Chapter 18

Imaging in Practice

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18.1 Visualisation

Contrary to the lower frequencies where continuum emission processes are dominant, mm interferometry most frequently deals with spectral lines, and hence involves handling and display of *data cubes.* Only a few astronomy packages have been designed for this: GIPSY, GILDAS, MIRIAD. Although the presentation which follows is general enough about the principles (e.g. for the noise analysis or flux density measurements), I will only present the tools which are currently available in GILDAS. Within GILDAS, two display tools are available:
- The GRAPHIC program
- The MVIEW task

In GRAPHIC, easy display is available using the following commands
- `GO MAP`, for simple channel contour maps
- `GO BIT`, same with overlaid color bit map
- `GO NICE`, with clean beam in addition
- `GO POS`, for Position-Velocity plots
- `GO SPECTRE`, for maps of spectra.

Easy access to the parameters of these procedures is available through the Windowing interface. GRAPHIC also provides access to all image processing tasks such as `UV_MAP`, `UV_STAT`, `CLEAN`, etc..., and flexible controls for publication quality plots.

Task MVIEW provides a different approach. It is a Window based application which provides simple, intuitive, and fast interactive 3-D data cube display. It provides spectrum display at cursor position, slices, moments, movie features, color manipulation, etc... It also has a direct interface to some important tasks (e.g. moments evaluation, subset extraction) for which interactively selecting parameters using mouse

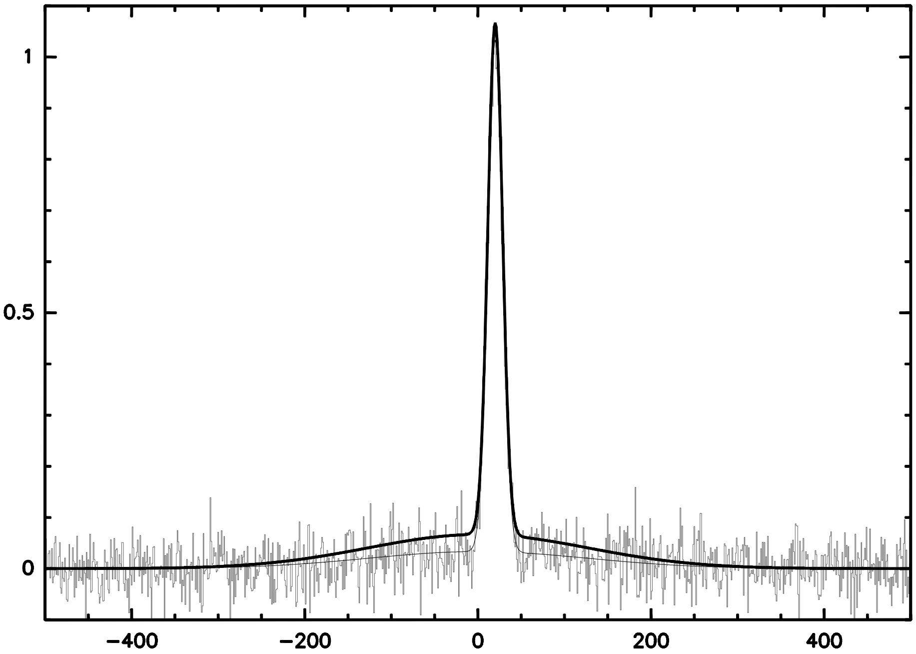

Figure 18.1: Illustration of the difficulty to deconvolve a weak, extended structure. In this 1-D example, half of the flux is in the extended structure, and cannot be recovered properly by deconvolution because of low signal to noise.

motion is convenient. However, contrary to GRAPHIC, it cannot be customized to produce publication quality images.

18.2 Photometry

18.2.1 From Flux density to Brightness temperature

The unit of the dirty map is ill defined. A single point source of 1 Jy appears with peak intensity of 1. But if more than 1 point source is in the field of view, the combination of positive or negative sidelobes from the other source modifies this result. It is thus necessary to deconvolve. After deconvolution, the beam area is well defined: the CLEAN map unit is Jy per beam area.

The conversion to brightness temperature can then be done using the standard equation

$$S_\nu = \frac{2k\Omega_s}{\lambda^2} T_B \tag{18.1}$$

$$= \frac{2k\pi\theta_s^2}{4\log 2\lambda^2} T_B \tag{18.2}$$

for Gaussian beams. `GO MAP` and its variants automatically display the Jy/K conversion factor mentioned above. The integrated flux density in a user defined area can then be computed on the clean map using command `GO FLUX`.

18.2.2 Accuracy of Flux density estimates

The accuracy of flux measurements is limited by several factors.

Deconvolution Errors and Missing Flux

Deconvolution limits are among the most important. Deconvolution is required (see Chapter 15), but it is impossible to deconvolve weak structures near the noise level. Nevertheless, these structures, when sufficiently extended, can contribute to a significant flux. The relevance of the missing flux to the astronomical interpretation is to be decided by the astronomer. In most cases, however, the missing flux does not correspond to any significant brightness, and its absence may not modify the astronomical interpretation. A schematic illustration is given in Fig.18.1: half of the flux is buried in the noise, but the brightness is measured properly (within the statistical error). Note also that WIPE ([Lannes et al. 1997]) offers an upper limit to the noise amplification factor due to the non linear deconvolution process. This upper limit is often discouragingly large for the rather poor dirty beams provided by current mm arrays (4 or 5 is not unusual).

Comparing the recovered flux to a single dish measurement can help you in estimating the corresponding brightness level and evaluate whether this is important in your astronomical case. To convert from flux to brightness, the characteristic size of the missed flux should be used. This is in between several synthesized beam widths and about half of the primary beam. Although in general the problem is not as severe as one would think (because, unfortunately, one is often signal to noise limited), this is an important information, specially in the case of mosaics.

Seeing

A second important effect which affects flux density measurements is the seeing. Seeing result in an underestimation of Point source flux. On the other hand, the total flux is spread over the seeing disk, and is in principle conserved. Insufficient seeing conditions limit the deconvolution process, since the effective synthesized beam (which should include atmospheric phase errors) is significantly different from the theoretical synthesized beam (computed from *uv* coverage and weights). A good check is to make an image of the two calibrators, and measure the corresponding point source flux and apparent size.

Noise estimate

Finally, the noise should be estimated. `GO RMS` gives the sigma of the image flux density distribution. This is an improper estimate, since it includes any possible signal, all spectral channels, and map edges where the noise level increases due to aliasing and gridding. A better estimate, derived from effective weights, is in principle given by task `UV_STAT`. However, this estimate does not take into account possible deconvolution problems or dynamic range limitations due to atmospheric phase noise. The optimal procedure is to use command `GO FLUX` on an empty area of the image to find out the point source rms noise. The precision of the estimate is limited by statistical uncertainties linked to the number of beams in the area. Then, another `GO FLUX` command on the emission area will give the total flux and number of independent beams, n; the rms on the total flux is $\sqrt{n}$ times the point source rms determined by the `GO FLUX` command applied to an empty region. Another good method to determine the noise level (yet to be implemented as a `GO NOISE` procedure...) would be to build the histogram of the pixel values and fit a Gaussian to it; if source structure only covers a small fraction of the image, this method provides a good estimate.

Primary beam

One should emphasize that primary beam correction is essential in any correct flux density estimate. All image plane analysis should be carried out on a primary beam corrected image. This introduces a slight complication, since the noise level is then not uniform. The `GO FLUX` commands discussed before should be applied in regions of similar extent and location vis-a-vis the primary beam(s).

uv plane analysis is also extremely useful both in measuring integrated flux densities and rms noise level, at least for simple, relatively compact, source models. Task `UV_FIT` provides statistical errors for all parameters of the fit. Primary beam correction should be applied a posteriori, based on the location of the region of interest.

Dynamic Range

As mentioned above, the dynamic range may be a limitation. The dynamic range D_r is defined as the ratio of the peak intensity to the lowest "believable" contour. D_r is obviously lower than the signal to noise ratio. It can be estimated as the absolute value of the peak to maximum negative contour ratio. As usual, map edges should not be included in this evaluation. Dynamic range is related to seeing and calibration errors. It is typically 10 to 40 at Plateau de Bure (if signal to noise ratio allows). Errors should include dynamic range effects.

Flux density scale

Finally, remember that the flux scale is determined by bootstrapping flux of (variable) quasars from that of reference sources. Any errors accumulated in this process must be transferred to the source flux estimate.

In summary, flux density estimates should quote errors which include

- Effective thermal noise
- Dynamic range problems
- Relative (calibrator) flux uncertainty
- Absolute flux scale uncertainty **OR** reference flux scale.
- Primary beam correction

18.3 Short Spacings

Extended structure are missed, attenuated or distorted in interferometric maps by lack of short *uv* spacing information. While this effect may be negligible for some astronomical problems, it could also be essential in a proper analysis. Deconvolution recovers some of them, but under-estimate the total flux because the integral of the dirty beam is zero (the integral of the dirty beam is the weight of the (0,0) *uv* cell in the *uv* data set).

Constructing a beam with a non zero integral can help deconvolution. This can be done by incorporating the **Zero spacing** flux or spectrum.

Short spacings provides even more information, because they give information on the spatial distribution of this flux on scales between half the primary beam and the primary beam itself. Short spacings can be provided by a smaller interferometer (e.g. BIMA) or a large single dish (e.g. 30-m). In theory, short spacings can also be provided by the interferometer antennas used in single-dish mode. However, because most interferometer have not been designed with total power stability as a goal, this has not been practiced so far.

Incorporating short spacings into interferometer data is a two step process. Task `UV_SINGLE` extracts short spacing information from single dish data (spectra) and creates a *uv* table. Task `UV_MERGE` merges the single-dish and interferometer tables. Coordinates system should be consistent and checked before (coordinates are always J2000.0 at Plateau de Bure, often B1950.0 at the other observatories...).

18.3.1 UV_SINGLE

Incorporating short spacings from the 30-m into Plateau de Bure data is a 3 step process for the user.

- Creation of a table of spectra
  First, one should resample (in frequency) all spectra to same frequency grid than interferometer data, using command `RESAMPLE` in CLASS. Then a table of spectra is produced using command `GRID` (with no options) in CLASS.

- Image creation
  The next step is the creation of "well behaved" map from the table of spectra. It starts with resampling (in space) on a regular grid by a convolution kernel (interpolation techniques such as the GREG command `RANDOM_MAP` are inappropriate). Weights are also resampled. Then, we follow by extrapolation to zero outside the convex hull of the mapped region, using a kernel twice broader than the single-dish beam, to avoid introducing spurious structure.

Because of noise, the map still contains spurious high spatial frequencies. These are removed during the *uv* table creation. The algorithm steps are

- Fourier transform of map and weight images
- Division by Fourier Transform of the single-dish beam
- Gridding correction (division by Fourier Transform of the gridding function)
- Truncation to some maximum *uv* distance (< dish diameter)
- Inverse Fourier Transform back to image plane
- Multiplication by primary beam of the interferometer
- Fourier Transform to *uv* plane
- Normalization of the weights so that the sum of weights is the weight of the total flux (derived from integration time, bandwidth and system temperature).
- Optional application of an amplitude scaling factor.
- Optional application of a weight scaling factor.

This produces a *uv* table with optimal weights in terms of signal to noise ratio for the total flux, and with effective tapering following the single-dish illumination pattern, except for the truncation at some *uv* distance.

- Merging with interferometer data
  The final step is to merge the resulting *uv* table with the interferometer *uv* table. Re-weighting and re-scaling is again possible at this stage. Note that the choice of weighting function is arbitrary. It may result in poorly behaved synthesized beams when combined with the interferometer *uv* data. Weights can be lowered by any arbitrary factor (increasing the weights is only allowed if signal to noise is not an issue). A good choice is to adjust the weights so that there is almost no negative sidelobe.

18.4 Dirty Tricks

Besides flux density estimate, which, as discussed before, is a non trivial task, analyzing spectral line images may force the astronomer to face some really tricky problems. The two most obvious are moment evaluation and continuum subtraction.

18.4.1 MOMENTS

The lowest order moment of a spectral line data cubes offer very convenient ways of interpreting images. The zero$^{\text{th}}$ order moment is the integrated intensity, the first order moment the velocity, the second order moment the line width. While these moments are linear combination of the channel maps, the deconvolution process is non linear. Accordingly, the two operations do not commute.

Hence, it is impossible to recommend deconvolving before computing the mean intensity, or summing up the individual cleaned channel maps. In the latter, limited signal to noise can prevent proper deconvolution. In the former, velocity gradients can spread emission over an extended area which is difficult to handle in the deconvolution. Choice can be a matter of trial (and errors).

To avoid introducing noise, a *window* in velocity is important. While noise on the integrated intensity only increases as the square root of the window width, the effect on the higher order moments is much more dramatic, and results in non-gaussian noise distribution on these variables. A *threshold* in intensity is useful to prevent spurious noisy features. The window should in principle be pixel dependent to allow for velocity gradients. Smoothing both in the spatial and spectral domains may help in obtaining better results in moment extraction. A line fitting procedure (e.g. a Gaussian line fit at each pixel) may sometimes be the best solution (under construction, check later...).

Moments can be computed using task `MOMENTS` and displayed using the `GO VELOCITY` command in GRAPHIC.

18.4.2 Continuum Subtraction

Continuum subtraction is a related problem. It is in principle needed to compute properly moment maps. However, it may be completely impossible, for example in the case of an optically thick line partially covering a continuum source. Continuum subtraction can be done in the image plane or in the *uv* plane. *uv* plane subtraction avoid the non linearity in the deconvolution, and thereby any amplification of errors induced in this process. Task `UV_SUBTRACT` performs this operation. Although signal to noise on the continuum is often much better than on the spectral line, it may be advantageous to subtract a source model rather than the measured visibilities; this is only true when thermal noise is more important than phase noise. Task `UV_MODEL` compute visibilities from an input image.