Multiresolution CLEANing in Obit

W. D. Cotton March 19, 2011

***Abstract*—This memo describes the multiresolution CLEAN implemented in the Obit package. Deconvolution using a number of resolutions helps recover images of sources with structure on a range of spatial scales. Results of several tests are presented. A constant set of tuning parameters appears to work for a wide range of cases.**

***Index Terms*—Radio Interferometry, Deconvolution**

I. Introduction

RADIO interferometers only sample the visibility plane constraining structure on some spatial scales better than others. In addition, the surface brightness sensitivity at the full resolution of a data set may be insufficient to adequately detect larger scale structures.

The incomplete sampling of the uv plane by most interferometers produces a less than ideal instrumental response leading to the need to deconvolve the derived images. CLEAN is the most popular technique for this deconvolution and a number of variants exist.

A given data set may be imaged with a variety of uv plane tapers to produce images with a range of resolutions which are better matched to the scale of structures than is a single, full resolution image. A joint deconvolution of this set of images is needed to recover a proper representation of the data. This memo describes an implementation of CLEANing at multiple resolutions in order to address these issues. This implementation is similar to the multiresolution CLEAN implemented in AIPS. The techniques discussed are implemented in the Obit package ([1], http://www.cv.nrao.edu/∼bcotton/Obit.html).

II. Problems with Single Resolution Imaging

The following discuss why imaging using a single resolution may produce less than ideal reconstruction of the sky brightness distribution.

A. Resolution and Sensitivity

Interferometric images are frequently sensitivity limited in the sense that below some level, weaker features are obscured by the thermal noise in the data. Thus, for a given sensitivity, only features with a flux density in a resolution element brighter than the thermal noise are detectable. A strongly resolved feature will have its emission spread over a number of resolution elements possibly rendering it undetected at that resolution.

The resolution of a data set can be reduced by "tapering" - down weighting data at higher spatial frequencies to produce an image at lower resolution. In this case, the larger scale structure will have more emission in a given beam and may be detectable. The noise will be higher in this case as fewer data are used in the image but this is frequently overcome by the larger flux density in each resolution element.

B. Poor Constraints on Large Scale Structure

Imaging smooth emission with a resolution element much smaller than the size of the emission is poorly constrained as many independent beam areas are used to represent it. CLEAN has well known difficulties in this regime and tends to create finer scale structures that are unconstrained by the data. Techniques such as the Prussian Hat CLEAN (Cornwell ?) and the Greisen AIPS variant of the Steer–Dewdney–Ito CLEAN [2] have been proposed to deal with this problem. An alternative approach is to model the data using resolutions appropriate to the size scales of the features for which CLEAN cannot over interpret the data.

III. Imaging with Multiple Resolutions

Imaging in Obit uses faceting to deal with the noncoplanarity of the array [3] and in the tests here, each facet was projected onto a common grid on a common tangent plane [4]. This allows parallel CLEANing of multiple facets. At the beginning of each imaging task, a mosaic is defined that covers the desired field of view plus any additional facets needed to include sources in a catalog provided. This defines a mosaic containing one or more facets.

When multiple resolutions are specified for the CLEAN, each facet in the mosaic is replicated at each resolution. Each facet image is derived as needed using a Gaussian uv plane tapering sufficient to produce the desired resolution. The tapering is achieved by multiplying the data weights by a factor:

$$factor \;=\; e^{(u^2+v^2)\ \log(0.3)(t/2.35/\pi)^2}$$

where u,v are the spatial frequency coordinates in wavelengths and t is the desired FWHM resolution in radians. Note: due to the limited sampling of the uv plane, the Gaussian fitted to the beam derived by this process will not be precisely *t*. In subsequent processing, the target beam size, *t*, should be used when calculating the instrumental response for tapered data and the fitted beam size to adjust units between various resolutions.

The number of additional resolutions to image are given by task parameter nTaper. The FWHM of the target resolutions are given in task parameter array Tapers in units of pixels. Specification in units of pixels simplifies usage in scripts which will not know the resolution in advance but can assume a full resolution FWHM on the order of 4 –6 pixels.

National Radio Astronomy Observatory, 520 Edgemont Rd., Charlottesville, VA, 22903 USA email: bcotton@nrao.edu

Manuscript received ; revised

IV. CLEANING WITH MULTIPLE RESOLUTIONS

Multi–facet CLEANing in Obit is described in detail in [4] and consists of three loops; an inner Clark CLEAN [5] loop using a subset of the pixels and beams of the factets being searched for components; a middle CLEAN loop in which components are subtracted using image plane techniques and the CLEAN window may be refined [6]; and an outer loop in which the newly found components are Fourier transformed and subtracted from the residual uv data and new residual images derived.

Multi–resolution CLEANing is implemented in the outer loop in which it is decided which resolution to search for new components. The inner and middle loops then only consider this resolution.

A. Selecting the Appropriate Resolution

Selection of the appropriate resolution for the next outer cycle of CLEANing is the most critical aspect of this technique. Fine scale structure needs to be modeled using the highest resolution to avoid digging bowls around it. Extended structure should be modeled with the tapered images to avoid the instabilities of CLEANing extended emission with too fine a resolution. The resolution decision needs to be as automated and robust as possible to minimize the need for user interaction.

The current choice algorithm is as follows.

1) For each facet modified in the previous iteration, re image the corresponding facets at all resolutions. Determine the statistics of the residual. This allows the decision to be made on the basis of fresh information
2) Chose the "best" facet at each resolution. This is done on the basis of the "quality" measure which is a weighted sum of the peak and average residuals. This is the criteria used to distinguish among facets at a given resolution.
3) An objective function is evaluated for the "best" facet at each resolution and the resolution with the highest value is chosen. The objective function is

$$fn \ = \ fact1 \ taper\_fn \ + \ fact2 \left(\frac{SNR}{(maxSNR)}\right) + fact3 \ quality$$

where

- $fact1$ is the taper factor used to bias the decision towards higher resolution and is decreased during the CLEAN:

$$fact1 \ = \ fact1_0 \left[0.1 + \left(1 - \frac{iter}{niter}\right)\right]^2$$

where $fact1_0$ is the initial value of *fact1*, *iter* is the number of CLEAN iterations completed and *niter* is the maximum number of CLEAN iterations allowed.
- *taper_fn* is given by

$$taper\_fn \ = \ \frac{(maxTaper - Taper)}{maxTaper}$$

where *maxTaper* is the highest request taper, *Taper* is the Taper value of the resolution in question,.
- *fact2* is the signal–to–noise weighting factor.
- *SNR* is the ratio of the highest residual pixel value to the residual RMS and *maxSNR* is the highest SNR of any facet.
- *fact3* is the "quality" weighting factor.
- *quality* is 0.95× the peak residual plus 0.05 × the average residual pixel value.

The objective function for a resolution is then further modified for a given resolution when the ratio of the peak to RMS ("SNR") in the best facet gets low or the CLEAN at that resolution has been completed according to the minFlux criterion. If the SNR drops below 5, the objective function function is multiplied by 0.75, below 2.5 by 0.25 and below 1.5 is set to zero. The objective function for resolutions deemed finished are set to zero.

The tuning parameters are specified in task parameter array Tapers as $fact1_0$ = Taper[0], *fact2* = Taper[1], and *fact3* = Taper[2]. The current default values are $fact1_0$ = 0.20, *fact2* = 0.33, and *fact3* = 0.20. When tapered images are being CLEANed, the CLEAN components are marked as Gaussians and given the Gaussian size used to determine the taper.

B. Stopping Criteria

The usual criteria for terminating the CLEAN is either the maximum number of components or the minimum flux density level. For multiresolution CLEANs the number of components depends strongly on the decisions about which resolutions to use and is not an effective means to specify the depth of the CLEAN.

The minimum flux density is given in units of Jy/beam and is numerically different for the different resolutions. A simple scaling by the beam areas gets the units correct but the surface brightness sensitivity with the lower resolutions will, in many cases, be better than this simple scaling suggests. The following compromise is adopted:

$$\mathrm{minFlux}_{\mathrm{low\_res}} = 0.5 \ \mathrm{minFlux}_{\mathrm{hi\_res}} \left(\frac{\mathrm{beamArea}_{\mathrm{low\_res}}}{\mathrm{beamArea}_{\mathrm{hi\_res}}}\right)$$

and $\mathrm{minFlux}_{\mathrm{hi\_res}}$ is the minimum flux density specified by the user (task parameter minFlux).

C. Sky Model with Mixed Point and Gaussian components

Calculation of interferometer responses in OBIT using the "GRID" method calculates the facets contributions separately and since a given facet only has components of a single type, nothing special is needed. Calculations using the "DFT" method can combine components from multiple facets; if point components are mixed with Gaussians, the points are "promoted" to Gaussians of zero size.

D. Restoring the CLEAN Image

After the CLEAN is completed, the final image consists of the high resolution residuals with all components restored. Components from tapered facets are restored with the uv taper beam size and are scaled by the ratio of the beam areas into the units of the high resolution residuals:

$$scale = \frac{High\_res\_beam\_area}{Low\_res\_beam\_area}$$

where $Low\_res\_beam\_area$ is the fitted beam area.

V. Test Examples

The multiresolution CLEAN described above has been implemented in Obit imaging tasks. A number of tests were run using tasks Imager and MFImage and the default multiresolution tuning parameters.

A. VLA: Survey Field

The first test is of a VLA medium depth 20 cm B configuration survey of a field in which only a handful of sources are more than a few resolution elements across and most are at best marginally resolved. Obit task Imager was used. This test determines how well a multiresolution CLEAN works when the full resolution is adequate for most of the sources in the field. Two resolutions were used, the full 4.1”×3.7” and the lower 19.2”. Imaging included a single stage of phase self calibration. Two selected regions of the derived image are shown in Figure 1. Extended sources showed a minor benefit from the multiresolution CLEAN and the unresolved sources suffered no harm.

B. VLA: Orion A

The second test case for multiresolution CLEAN is the star forming region Orion A. This is a very strong extended source with copious emission on a wide variety of scales. A simple CLEAN does a really bad job of reconstructing this source.

The test data set is a multi configuration VLA observation at 20 cm using the B, C and D configurations. These data were imaged by Obit task Imager using three resolutions, the full resolution was 8”; tapered resolutions were 24” and 80”. The resulting image is shown in Figure 2 giving a comparison simple CLEAN result.

C. EVLA: Hercules A

EVLA Science Demonstration observations of the radio galaxy Hercules A were imaged by the wideband imaging task MFImage using combined B, C and D configuration data. The test example is the frequency range 4-6 GHz. The data were subjected to 2 iterations of phase self–cal and one of amplitude self–cal using a single resolution in Obit task MFImage. The self–calibrated data were then imaged at 1.0”, 4.6” and 18.5” resolutions using MFImage and the default tuning parameters. The resulting image is shown in Figure 3.

VI. Usage Notes

Since the implemention described above only switches resolutions for major cycles, aggressive CLEANing may result in degraded results. A low value of the CLEAN loop gain (Task parameter Gain), e.g. 0.03 is recommended as is a high value of the fractional depth of each CLEAN (task parameter ccfLim) of 0.6 or higher. This will result in more major cycles and the opportunity to switch resolution more often.

Using a multiresolution, wideband CLEAN model as the self–cal model seems to add some instability to the process as well as generally being slower than a single resolution self–cal. The recommended procedure when using the wideband imaging task MFImage is to image and self–cal with the single, high resolution followed by a deep multiresolution CLEAN on the resultant calibrated data.

VII. Discussion

The examples shown above demonstrate that the technique described gives satisfactory results using a constant set of tuning parameters for data sets with very different properties. The reduced need for the user fine tuning the tuning parameters allows this method to be applied in fully or partly automated processing scripts. It is fairly straightforward to integrate this method in the various imaging tasks in Obit, e.g. wideband or imaging with direction dependent gain corrections. The multiresolution models are automatically used in self calibration (but see the Usage Notes).

References

[1] W. D. Cotton, “Obit: A Development Environment for Astronomical Algorithms,” *PASP*, vol. 120, pp. 439–448, 2008.

[2] D. G. Steer, P. E. Dewdney, and M. R. Ito, “Enhancements to the Deconvolution Algorithm ’CLEAN’,” *A&A*, vol. 137, pp. 159–+, 1984.

[3] R. A. Perley, “Imaging with Non-Coplanar Arrays,” in *Synthesis Imaging in Radio Astronomy II*, ser. Astronomical Society of the Pacific Conference Series, G. B. Taylor, C. L. Carilli, and R. A. Perley, Eds., vol. 180, 1999, pp. 383–+.

[4] W. D. Cotton, “Multi–facet CLEANing in Obit,” *Obit Development Memo*, no. 15, 2009.

[5] B. G. Clark, “An efficient implementation of the algorithm ’CLEAN’,” *A&A*, vol. 89, pp. 377–+, Sep. 1980.

[6] W. D. Cotton, “Performanence Enhancement of the autoWindow Technique,” *Obit Developement Memo Series*, vol. 9, pp. 1–3, 2009.

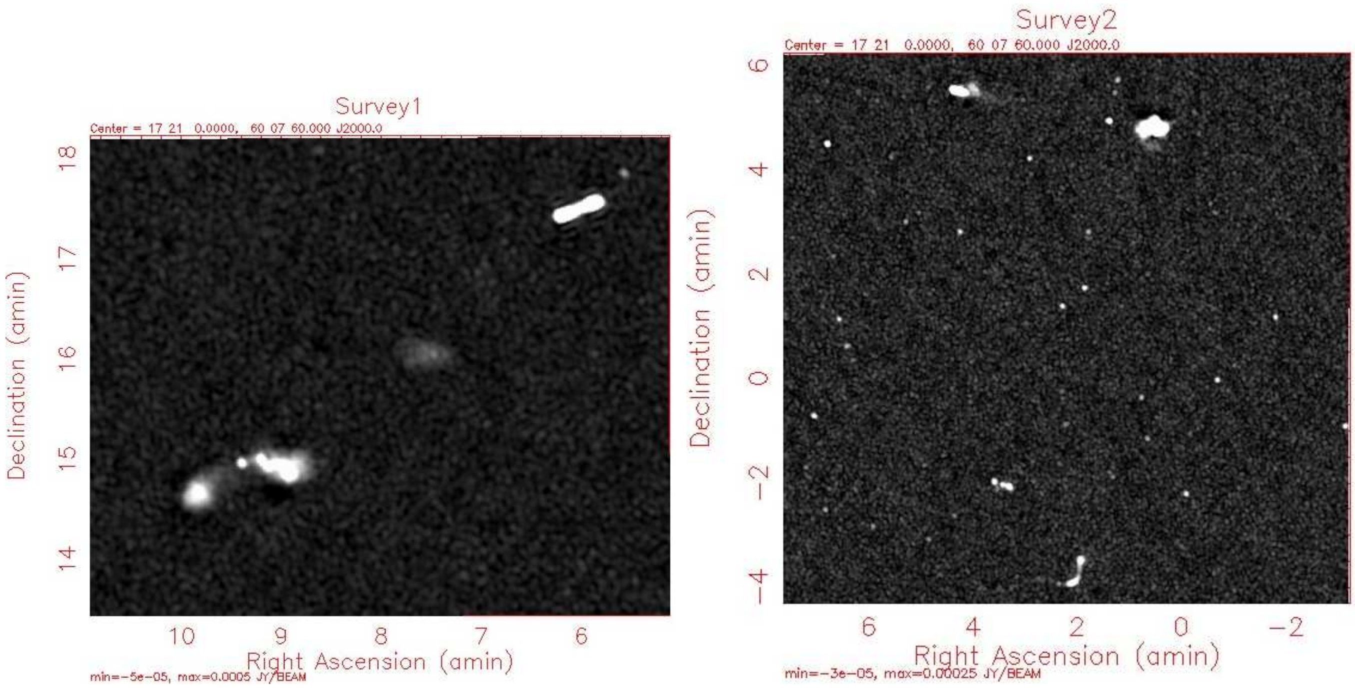

Fig. 1. VLA 20 cm B configuration survey fragments using multiresolution CLEAN. Left figure shows several extended sources, Right shows a region dominated by point sources. Note different scales.

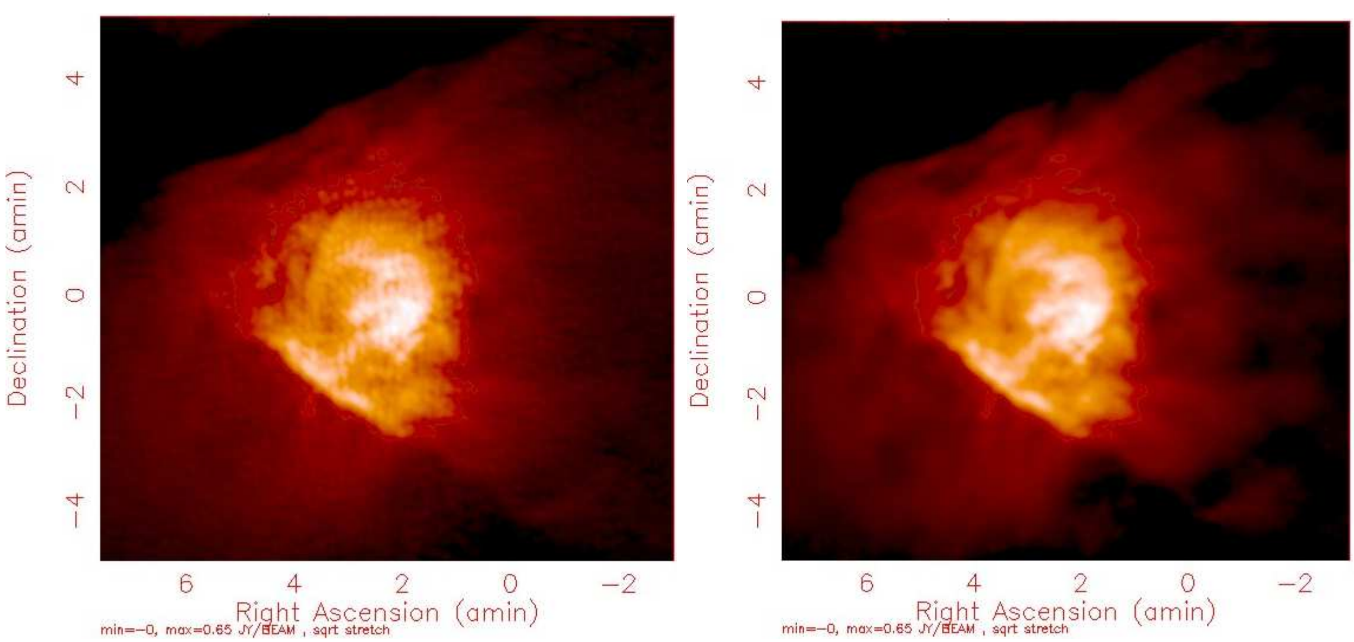

Fig. 2. VLA 20 cm image of Orion A using B+C+D configuration data. On Left is image derived using simple CLEAN, on Right using multiresolution CLEAN. A square root stretch is used.

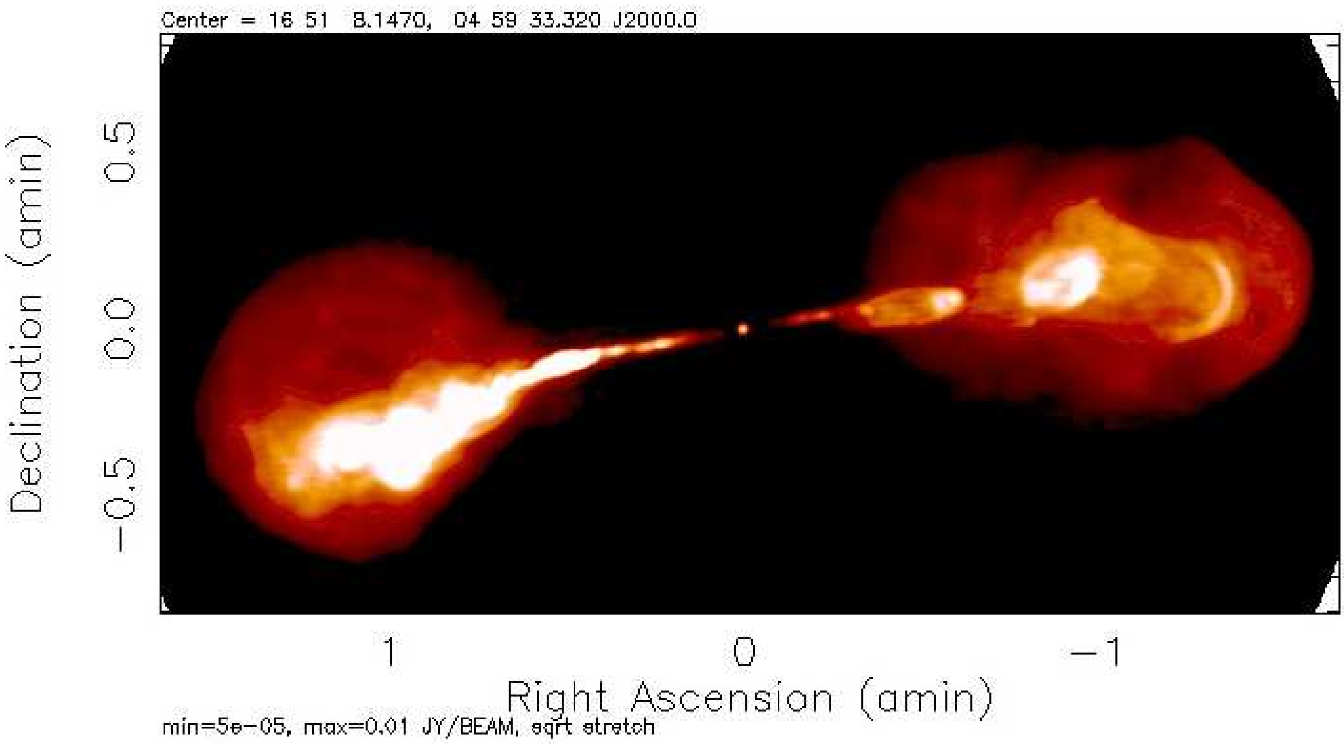

Fig. 3. EVLA 4-6 GHz of Hercules A using B+C+D configuration data. A square root stretch is used.