WIDE-FIELD IMAGING IN CLASSIC AIPS

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ABSTRACT

When non-planar interferometers construct images with a 2-dimensional FFT, the accuracy degrades away from the phase center. NRAO's AIPS (Classic) software avoids this problem by imaging a mosaic of small planes ("facets") each tangent to the celestial sphere. This tactic also allows the imaging program IMAGR to remove the effects of distant interfering sources. Furthermore, multiple facets allow experimental algorithms to deconvolve the source with a mix of point- and extended-component models. Classic AIPS provides tools for the preparation of inputs to IMAGR and fully supports the multiple-facet, multiple-resolution models in all applications including self-calibration.

INTERFEROMETRIC IMAGING

Numerous authors (see for example Thompson, Moran, and Swenson [1]) have shown that a radio interferometer responds to the Fourier transform of the sky brightness on the celestial sphere. This is not tractable computationally, so traditional imaging software has approximated the sphere with a plane tangent to the sphere at the phase tracking position. The phase error in radians due to this approximation is shown in [1] to be $\pi w \sqrt{1 - l^2 - m^2}$ where w is the baseline length in wavelengths in the direction of the source and l and m are the direction cosines. The maximum value of w is approximately one over the synthesized beamwidth θ_s. Therefore, to keep the worst phase error less than f radians, the largest angle imaged θ_m must be approximately

$$\theta_m < \sqrt{f \theta_s} \tag{1}$$

where both angles are measured in radians. The left-hand side of Fig. 1 illustrates this point. The phase error in radians is approximately the distance between the tangent plane and the celestial sphere $(1 - \cos\theta)$ measured in synthesized beamwidths. Since both the field of view θ_m and the synthesized beam θ_s scale as wavelength on a particular interferometer, Eq. 1 affects longer wavelengths more than it does short wavelengths.

CLASSIC AIPS' IMAGR

The Classic AIPS software system of the National Radio Astronomy Observatory uses a program named `IMAGR` to construct and deconvolve images from interferometric data. Beginning in 1997, `IMAGR` has the option of breaking up a single large image (with correspondingly large phase errors) into multiple small images ("facets") each of which is tangent to the celestial sphere. This "3D" imaging, illustrated in the right-hand side of Fig 1, involves a large amount of computation. For each facet, the visibility data must be shifted in phase to the center of the facet and the visibility coordinates (u, v, w) must be rotated to the new tangent point. Then the data are gridded and Fourier transformed to make an image of the facet. Since the (u, v) values are different for each facet, the synthesized beam patterns will be different. Thus the deconvolution ("Clean") must be done one facet at a time. Furthermore, each facet contains sidelobes of sources in other facets. These sidelobes must be corrected as the Clean progresses, or they will be taken to be sources within the present facet. Thus, after some number of components are found in a facet, the visibility of these components must be computed, shifted back to the original phase tracking point, and then subtracted from the visibility data. Surprisingly, the 3D option is found to cost only about 1% in computer time when it is not needed, and will actually save time by speeding the Clean when it is needed.

`IMAGR` has two modes of deconvolving the facets. In the simpler, each facet is imaged, Cleaned for some modest number of iterations, and its components subtracted from the visibility data. After each facet has been (lightly) Cleaned and its components subtracted, the residual visibility data are used to construct new residual images of all facets and the process is repeated. The second mode is more complicated: after one facet is lightly Cleaned, its components are subtracted from the visibility data. A new facet is selected and re-imaged from the current residual visibility data before being Cleaned.

[1]The National Radio Astronomy Observatory is a facility of the (U.S.) National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

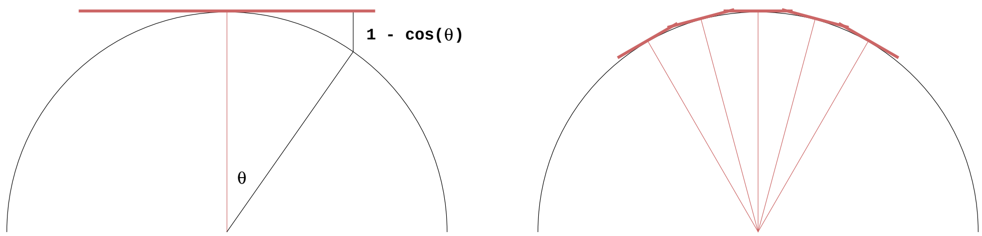

Figure 1: Unit celestial sphere with large image and phase errors (left) and with multiple small facets (right)

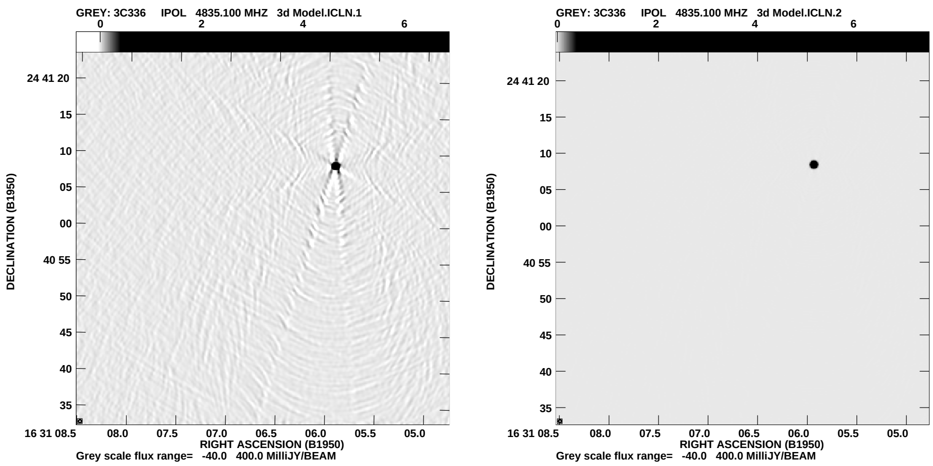

Figure 2: Model image without (left) and with 3D correction.

In this way, noise bumps due to strong sources in one facet are not taken as weak sources in another facet and instabilities do not develop when a given point in the sky is cleaned from more than one facet.

The results of using the 3D option are illustrated in Fig. 2 which shows the Cleaned image of a model source separated from the pointing direction by 2° (18575 synthesized beams) and separated from its facet center by 14.9 arcsec (36 synthesized beams). The non-signal rms of the image corrected only for phase at its center is 35 times that of the fully 3D one.

Tracy Clarke [2] has provided data on Abell 2256 from the VLA's most compact configuration at 20-cm wavelength. A single facet covers the single-dish primary beam well past the half-power point and still satisfies Eq. 1. However, 19 facets are used to cover a very much larger area as illustrated in Fig. 3. Both images in the figure are constructed with a multi-resolution Clean to be described below. In the upper image, only the central 256x256 facet is allowed to have Clean components. The sidelobes of a source to the north of the main facet are seen to have serious effects over many of the facets including the central facet with its interesting intra-cluster emission. When `IMAGR` is allowed to find components in all facets, these sidelobes are greatly reduced. They are not eliminated because that interfering source is seen in sidelobes of the individual antennas of the interferometer not their main beams. The phase and amplitude calibration of such sidelobes is unlikely to be exactly that of the main antenna beams. Minor pointing errors and beam squint also compromise the observed visibilities of such a distant source. In fact, it is surprising that the deconvolution of that source works as well as it does, but this figure (and many others like it) shows that it is essential to include distant objects in the imaging process. In principle, we could even measure the complex gains for important objects in the sidelobes in order to remove them from the data. In practise, this is done only for extremely strong interfering sources..

MULTI-RESOLUTION CLEAN

Since the Clean deconvolution algorithm normally works by modeling the image as a collection of point sources, it is inclined to make the sky look like point sources even when it consists in large part of extended emission. In the mid 1970's, this author investigated using the Clean algorithm to model an image as a collection of Gaussians of a fixed and

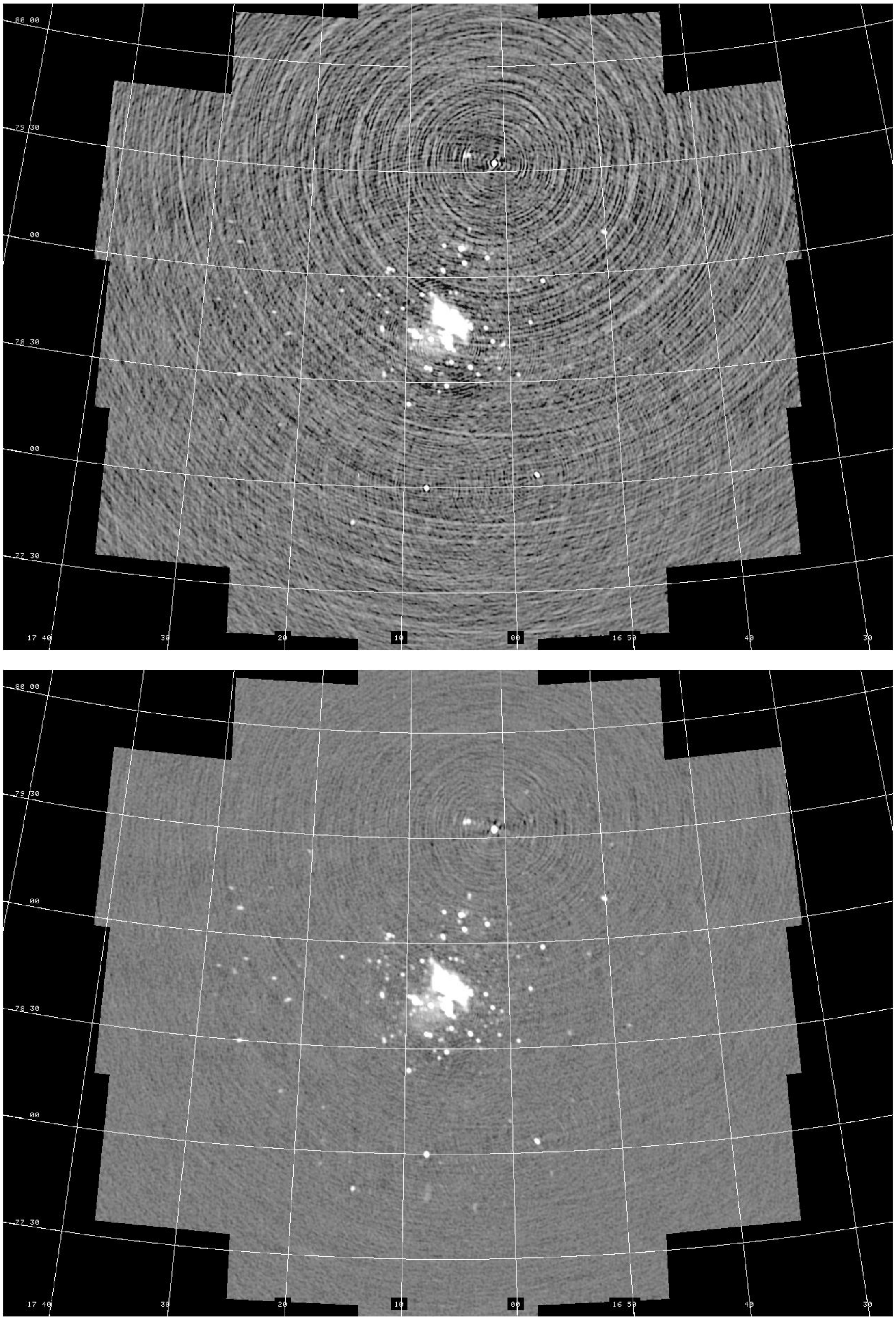

Figure 3: Top: Clean center facet only with multiple resolutions; Bottom: Clean all facets with multiple resolutions. The two images are on the same gray-scale display range. The primary beam of the individual antennas in the interferometer covers only a little more than one of the coordinate "squares."

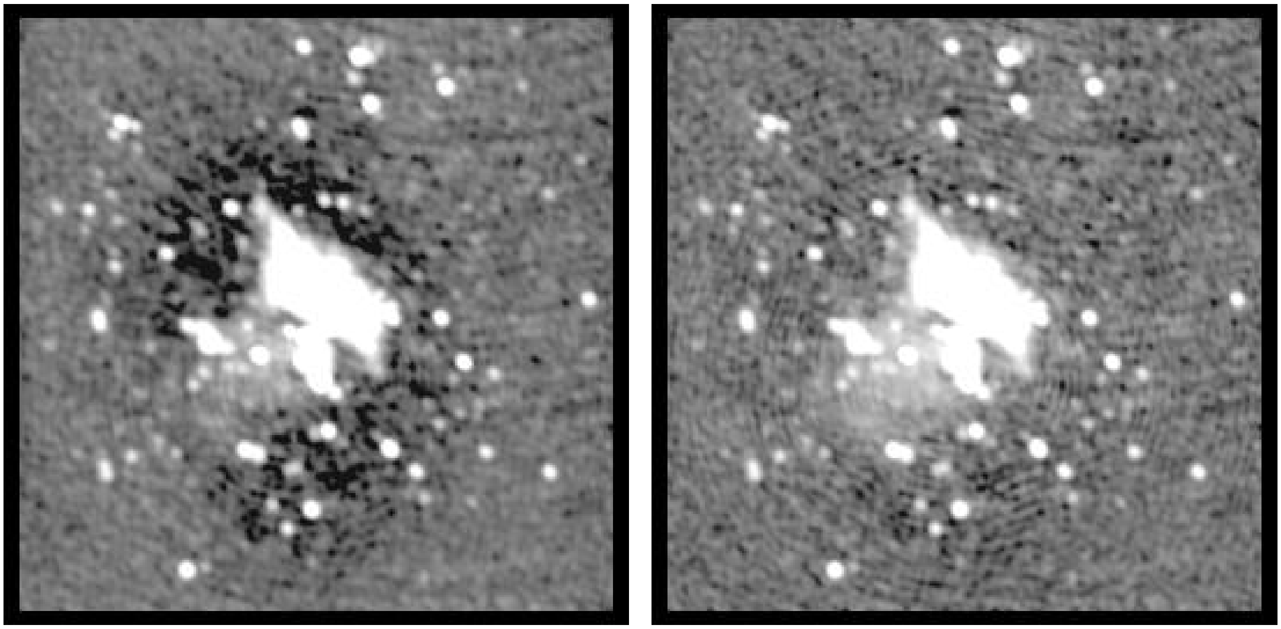

Figure 4: Center facet of the 19-facet image shown in Fig. 3, Cleaned with point (left) and multiple-resolution (right) models shown on the same gray-scale display range.

finite width. The algorithm failed since a Gaussian model requires a non-physical Bessel function $J_1(x)/x$ distribution of Gaussians to represent a point object and any real astronomical field always contains point-like objects as well as extended ones. The extended source modeling worked well on extended sources, but painted "bull's eyes" around all of the unresolved sources.

Holdaway and Cornwell [3] describe an algorithm which attempts to solve this problem. Unlike my 1970s attempt, their algorithm does a point-source Clean on one image of the field, plus one or more extended-source Cleans on suitably tapered images of the same field. Classic AIPS' `IMAGR` is particularly well suited to this algorithm since it is able to image many facets at once and to Clean facets that overlap. `IMAGR` uses Gaussians as the extended source models and provides several "steering" options to control the algorithm's natural tendency to favor the largest of the source models. I regard the algorithm as experimental, with a need to improve its efficiency and to understand its behavior. Nonetheless, as may be seen in Fig. 4, the algorithm is capable of producing a somewhat smoother image, while reducing the effects of missing short spacings. That reduction is present over the entire area shown in Fig. 3.

SUMMARY

Classic AIPS contains the ability to construct a large-angle image from multiple facets each tangent to the celestial sphere. It may deconvolve these multi-facet images with a point-source model or with multiple model resolutions. The model found with the multiple facets and resolutions may be used in all subsequent programs that use source models including the self-calibration that allows still more refined images to be made.

REFERENCES

[1] Thompson, A. R., Moran, J. M., and Swenson Jr., G. W., *Interferometry and Synthesis in Radio Astronomy*, 2$^{\rm nd}$ ed., New York: John Wiley & Sons, Inc., 2001.

[2] Clarke, T. E. and Ensslin, T. A. "Cluster Mergers and Diffuse Radio Emission in Abell 2256 and Abell 754," to appear in *Galaxy Clusters and the High Redshift Universe Observed in X-rays*, Neumann, D., Durret, F., and Tran Thanh Van, J. Eds., Proceedings of XXI Moriond Astrophysics Meeting, in press, astro-ph/0106137, 2001.

[3] Holdaway, M. and Cornwell, T., "Multi-scale Clean," Mosaicing Workshop, Socorro, NM, July, 1999, `http://aips2.nrao.edu/docs/user/General/node16.html`