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Joint Imaging Across Multiple Beams

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Abstract

Phased array technology provides the capability to form multiple beams simultaneously. This can be used to significantly enhance the field-of-view of radio astronomical instruments as demonstrated by the recent upgrade of the Westerbork Synthesis Radio Telescope and the Australian Square Kilometre Array (SKA) Pathfinder (ASKAP). At the moment, the data associated with each beam are treated as a separate observation. In this paper, an extension of facet based imaging is presented that produces a single image for the combined field-of-view of all beams. The proposed method is illustrated using simulations for a linear array composed of multiple subarrays with multi-beaming capability. As this approach significantly reduces the size of the sub-images to be made for each individual beam, it may significantly reduce the compute costs of image reconstruction for the combined field-of-view of all beams.

1 Introduction

Phased array technology provides the capability to form multiple beams simultaneously. This can be used to significantly enhance the field-of-view (FoV) of radio astronomical instruments [1]. With the commissioning of the Aperture Tile-in-Focus (APERTIF) receivers on the Westerbork Synthesis Radio Telescope (WSRT) [2, 3] and the Australian Square Kilometre Array Pathfinder (ASKAP) [4], two radio interferometers have recently come online that exploit this capability. The future Mid-Frequency Aperture Array (MFAA) system for the second phase of the Square Kilometre Array (SKA) is envisaged to exploit this on an even more massive scale, forming hundreds of beams simultaneously [5, 6].

At this point in time, the visibility data associated with each beam is processed independently, although there may be some common meta-data from bandpass calibration and phase referencing. This implies that the fact that the measurements for all beams are taken by the same instrument under the same observing conditions is hardly exploited. In [7], a method was suggested to exploit this for direction-dependent calibration of the telescope across the full FoV of all beams together. In most observations done by telescopes relying on multi-beaming to enhance their FoV, most of the beams will be pointed close to each other to form a contiguous compound FoV. In this paper, an extension of the standard facet-based imaging approach [8] is proposed by applying it to the compound FoV, i.e., across multiple beams. This idea is tested in a simulation for a one dimensional array of one-dimensional stations with multi-beaming capability, demonstrating that a high dynamic range is achievable with suitable adaptation of the CLEAN-based deconvolution cycle [9, 10] to work across multiple beams. As high-dynamic range imaging usually requires to image not only the main beam area but also the first sidelobes, the proposed multi-beam imaging method has the potential to reduce the computing costs of image reconstruction significantly by only doing image reconstruction for a given area in the compound FoV for the beam most optimally positioned for that area and using the constructed source model to remove the sidelobe responses of those sources in neighbouring beams.

2 Extending facet based imaging

Figure 1 shows a top-level diagram of the proposed imaging pipeline for the SKA [11] when applied independently to the visibility data sets produced by each beam. If the FoV of an individual beam is sufficiently large, it will be split into multiple facets as that saves computational costs in two ways. First, a smaller FoV reduces the w-term allowing the use of a smaller kernel in the gridding process. Secondly, a smaller FoV allows further baseline dependent averaging (BDA) [12]. This pre-averaging of the data reduces the number of visibilities that need to be gridded. Both effects thus reduce the computational load of the gridding step, which is the most computationally demanding step in the imaging process [13].

After pre-processing, the imaging stage starts. In this stage, the data is gridded and Fourier transformed to obtain a dirty image. Based on the dirty image for each facet, the locations and fluxes of the brightest sources are estimated and the source model updated, as indicated by the arrow to the source model. The updated source model constructed from all facets is used to predict the visibilities for each facet, as indicated by the arrow from the source model to the imaging processes for the respective facets. The predicted visibilities are subtracted from the visibility data from which a new dirty image, the residual image, is calculated. This residual image is the starting point for the next iteration of

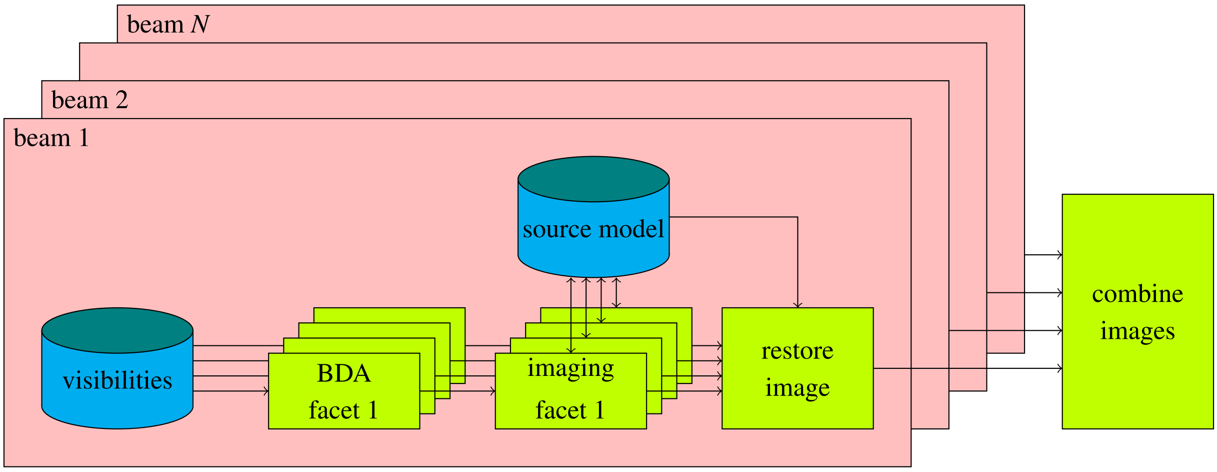

Figure 1. Block diagram for conventional imaging approach for multi-beam observations.

the major cycle. This process continues until the residual image only contains noise. Finally, the image is restored by convolving the constructed sky model with a socalled clean beam (a beam with the same size as the point spread function (psf) of the array but without its sidelobes) and adding this to the residual image. The images constructed for all beams are then combined into a single image covering the compound FoV.

In the conventional approach, the image produced for each beam is significantly larger than the main beam area of that beam. This is necessary, because many sources in the first sidelobe(s) of the beam may be bright enough to have a significant psf sidelobe response in the main beam area and therefore need to be incorporated in the constructed source model to ensure proper deconvolution. However, in a multi-beam observation, the area on the sky covered by the first sidelobe of one beam may be covered by the main beam of a neighbouring beam. As the latter has a much higher sensitivity in that area of the sky, it is much better positioned to construct an accurate soure model for that area of the sky. If the direction dependent response of the instrument is known (or calibrated), the source model constructed using the neighbouring beam may then be transferred to the sidelobe of the former beam.

This suggests that we should, in principle, be able to limit the area on the sky to be imaged by a given beam to its main beam area and use the sky model constructed from neighbouring beams to remove the psf sidelobe responses of bright sources in its sidelobes. This leads to the scheme depicted in Figure 2. For simplicity, we assume that the main beam area of a single beam is small enough to be imaged by a single facet, but it is straightforward to generalise this approach to split the FoV of each beam into multiple facets. In principle, the pre-processing stage remains the same. The big difference is in the image reconstruction process. As the area imaged by each beam is confined to its main beam area, we can only update the source model for that area. To ensure proper deconvolution, we need to combine the source model update in each major cycle of the image reconstruction stage with the the source model updates of the other beams. This is indicated by the two-way connection with the source model for all beams.

This scheme effectively treats the main beam area of each beam as a facet in a facet imaging approach. This is slightly more involved as source model updates from multiple beams need to be combined. However, the image to be made for each beam has become much smaller, implying a smaller w-component, which reduces the imaging compute costs per beam significantly. Assuming a large number of beams (allowing us to ignore the additional work required for beams at the edge of the compound FoV, which are not fully surrounded by neighbouring beams), an initial analysis based on numbers for the Dutch part of the Low Frequency Array (LOFAR) [14] using the compute model described in [13] indicates that this may save about an order of magnitude in compute costs required for image reconstruction across the whole compound FoV.

3 Simulation

In this section, the feasibility of the proposed approach is demonstrated by simulation of a one-dimensional example. This simulation assumed an array of twenty 20-m stations placed at exponentially increasing distance from each other forming a maximum baseline of 3.1 km. Each station consisted of 20 antennas randomly distributed (without restriction on minimum element spacing) over the station aperture with a uniform distribution. A random antenna placement was preferred here to aggravate the issues caused by the relatively high far sidelobes. The resulting station and array layout are shown in Figure 3.

An observing wavelength of 2 m was assumed, ensuring that 20 beams were sufficient to cover the hemispheric FoV. Hundred sources were regularly spaced across the FoV with an exponential power distribution spanning five orders of magnitude to emulate a high-dynamic range observation.

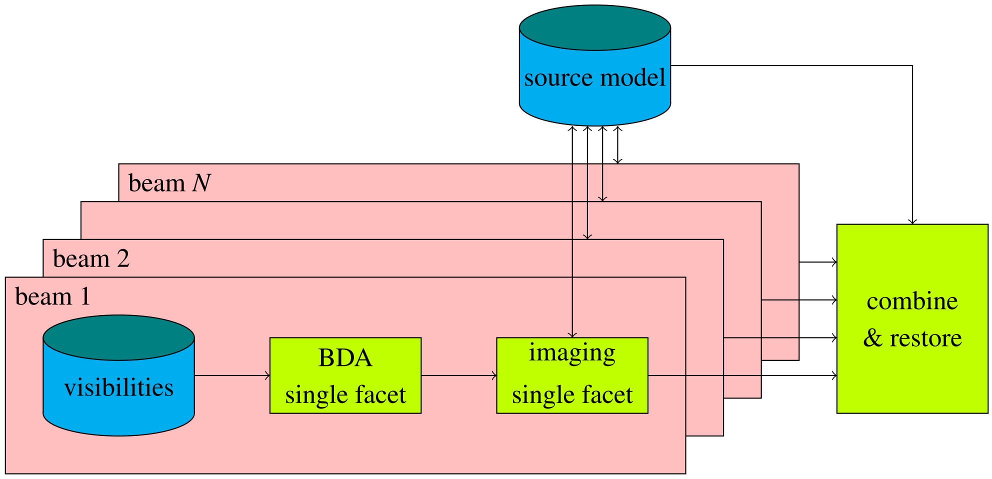

Figure 2. Block diagram for proposed multi-beam imaging approach.

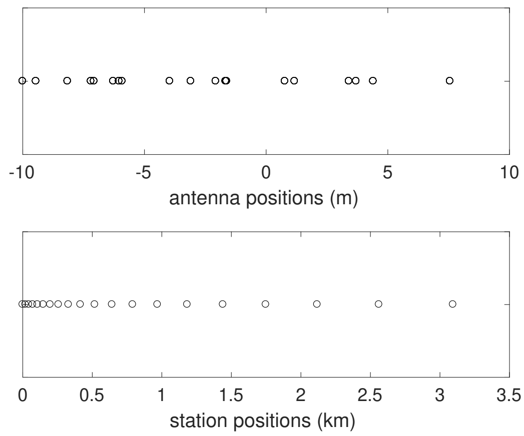

Figure 3. Positions of antennas within each station (top) and positions of stations within the array (bottom).

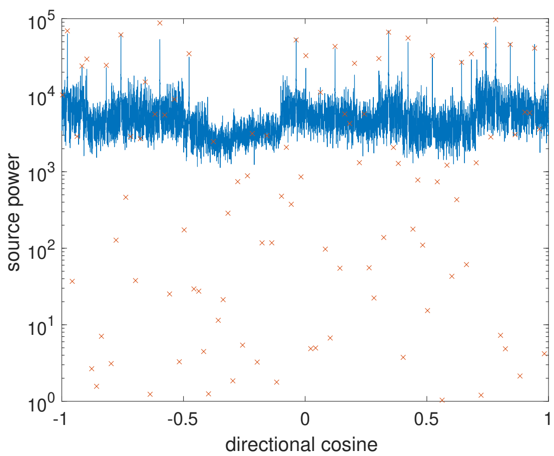

Figure 4. Dirty image obtained by simply stitching the dirty images in the respective main beam area obtained for each individual beam (blue curve) and the source model (red crosses).

Figure 4 shows the source model along with the dirty image across the hemispheric FoV. The latter was obtained by stitching the dirty images in the main beam area (defined as the area between the cross-over points to neighbouring beams) of each individual beam. This shows that many sources are invisible due to the high psf sidelobes for this array. As the dirty image is made without primary beam correction, the power observed in the dirty beam is lower than the actual source power when the sources are not in the center of one of the beams.

This dirty image was used as a starting point for a regular CLEAN process [10]. The locations of the brightest sources were identified, followed by a simultaneous estimation of their source fluxes. A fraction of the estimated source fluxes (determined by the loop gain of the CLEAN algorithm) was then added to the source model. This source model, which spanned the entire FoV was then subtracted from the visibilities associated with each beam. This resulted in a new dirty residual image for each beam that was used as starting point for the next major cycle. Due to the high psf sidelobes, as seen in Figure 4, the loop gain had to be set quite small, resulting in a relatively large number of iterations (20). It should be emphasised that this is not caused by the proposed method, but by the scenario proposed here, which aims to demonstrate that it is feasible to achieve a high dynamic range while significantly reducing the size of the reconstructed image for each beam (in this case, the overlap is even reduced to zero).

Figure 5 shows the reconstructed image after 20 iterations with the source model superimposed. The reconstructed image was made by adding the primary beam corrected source model to the residual image. This shows that all sources have been reconstructed perfectly and that the residual image only contains noise. We may thus conclude that the proposed approach, which removes the overlap between images formed for the individual beams (or at least reduces that overlap significantly), is a viable method to form high dynamic range images across the compound FoV

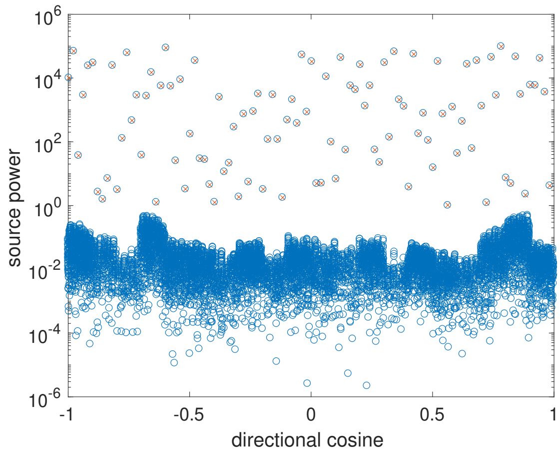

Figure 5. Reconstructed image at the end of the CLEAN process (blue circles) and the source model (red crosses).

created by multiple beams.

4 Conclusions

In this paper, a joint multi-beam imaging approach was proposed for image reconstruction across the compound field-of-view provided by clustered beams in a multi-beam measurement. This method effectively treats each main beam area as a facet of the image spanning the compound field-of-view. This facet based approach has the advantage that the size of the image to be made for each individual beam is significantly reduced. This opens the path to a significant reduction of the imaging compute costs for instruments relying on multi-beaming to enhance their field-of-view. The proposed method was demonstrated in simulation using a one-dimensional array as an example. The results indicate that, if the direction dependent response of the instrument is known (or calibrated), the proposed method does not impose a dynamic range restriction.

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