SKA SDP Memo 001

PAF De-rotation options trade-off: initial SDP response

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Introduction

The SDP, along with the DSH consortium has been asked to provide the SKAO with feedback on three distinct options for handling the rotation of the parallactic angle as a function of time, specifically for Phased-Array-Feeds on the offset Gregorian dishes as described in the Baseline Design Document [2].

There are three approaches to consider:

1) Mechanical counter-rotation of the PAF on the antenna. Note that for ASKAP the entire reflector and focal assembly is rotated, but this is not possible for SKA antennas, which are of an offset Gregorian design.

2) Electronic counter-rotation in the beam-former, by changing the weights quasi-continuously so as to form beams that follow paths on the PAF surface that counter-rotate. This will require weights to be updated at a rate sufficient to reduce associated artefacts below that required to achieve the required imaging dynamic range.

3) Incorporate the counter-rotation into the A-projection component of gridding. This will require that the gridding function pattern, incorporating the appropriate A-projection filter, adapts at a sufficient rate.

This is a record of the initial position of the SDP consortium; it does not represent the results of any sizeable study. We have not sought input from every member of the consortium.

In several areas, whilst the impact of an approach may by qualitatively assessed, much more significant work is required in order to make complete quantitative comparisons between options. We attempt to highlight areas where work is needed.

SDP Comments

The document [1] by Peter Dewdney identifies two problems: A) parallactic rotation of the pattern of PAF beams; B) parallactic rotation of the individual PAF beams.

The parallactic rotation of the pattern of PAF beams can either be countered by mechanical rotation of the PAF (mechanical rotation of the entire SKA dish is not feasible given its mechanical design) or by electronic tracking with the off-axis PAF beams. This will ensure that each beam tracks a constant patch of the sky during an observing run.

The impact that these options have on mechanical dish / PAF and electrical beamformer design we leave for the DSH consortium to comment on, here we assume that both options are feasible and consider what the SDP would then need to do in response.

For option 1, the centres of each PAF beam are fixed on the sky and the orientation of each beam (in each polarisation) is also fixed. However, the dish primary beam continues to rotate with parallactic angle, so the optical paths through each PAF receiver and therefore contributing to each of the output PAF beams do still change with time. The SDP consortium cannot comment on the polarization beam shape for offset Gregorian dishes.

For option 2, the beam centres are still fixed on the sky but each beam now rotates with parallactic angle. The optical path through each PAF receiver is constant in time but weights applied to each signal to produce each output beam must be updated appropriately. However, assuming that the beamformer can behave appropriately, the SDP just sees a rotating beam pattern for each PAF beam.

Both options 1 and 2 must undergo parallactic angle calibration in the SDP, to account for the changing polarisation state of the beams and for non-circularly symmetric responses in the "effective" beam shape of each beam. However, the problem now looks akin to typical parallactic angle calibration for an Aperture Array Station, except that because of the projection effects, the AA beam will change overall shape as a function of time too.

The temporal update rates for the polarization beam needed for the A projection depend upon the rate of change of parallactic angle but also on how significantly the polarization beam shapes alter with parallactic angle themselves. In this latter respect options 1 and 2 may differ: For option 2, there is no rotation of PAF w.r.t. dish, so the update rate should depend upon the uniformity of each *individual* output PAF beam (i.e. of much smaller radius O(1/2 degree) radius), as each beam can be treated in parallel. Whether or not this is significantly improved c.f. option 1 must depend upon how accurately new PAF beamformer weights are calculated and how frequently they themselves are updated.

Option 2 has implications for integration of the 36 existing ASKAP antennas: the existing ASKAP beamformers may not be capable of forming output beams at the appropriate weights or of including contributions from a large enough number of PAF element responses, for example. These antennas account for a significant fraction of the SKA1 SURVEY array (around one-third, so the ASKAP antennas will be involved in around half of the baselines), so their compatibility with whichever option is selected will have a huge impact on performance. This is a major issue.

For Option 3, we assume that the weights used to combine PAF receiver signals are fixed in time and that the beamformer generates 36 (or some number, N_{PAF}) of beams in a particular pattern which is fixed with respect to the dish / PAF structure, i.e. which rotates with parallactic angle. For simplicity, imagine a square beam "footprint" pattern made up of 6x6 adjacent output beams. This footprint will rotate with parallactic angle and as a result, a single direction (say, a point source) on the sky moves from one beam to another, with a varying sensitivity as it moves from the centre to the edge of the first beam and then into the next beam. We are not aware of software that can handle such behaviour. Presumably we could mitigate the rotation if we imaged the entire footprint field of view on an appropriate timescale (now set by the speed of the sky as it moves through the outermost PAF beam – this speed is determined by the effective radius of the footprint pattern, i.e. O(4) PAF beam-widths).

Alternatively to what we have discussed above, in principle, the parallactic rotation of individual PAF beams could be handled in the beamformer. However, this approach has two disadvantages: 1. it can only apply one polarimetric correction for the entire beams, i.e., this approach will ignore the gradients in the polarimetric responses of the PAF elements; 2. it will require very accurate characterization of the polarimetric response of the system. Due to these issues, the imaging software will have to deal with polarimetric direction dependent effects anyway. If option 2 is carried forward, the precise nature of the output PAF beams needs to be specified more clearly – i.e. have the polarisation axes been de-rotated too or not.

We do not know how computational load depends on the required dynamic range, since we are not able to tell which parameters are driving the update rates etc. Simulations comparing different algorithms, especially for option 3, are required to enable us to estimate compute and memory load. Analysis of a signal-chain error budget is also required to give an understanding of the level of accuracy needed in the A-projection.

Risks

Option 1: Each PAF beam can be imaged in parallel. Problem is similar to AA beam tracking and station beam rotation, but simpler in the sense that the orientation of the polarisation feeds is fixed w.r.t. the sky. Complications arise as to the effect of the dish beam rotating through the PAF pattern: this may mean that the calibration / A projection kernel update rates are not reduced enough to justify the increased mechanical complexity of the system, but the effect depends on the off-axis dish performance. As far as the impact on the SDP design goes, we do not have sufficient information to rule out this approach, or to opt for it. Is it plausible that this information will be available in time for work to be done prior to PDR?

Option 2: (Assuming PAF beams that rotate about their centre point, footprint is fixed on the sky): Again, output PAF beams can be imaged in parallel. Combined PAF+Dish beam now rotates with parallactic angle. Polarisation orientation rotates with parallatic angle, so resulting problem is very similar to AA beam tracking (apart from the extra projection effects in AA stations) – this allows re-use of LOFAR / MWA / PAPER expertise and must also be handled in SDP for LFAA.

(However, just because we need to solve this to make another aspect of the observatory work does not mean that it will be simple: it may fail in both cases. Also, decisions to include / exclude a method on these grounds would need to be revisited in the case of an altered observatory plan - e.g. removal of LFAA).

Option 3: This is the highest risk as far as the SDP consortium is concerned, since the know-how for calibrating and imaging in this regime does not exist already and is not required elsewhere within the SDP. Work needs to be done to estimate increase in processing load, and memory requirements. A first estimate (based on SKA Memo 132 [3]) suggests that if we image the full (e.g. 36 beam) field of view at each time convolution kernel needed would be ~36-squared times larger (in total pixels), so compared to options 1 and 2, we might see an increase in total (gridding) processing rate by a factor of 36 (or N_{PAF}). This option does not remove the need for a beamforming system for the PAF beams, but the rate at which new weights need to be applied is presumably very much lower. Whether sufficient work on the effect of using this approach can be done in time for PDR is not clear: we therefore *cannot presently support a decision to select* ***only*** *option 3.*

Analysis of resourcing implications within the SDP project will be required before the SDP Consortium could consider any request to carry option 3 to PDR.

Integration with ASKAP: the compatibility of the selected derotation approach with the existing ASKAP system must be considered; potentially the ASKAP beamformers would need to be upgraded in order to be compatible with option 2, though it may still be the case that changes are required in order to make options 1 and 3 viable too. The mis-matching fields of view will increase complexity, perhaps lending favour to those options where the footprint patterns remain fixed (1 and 2).

Incorporation of ASKAP dish beams into A-projection algorithm may also present difficult challenges due to the scattering from the feed legs. If the ASKAP dishes have their mechanical de-rotation switched off in order to follow the same method as the SKA dishes, then we will have parallactic rotation of the dish primary beam, with significantly non-axisymmetric responses due to the feed legs. Otherwise, if the ASKAP rotation is enabled, the SDP will need to combine data from two heterogeneous implementations.

References

1) Notice of Initiation: SKA Telescope or System Trade-off:
2) PAF De-rotation, V4-2013Nov11, 2013 Peter Dewdney
3) SKAO Baseline design document: SKA-TEL-SKO-DD-001, 2013, Peter Dewdney http://www.skatelescope.org/wp-content/uploads/2012/07/SKA-TEL-SKO-DD-001-1_BaselineDesign1.pdf
4) SKA Memo 132: Analysis of Convolutional Resampling Algorithm Performance. 2011 Ben Humphreys and Tim Cornwell. (https://www.skatelescope.org/publications/)