution of these gains in time, the calibrator cycle time requirement could be relaxed significantly. The parameters of this model could be solved for as an alternative to the assumption that the gains at different solution intervals are independent. A more appealing approach is to use all sources available in the field of view and always do a self-calibration. It was demonstrated to work for wide-field VLBI experiments at 1.4 GHz (Garrett et al., 2004). This approach is probably good up to the high frequency limit of xNTD (currently 1.8 GHz). It is questionable whether it would still work at the frequencies much higher than that (sources become fainter at higher frequencies and the field of view decreases) and it can be further studied by simulations. Another problem in the wide-field regime is the large fractional bandwidth. In the ordinary calibration using a separate calibrator source, its spectral index is typically ignored because the amplitude factor is automatically corrected when the flux scale is fixed using the primary calibrator, which has a known spectrum. The full-beam self-calibration is different in the sense that the primary beam attenuation factor is notably different for upper and lower edge of the observed frequency band for off-axis sources. This effect can easily be predicted (more accurately if the spectral indices are also included in the model of the sky brightness) and studied by simulations. The simulations can also show whether a superior gain solution can be obtained in the scanning mode as opposed to single pointing observations (i.e. due to a better filling of the aperture plane). A continuum source can still be observed periodically as a secondary calibrator to calibrate the position and fix the flux scale. However, an observation with a single feed is sufficient for this purpose as the relative gain amplitudes and phases corresponding to individual feeds are corrected by the self-calibration.

3 Feed-dependent bandpasses

The bandpass calibration is very similar to the gain calibration. It is intended to determine a frequency-dependent complex gain. If the sensitivity were not an issue, the same procedure, which is used for the gain calibration, could have been used for bandpass calibration. However, because the bandwidth of each individual spectral channel is usually much smaller than the total bandwidth observed, bandpass calibration requires a strong source and a relatively long observation (typically at least several minutes with existing telescopes). From another side, the bandpass shapes are typically much more stable than the LNA gains. Therefore, the usual practice is to determine these shapes infrequently (e.g. once a day) and solve for frequency-independent gains on a much shorter timescale (e.g. each 30 min) using the whole observed bandwidth. The multi-feed interferometers require a separate solution for each feed. Obtaining these solutions this by looking at a bright source is hard because the source is visible by only one beam at a time. This effectively divides the integration time by the number of beams and significantly increases the overheads. The calibration of a 10x10 array spending 5 minutes per feed would take more than 8 hours; less stringent requirements for the KAT as the number of feeds is smaller. The selfcal approach outlined in the previous section can be used for the bandpass calibration as well. However, the solution interval should be the number of spectral channels times longer than that for the gain calibration (the signal to noise ratio depends on the product of the bandwidth and the integration time). For a reasonable number of spectral channels, e.g. more than 8192, the solution interval will be of the order of days. Therefore, the bandpass should be stable at these time scales. This stability may be hard to achieve if there are resonances between elements (especially for a focal-plane array design such as that for the xNTD), which could vary when the orientation of the antennae with respect to the ground changes. The detailed behavior of the bandpass shape needs a further study. The large fractional bandwidth imposes a similar problem to that seen for the gain calibration. However, because the relative gain at various parts of the band is to be calibrated, the spectral indices of the sources must be taken into account in the model. As for gains, a theoretical or empirical model of how bandpass shapes evolve in time can significantly relax the calibration requirements and reduce overheads. Even if the time-dependence cannot be predicted well or bandpass is not stable enough, fitting a certain function (e.g. a polynomial) to the bandpass typically improves the overall quality of the fit by decreasing the number of free parameters. The computing implications of this calibration are relatively minor and similar to that for the gain calibration.

4 Feed legs and field rotation

The blockage due to feed legs leads to a diffraction pattern in the primary beam. For an alt-az mounted antenna this pattern rotates on the sky, which causes a periodic modulation of the off-axis sources. Sidelobes from these sources cannot be cleaned out unless this effect is modelled by the imaging algorithm. Accurate correction for this effect requires a model of the primary beam in the sky coordinates at any given moment of time. In the existing software it is done by regridding the model at certain time intervals. For the majority of sources (which transit at some distance from the zenith) the parallactic angle changes slowly with time. Therefore, the regridding of the beam model is not typically required for each visibility to get an acceptable image quality if a single-feed receiver is used. In the multi-feed case, the pointing centres of all off-axis feeds trace a circular track on the sky. Due to this more regridding operations are required per unit of time unless the rotation of the whole multi-feed receiver is compensated (e.g. mechanically). The field rotator does not remove the effect completely as the feed legs still rotate with respect to the sky (the whole antenna should be rotated to remove it; that is what the equatorial mount does), but allows to reduce the computing load by fixing the receiver orientation. It must be noted, that a hybrid approach where this effect is accurately modelled for a few brightest sources (which does not require an expensive regridding operation for an alt-az mount), but ignored for the rest of the sources. Simulations have a high potential to determine the dynamic range limitations if the effect of feed legs is totally ignored or a hybrid approach is used and to calculate the performance penalty of using a field rotator instead of the equatorial mount. A good uv-coverage reduces the sidelobe level from any source in the field, including off-axis sources near the null of the primary beam, where the modulation due to feed legs is the strongest. Therefore, for a good uv-coverage the sidelobe level can be tolerable even if it cannot be further reduced by the deconvolution. The beamformer of the xNTD provides an additional possibility to (further) reduce the primary beam sidelobes by choosing an appropriate weighting scheme. One is not restricted to a single weighting scheme: one may optimize the sensitivity and be used for spectral line observations and another may optimize sidelobes for high dynamic range continuum observations. If the modulation due to feed legs is to be corrected (i.e. an alt-az mount has been used and a cleaning of side-lobes is required) and there is no field rotator the computing implications are quite severe. A deconvolution of a simulated 12 hour dataset with a 6 antenna 5 beam interferometer on a 64-bit dual core dual CPU computer with 8 Gb RAM took 10 days for the alt-az mount and about 2 hours for the equatorial one. There are new algorithms which promise some improvement of these figures, but the detailed performance study is yet to be done. The presence of a field rotator requires an additional parameter per antenna (the actual parallactic angle of the focal array) to be calibrated. This can be incorporated to the pointing or gain solution, which has to be done anyway. From another point of view, the field rotator adds an additional flexibility to calibration as the observations can be done for various orientations of the multi-feed receiver with respect to the sky in a short period of time. It may simplify a polarization calibration.

5 Element coupling

This effect is somewhat specific to the xNTD, which is expected to use a focal plane array and beamformer, and should be negligible for the multi-beam design of the KAT. The receptors of the focal plane array are almost certainly will be coupled electrodynamically and therefore can not be considered as independent receptors. According to Hamaker, Bregman & Sault (1996), the visibility measured by a two-element interferometer can be described as a linear transformation of the coherency vector with the matrix formed by the outer product of Jones matrices corresponding to individual elements A and B

$$v = Je, \text{ where } J = J_A \otimes J_B^* \text{ and symbol } \otimes \text{ denotes the outer product.} \quad (1)$$

In the case of the linear coupling between elements, (1) can still be generalized. The coherence vector e remains to be the outer product of two vectors e_A and e_B corresponding to the first and the second antennae. The length of each of these vectors is $2N$, where N is the number of feeds (two polarizations). At each antenna the beamforming and the coupling of elements can be described by a linear transformation (matrix multiplication). For the coherency vector, it would take a form of the outer product. For N feeds, this additional matrix would have $16N^4$ elements. There is some degeneracy because the matrix describing the element coupling is Hermitian. In addition, the coupling is expected to vary significantly depending on the location of two feeds in the array and for some of them may be assumed safely to be negligible. A further factorization to the parallel-hand and cross-polarization coupling terms is reasonable as these terms should be different in magnitude. The same procedure as used for bandpass or gain calibration can be used, in principle, to extract the coupling coefficients. The beamformer reduces the amount of available information. Therefore several sets of weights per antenna pointing are likely to be required to get a complete picture.

6 Pointing

The image quality can be limited by the pointing errors, especially if a strong source lies close to a null of the primary beam. Although, an algorithm intended to correct for pointing errors during the data reduction exists (Bhatnagar et al., 2004; 2006), it may be more practical to solve for these errors at the time of observations. Such a solution can be made for multi-feed interferometers using just a single pointing observation. It could be incorporated with the gain solution described above. Simulations have a great potential to reveal the dynamic range limitations caused by the pointing errors. Such a study carried out for ATCA continuum measurements (Voronkov 2005) revealed that one begins to notice the pointing errors at dynamic ranges exceeding 5×10^4-10^5. This study assumed a purely Gaussian error with a 2 arcsecond variance. Adopting a realistic model of the pointing errors (mainly their time dependence) is the main difficulty for such simulations. Coherent periodic variations in the antenna pointing can have a large impact on the image. The simulations of ATCA continuum measurements mentioned above have shown that the multi-frequency synthesis reduces the influence of the pointing errors. This is most likely because the primary beam scales with frequency. Because the random errors were assumed, there is a some degree of averaging at the gridding stage.

7 Beamformer weights

This question is specific to the xNTD, which is proposed to work with a beamformer. The beamformer output will be a linear combination of signals received by each individual feed. The weights will vary in time (which allows to synthesize a good primary beam), but will be constant in frequency due to hardware limitations. The two main questions which have to be studied are how often should these weights be updated to achieve a desired property of the primary beam (e.g. to maximize the efficiency or minimize the sidelobe level) and whether there are additional limitations for wide-band data and multi-frequency synthesis? Most likely a desired optimization of a certain property of the primary beam will be hard to sustain over a finite bandwidth. The computing implications of having a synthetic primary beam depend strongly on its structure and the sidelobe level. As with the diffraction pattern caused by the feed legs, a good uv-coverage can make neglecting this effect a viable option. For high dynamic range observations it is possible to have a special weighting scheme which would minimize the sidelobes or make them more uniform in the azimuthal direction. This could simplify imaging, although with a sensitivity penalty. These questions can be studied by simulations in a way similar to the study of Brisken and Craeye (2004), given the voltage patterns of individual elements, which are expected to be calculated for xNTD by DRAO.

8 Polarization

The instrumental polarization calibration involves solving for leakages between orthogonal channels for all feeds. The element coupling described above can appear between orthogonally polarized receptors as well, which increases the number of unknowns in the calibration procedure. To increase the number of measurements several antenna pointings and various orientations of the multi-feed receiver with respect to the sky are likely to be required. Although this calibration is unlikely to put a significant stress on the software, performing the actual observations may take a long time for similar reasons as for the bandpass calibration. Therefore, a stable polarized response or that with a known time dependence is required to avoid extreme overheads. Using a field rotator may speed up the calibration. Off-axis observations of an unpolarized source is an alternative way to extract the information about polarization leakages occuring in the feeds and electronics because the polarization properties of the antenna itself can be measured once and assumed stable. A model of the cross-coupling is required to estimate the computing and operational requirements as some of these terms (e.g. cross-coupling of orthogonal polarization of two distant elements) are most likely negligible. The instrumental calibration accounts for transformations occuring in the antenna optics and electronics only. Ionospheric Faraday rotation is an additional factor, which may be a serious complication at low frequencies with a high impact on the off-line data processing; it requires a further study.

Conclusions

The implications of individual effects are summarized in Table 1. In this table, the operations column reflects mainly the time required to perform the actual observations and the computing column reflects the difficulty of the data processing. It should be pointed out that to calibrate some effects (e.g. the pointing) a real time feedback to the observing system is required. This has considerable implications on the real time software, although obtaining the solution itself is inexpensive.

The current state of the software allows to study

- The effect of the pointing errors. Given a uv-coverage and the dynamic range requirements the simulations can give an upper limit of the pointing errors for which their effect can be ignored in the data processing.
- The effect of the feed legs. An estimate of the relative performance can be made for the following cases: the equatorial mount, the azimuthal mount with the field rotator, the azimuthal mount without a field rotator.
- Full-beam self-calibation of the feed-dependent gains.
- Bandpass self-calibration. An estimate of the shortest possible solution interval (which determines the required bandpass stability) can be made.
- Effects of the large fractional bandwidth on the full-beam self-calibration solutions for gains and bandpasses.

Other effects require a further consideration (and probably a test on a demonstrator like NTD) as their magnitude can significantly alter the optimization of the software.

Table 1: Implications of individual effects for operations (mainly a time required for calibration), computing and hardware requirements

Effect	Implications for operations	Implications for computing	Implications for hardware requirements
feed gains	minor (self-calibration)	minor	stable at time-scale of hours
bandpasses	minor (self-calibration) serious (on a calibrator)	minor	stable at time-scale of days or predictable
feed legs	none	serious (alt-az mount) moderate (alt-az with field rotator) minor (equatorial mount)	telescope mount and/or field rotator are important
element coupling	minor	minor	stable or predictable
pointing	none or minor	minor or moderate	?
beamformer	?	?	?
polarization	?	?	stable at time scale of days field rotator can help

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