Bima memo 59 - Aug 1997

MMA Memo 180: Imaging With Heterogeneous Arrays

M.C.H. Wright
Radio Astronomy laboratory, University of California, Berkeley, CA, 94720

ABSTRACT

This memo *briefly* reviews some considerations for imaging with aperture synthesis arrays containing mixed antenna sizes. At millimeter wavelengths, where mosaicing observations are important, the effect of the mixed primary beams is significant. For mosaicing observations, the sensitivity depends on the number and diameter of antennas with each primary beam type. The array configuration can be optimized to use the different antenna sizes, and depends quite strongly on the source structure. Data sampling rates are set by both the largest and smallest antenna diameter, and are larger than for an equivalent homogeneous array. The negative primary beam from mixed antenna baselines may be a problem in the mosaicing algorithms. Conceivably it might also serve to knit together the mosaic by providing different weightings of the overall image. The dynamic range of mosaiced observations is often limited by pointing errors. Pointing is more of a problem for larger antennas, but the mixed primary beam patterns *may* make it easier to implement a pointing self-calibration algorithm. Mosiacing with mixed antenna baselines needs detailed study.

1. Introduction

Aperture synthesis arrays containing mixed antenna sizes are being considered for the combined BIMA & OVRO arrays (CCA: 10 6m-antennas + 6 10m antennas) and for the combined US and European millimeter arrays (MMA/LSA: 40 8m antennas + 25 to 35 15m antennas). In order to get the full sensitivity of the combined arrays, cross-correlations between all antennas should be made. With 2 antenna types, this results in 3 different primary beam patterns; N(N+1)/2 with N antenna types. The primary beam between different antenna sizes will have a large negative response pattern where the voltage pattern of the larger antenna is negative, and the smaller antenna is still within the main lobe. Imaging sources smaller than the primary beam of the largest array antenna is uncomplicated by mixed primary beam patterns. For larger sources where mosaicing observations are required the effect of the mixed primary beams is significant.

2. Science

* The median source size of objects I have observed in last few years at millimeter wavelengths is about 1 arcmin. (comets, YSO's, SNR, radio galaxies, galactic nuclei, clusters)

* The fraction of mosaicing projects with the BIMA array at λ3mm, FWHM = 2 arcmin, has increased from almost none 3 years ago to about 30% in the last quarter. Possible reasons: 1) more convenient software, no extra work for user to make mosaiced images. 2) move from discovery phase to detailed images as the science matures.

* Understanding the astrophysics, and distinguishing between competing theories often requires quantitative comparison of detailed images at several wavelengths. This requires high fidelity images.

The implication is that high dynamic range mosaiced images will be important for future millimeter wavelength observations.

3. Sensitivity

The optimum antenna size depends on the science goals. For a homogeneous array of N antennas of diameter D, the single pointing sensitivity goes as ND^2 and the mosaicing sensitivity goes as $ND\lambda$ (note the λ dependence of mosaic observations). For a heterogeneous array, where all the antennas observe the source for the same total time, the sensitivity also goes as the total collection area when cross-correlations between all antennas are made. For mosaicing observations, a heterogeneous array can be considered as a set of sub-arrays for each primary beam pattern. Each sub-array observes the same patch of sky for a time inversely proportional to it's primary beam area. The best sensitivity is obtained by weighting each sub-array by it's sensitivity, and depends on how the negative part of the primary beam pattern is used. The sensitivity for various MMA/LSA options (Holdaway, 1997) is somewhat better for heterogeneous, than for homogeneous arrays using either large or small antennas with the same estimated total cost. Installing array receivers, e.g. on the larger antennas, is a clear way to increase the sensitivity for mosaiced observations, but has a major impact on the optimum antenna size and array design, and is not considered further in this memo.

4. Observing strategies

The array configuration can be optimized to use the different antenna sizes. The smaller antennas are best suited for mapping large source structure, and are best placed close together at short baselines in order to sample short uv spacings. The mosaicing algorithms recover visibilities about 1/2 a dish diameter shorter than the shortest measured spacing (e.g. Cornwell, 1988). A direct Fourier transform of the uv-data w.r.t pointing center (Ekers & Rots, 1979) to generate more closely sampled uv-data (e.g. BIMA memo 45), also extends the sampled uv-data by about 1/2 to 3/4 of a dish diameter. The larger antennas at longer baselines provide a more uniform weighting of the uv-data. The best array configurations for mixed antenna sizes also depends quite strongly on the source structure.

There are several calibration options for both large and small sources. E.g. using a clustered array with one dish observing a calibrator. Phased large antennas can observe a compact weak source with one of the smaller antennas observing a strong calibrator, and vice-versa for an extended source.

5. Sampling requirements

Sampling rates are set by both the largest and smallest antenna diameter. The uv-data sample interval, δuv = D/2λ. The number of pointings, Npts = $\Omega/(\lambda/2\mathrm{D})^2$. Thus the sampling rate = baseline/λ x $(2\mathrm{D}_{max}/\lambda)^2$ x $2\lambda/\mathrm{D}_{min}$ x Ω x sdot (D=antenna diameter, Ω=source size, and sdot=$2\pi/24/3600$). The uv-data for each subfield are oversampled by the larger antennas, and the number of subfields is oversampled by the smaller antennas. There is no loss in sensitivity since the oversampled data are properly accounted for in the imaging algorithms, but it does increase the bulk of uv-data compared with an homogeneous array. It is best to sample all pointings within the same uv cell (advantage of common pointing, calibration, etc), but Npts is limited by the sampling rates and antenna settle time. OTF mosaicing may help, but requires synchronous slew of the antennas and fringe rates.

6. Mosiacing algorithms

A linear mosaic is a linear combination of sub-images weighted by their primary beam patterns. Different primary beam patterns are readily combined using existing algorithms. Non-linear mosaicing algorithms (Cornwell, 1989; Sault etal, 1996), which combine image deconvolution with the mosaicing process, should also work provided that sub-images are maintained for each primary beam pattern. The sidelobe level in each subimage is higher than that for a mosaic for a homogeneous array with the same total number of antennas. Too many primary beam types, resulting in sparse arrays, will almost certainly limit the dynamic range. Comparing the MEM image directly with the uv-data may alleviate the sidelobe problem, but keeping the uv-data into the imaging process adds considerably to data management problems. The negative primary beam from mixed antenna baselines may be a problem in the mosaicing algorithms. Conceivably it might also serve to knit together the mosaic by providing different weightings of the overall image. Mosiacing with mixed antenna baselines needs detailed study.

7. Pointing calibration

Better pointing leads to higher dynamic range imaging. In the recent CygA mosaic with the BIMA array (Wright etal, 1997), the dynamic range was limited by 1/26 FWHM primary beam pointing errors. Admittedly CygA was a difficult source with emission concentrated at the 1/2 power points, but pointing is a problem. For larger antennas, the primary beams are smaller, and the pointing errors are likely to be larger. Pointing and primary beam errors can seriously corrupt the uv-data. Pointing self-calibration might improve the dynamic range for mosaiced images. It would be reasonable to assume that the pointing errors are a function of the antenna design, and the ambient conditions. For well insulated antennas, the time scale for the pointing errors is longer than the cycle time through all the pointing positions, and can then be represented by relatively few parameters common to all the pointing positions and antennas. These parameters could be fitted to minimize the residuals in the mosaicing algorithms. A heterogeneous array with multiple antenna designs increases the number of parameters, but the negative primary beam from mixed antenna baselines might provide a good tool in fitting the pointing errors; another problem requiring detailed study.

8. Conclusions

This brief review of imaging with a heterogeneous arrays has uncovered no fundamental problems. The existing imaging algorithms will work with mixed antenna sizes, but may not be optimum. A number of problems need detailed study to optimize array configurations and imaging algorithms for mixed arrays. Too many primary beam types, resulting in sparse arrays, will almost certainly limit the dynamic range. Additional complexity in the already daunting process of radio-astronomical imaging for the non-specialist is undesirable.

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