Image Combination by Feathering

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***Abstract*—Astronomical objects frequently exhibit structure over a wide range of scales whereas many telescopes, especially interferometer arrays, only sample a limited range of spatial scales. In order to properly image these objects, images from a set of instruments covering the range of scales may be needed. These images then must be combined in a manner to recover all spatial scales. This memo describes the feathering technique for image combination in the uv plane as implemented in the Obit package. An example combination of single dish and interferometric observations of a model source is given.**

***Index Terms*—interferometry, image combination**

I. Introduction

CELESTIAL images may contain structure on a wide variety of size scales whereas a given radio astronomical instrument may be sensitive to only a limited range of size scales. A common solution to this problem is to image the desired object with a number of different instruments, or configurations of a given instrument, to recover the structure on the total range of size scales needed. These range from single dishes for the largest scales to short baseline interferometers to longer baseline interferometers. Furthermore, each instrument and/or array configuration may have artifacts which are best dealt with using that data-set alone. This memo considers the combination of images derived from several instruments or configurations by the "feathering" technique. In this technique, images are combined in the Fourier transform domain by a weighted average of the transform of the various input images in order to extract the most appropriate spatial frequencies from each. This memo describes a feathering technique implemented in the Obit package [1] [1].

II. Resolution and Spatial Dynamic Range

Diffraction limited astronomical instruments have a resolution that is proportional to the diameter of the aperture measured in wavelengths of the light being observed. The range of larger spatial scales to which the instrument is sensitive depends on the details of the instrument and in particular, the distribution and fraction of its aperture which is filled. Filled aperture instruments (AKA "single dishes") sample all spatial frequencies up to those defined by the total aperture. Cost and other practical constraints limit the maximum size, hence resolution of single dishes. On the other hand, interferometers generally sample only a fraction of the spatial frequencies less than that defined by the maximum baseline. The largest scale size that can be imaged is defined by the shortest spacing that are adequately sampled. Interferometers can be constructed to an arbitrary size, hence, resolution but practical constraints limit the fraction of the aperture that can be filled thus the largest scale size. Some interferometers such as the VLA and ALMA have a "zoom" capability in which the antennas can be reconfigured to produce a range of resolutions and surface brightness sensitivities. In addition, ALMA has an array (ACA) of smaller antennas that can be arranged in a more compact configuration to measure even lower spatial frequencies. For objects with a wide range of spatial scales, multiple instruments or configurations may be needed.

Every instrument can produce artifacts or spurious features in its images. Techniques to reduce these may be deployed but these are generally specific to a given instrument of configuration. An example of this is a bright source far from the pointing center of an interferometer. Even when not in the field of interest, such a source may produce sidelobes in the field of view that are subject to bandwidth smearing and details of the far antenna pattern. Bandwidth smearing is locally convolutional and the effects of the offending source can largely be removed from the data from a single interferometer or configuration by deconvolution including that source. Artifacts from asymmetries in the antenna pattern are not convolutional but may be greatly reduced by corrections based on known antenna patterns or by "peeling".

III. Feathering

An image may be characterized by the spatial frequencies which are well represented in the image; these correspond to the regions in the Fourier transform ("uv" space) of the image which were well measured by the instrument. Interferometers generally cover a range of spatial frequencies which is limited by the longest and shortest baselines. Single dishes, in principle, measure all spatial frequencies up to those corresponding the the instrument diameter[2]. Ideally images with overlapping, well–sampled spatial frequencies can be combined to derive an image reproducing all the spatial frequencies in the initial images.

Feathering is the technique of combining images in the uv plane to recover the spatial frequencies in the input images. While this is a generic technique and is widely implemented, the details may vary from implementation to implementation. The following is a description of that employed by Obit task Feather.

IV. Obit Implementation

The Obit implementation allows a relatively arbitrary number of images to be combined although task Feather is limited to 10. Images are ordered by decreasing resolution. Images are presumed to have an annular region in the uv–plane which

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[1]http://www.cv.nrao.edu/∼bcotton/Obit.html

[2]However, spatial filtering to remove atmospheric or instrumental variations may filter out some spatial frequencies

is well sampled and a weighting mask is constructed for each which tapers to zero at lower spatial frequencies. The weighting mask of the lowest resolution image is not tapered to its center. The various steps in feathering are described in the following.

1) **Re-sample images**
The first step is to re-sample images with resolutions less than the maximum to the grid of the maximum resolution image with sufficient zero padding on the outside to allow an efficient FFT. The interpolation uses the Lagrangian technique in 2D to interpolate the pixels in the lower resolution images at the locations of the highest resolution image using a 5x5 pixel kernel. Input images need not use the same projection or even the same equinox as this will be corrected in this step.
2) **Generate weighting masks**
For each resolution except the lowest, a real weighting mask is generated with a Gaussian hole in the center representing the spatial frequency range of the next lowest resolution. A sampling mask representing the spatial frequencies of each image is generated by:
   a) Create image with the CLEAN beam at the center
   b) FFT
   c) Take real part
   d) normalize to 1 at (0,0) spatial frequency

   The weighting mask for each image i is
$$weight\_mask_i \;=\; 1.0 - sampling\_mask_{i+1}$$
   where $i+1$ indicates the next lowest resolution. The weighting mask for the lowest resolution is 1.0 everywhere. The weighting masks are multiplied by the weights assigned to the input images.
3) **FFT**
Each image is FFTed to the uv plane
4) **Weight**
Multiply Fourier transform of image by its weighting mask.
5) **Accumulate**
Sum the Fourier transform of the images times weight.
6) **Inverse FFT**
Fourier transform back to the image plane.
7) **Normalize**
The normalization factor is determined by repeating the process but replacing the image with its corresponding CLEAN beam. The normalization factor is 1.0/center_pixel.

A. *Primary beam correction*

Interferometric images should be “Primary beam corrected” before feathering such that features in the image are at the strength they would be have without off–center attenuation of the power pattern of the interferometer elements

B. *Mosaics*

Mosaics are suitable candidates for feathering as long as the combination into the mosaic removes the primary beam pattern.

C. *Weighting*

Not all images are created equal and it may be desirable to allow different images to have different weights where their uv regions overlap. A simple relative weight is the inverse variance of the noise.

D. *Spectral cubes*

Feathering spectral line cubes is a straightforward feathering of each set of channel images. The Obit implementation allows spectral cubes although all must have the same channelization.

V. CONSTRAINTS ON IMAGES

Images to be combined need to be astrometrically and photometrically aligned. The Obit implementation requires only that the astrometric parameters in the image give the same positions for given features in all images and need not be on the same grid, projection or even equinox. The photometric (flux density) scale must be the same for all input images. If this cannot be achieved from the calibration of the data, an adjustment can be derived from the average ratio of amplitudes in the overlapping region of uv space. The Obit implementation depends on the “CLEAN” beam size given in each image descriptor to accurately reflect the resolution of the image.

Image combination will work best when the images combined have overlapping regions of the uv–plane. In the case of non-overlap, structure represented by the portions of uv space not sampled will not be well represented in the feathered image. Clearly, combining single dish and VLBI images will not generally be productive.

The technique described above assumes that each input image has been appropriately filtered to remove power at spatial frequencies beyond the range sampled by the instrument used to derive the image. For interferometric images this is simply that the emission CLEANed is restored with a CLEAN beam that accurately represents the psf of the instrument. Images derived from single dish measurements may not have had similar filtering and may need to have spatial frequencies outside of the telescope aperture filtered before combination.

Interferometric images of sources with extended emission generally need extra care as emission poorly sampled in the uv–plane can lead to image artifacts. Multi–resolution CLEAN can help with reconstructing large-scale emission. In extreme cases, setting a short baseline limit can help suppress large waves from very poorly sampled structure. Negative bowls around extended emission are common but should be removed by feathering if the relevant spatial frequencies are obtained from other images.

VI. EXAMPLE

To illustrate the power of this technique, noiseless synthetic data sets were derived for the model source distribution shown in Figure 1. A simulated single dish image was derived by convolving the model image with the resolution of the single dish. To simulate an interferometric image, a sample full track, VLA–like array uv coverage was generated (Obit/UVSim)

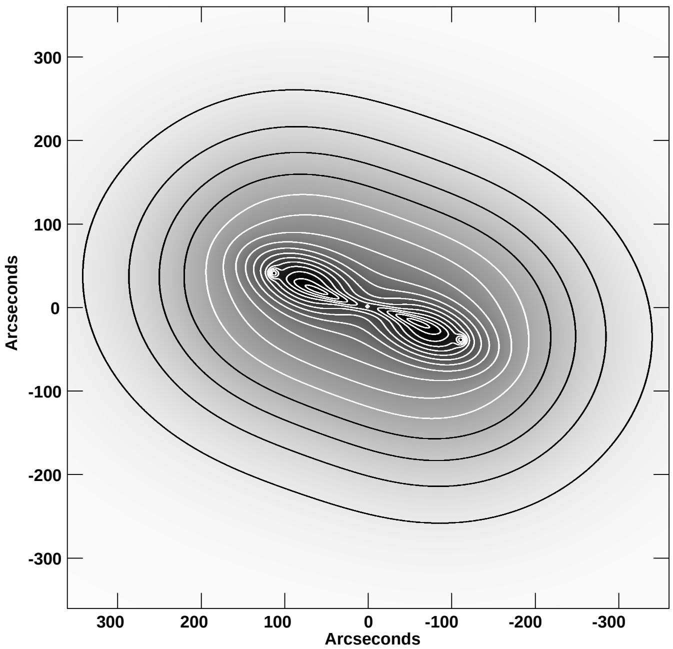

Fig. 1. Model source.

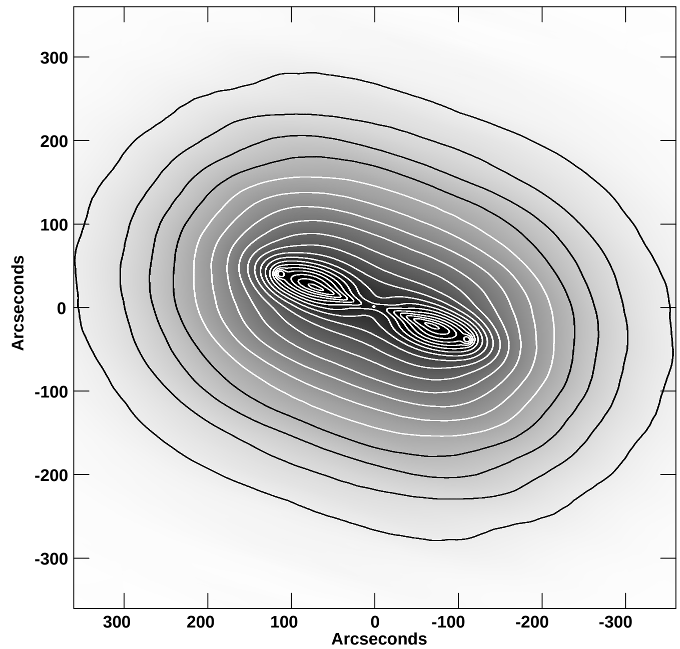

Fig. 3. The feathered combination of the images in Figure 2. Contours are at the same levels as Figure 1.

and the Fourier transform of the model was evaluated at the locations in the data-set. These data were then imaged with multi–resolution CLEAN (Obit/Imager). The simulated single dish and interferometric images are shown in Figure 2. The very extended emission is only visible in the single dish representation and the most compact emission only visible in the interferometric version. These two images were then feathered together with equal weights using Obit/Feather giving the image shown in Figure 3.

The overlapping coverage in Fourier space is illustrated in Figure 4. The relative sensitivity of the single dish data was derived from the Fourier transform of its psf. The relative sensitivity of the interferometer data was derived by averaging the Fourier transform of the dirty beam (= uv sampling function) in annuli. The amplitude of the Fourier transform of the model image along one cut in the uv-plane is shown in the lower panel. The Fourier plane overlap shown in this example is minimal.

VII. Discussion

The feathering technique for image combination in the Fourier plane as implemented in the Obit package is described and an example of its use shown. In the example of a model source observed with a single dish and an interferometer, the extended structure was only visible in the former and the most compact structure only in the latter. The feathered combination displays both the extended and compact emission.

The feathering technique described here allows an arbitrary number of images at different scales to be combined. This allows the best approach to reducing artifacts to be used for each of the images before their combination. This approach to image combination is especially useful for combining single dish and interferometric images.

References

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

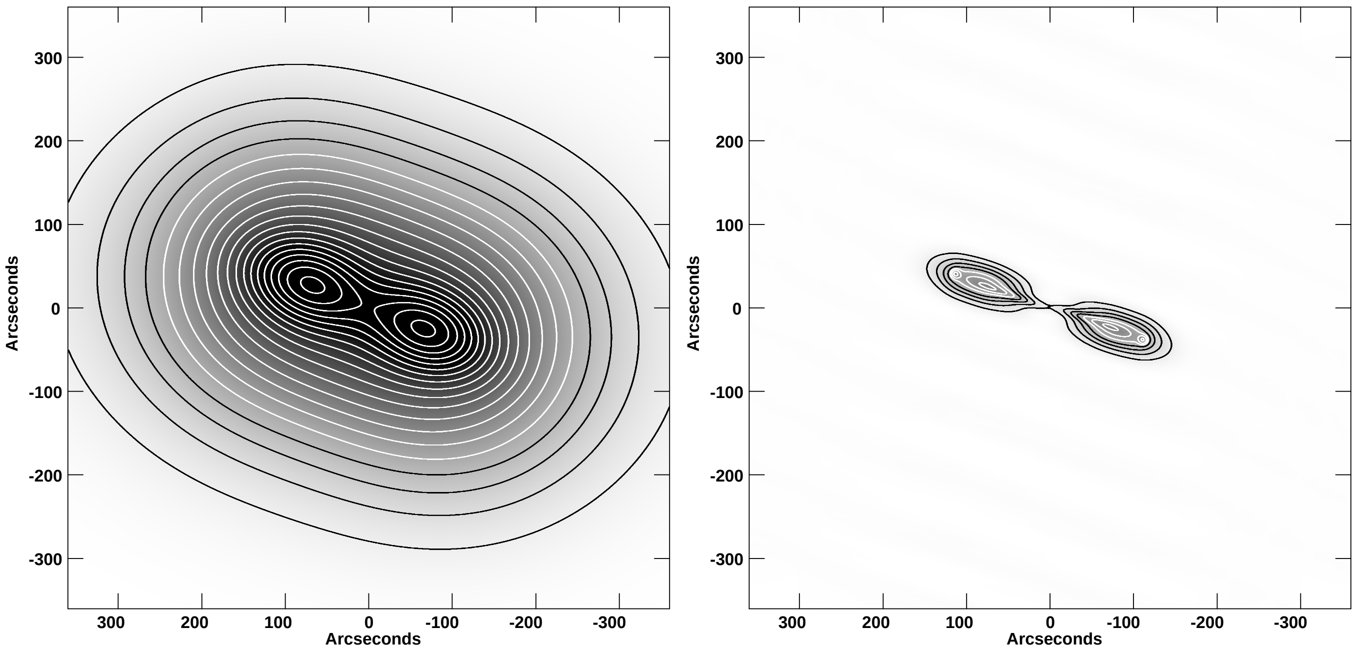

Fig. 2. On left is the model source as observed with a single dish and on the right with an interferometer. Contours are at the same levels as Figure 1.

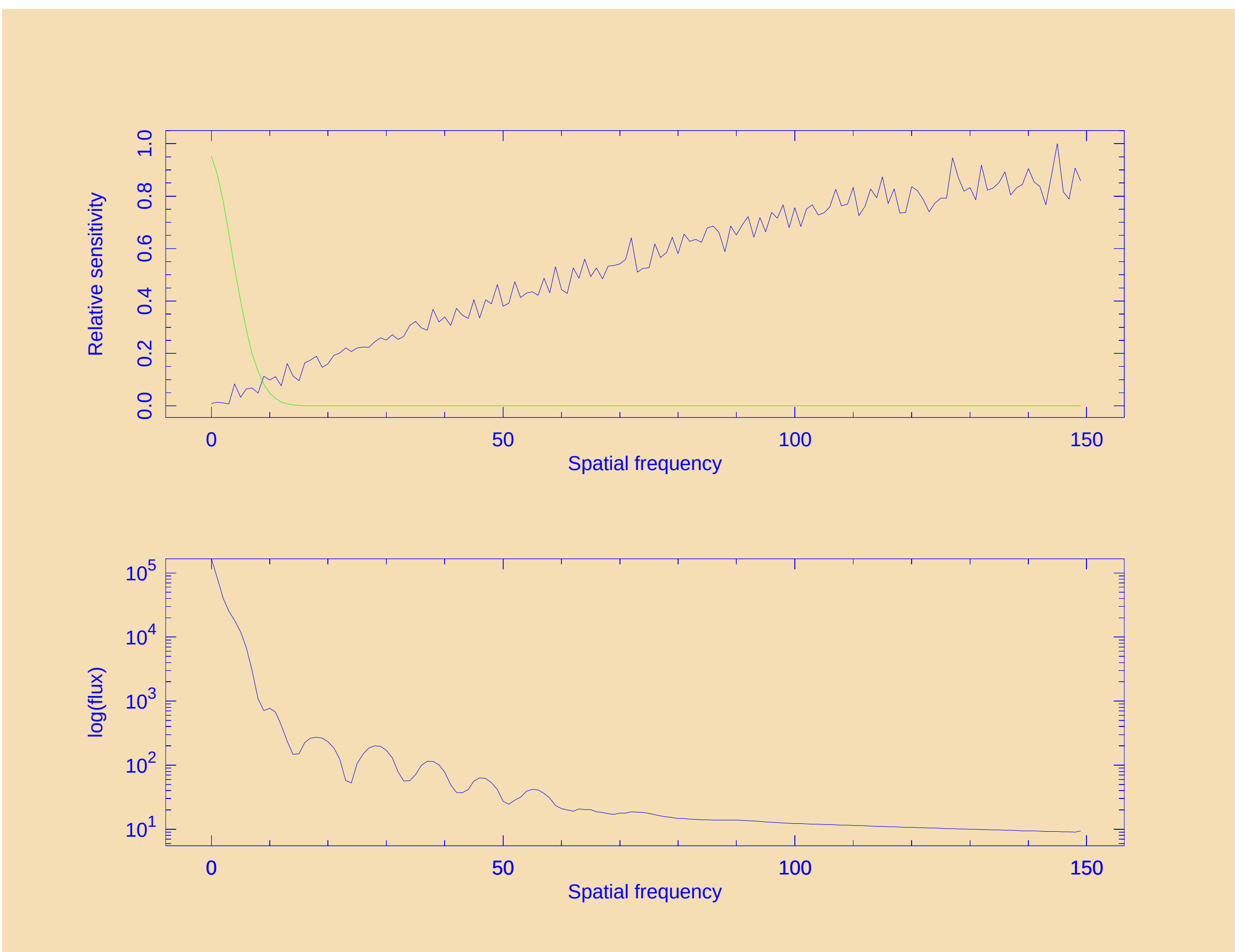

Fig. 4. Illustration of the overlap in uv space of the single disk and interferometer data. Top plot shows the relative sensitivities of the single dish data (green line) and the interferometer (blue line) as a function of spatial frequency in arbitrary units; see text for a more detailed description. Bottom plot shows the amplitude of the Fourier transform of the model along one cut through the uv plane.