# DEVELOPMENTS IN CONTINUUM IMAGING

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ABSTRACT. We review recent progress in the practical aspects of making VLBI images from continuum data.

## 1. INTRODUCTION

Aperture synthesis with intercontinental baselines came of age with the publication of the Wilkinson *et al.* (1977) map of 3C147. The subsequent development of 'hybrid mapping' or 'self-calibration' was rapid and by 1981 it had largely reached its present, widely used, form. Several accounts of this development are now available (Ekers 1983; Cornwell and Wilkinson 1984; Pearson and Readhead 1984). However innovations are still being made, most notably in the 'difference-mapping' technique, a brief outline of which is given by Muxlow *et al.* (this volume).

There were very few presentations of fits to data or even of $(u, v)$ curves during this meeting, clearly VLBI arrays can now be regarded as tools with which to do astrophysics. The number of resolution elements in the images and their dynamic range has increased by more than 100 since the early days, and as a result of all this the astronomical output has mushroomed. It is easy to forget how much we now take for granted about central engines, beams, bulk relativistic motion etc. which would still be mere conjecture if VLBI images had not been available.

Software developments have played only a part in this success story. The development of the U.S. and European Networks and their joint scheduling, the accessibility of the correlators, and the widespread availability of the latest data reduction programs have all played a role. And last, but not least, MERLIN has blazed the trail ahead, showing how much can be achieved with a well-understood sparse array.

It goes without saying that there are many astronomical reasons why we should try to achieve images of ever greater resolution, sensitivity and overall quality. The astrophysical payoff has only just begun.

## 2. DATA ACQUISITION

The quality of the images depends fundamentally on the quality of the original data. As one of us has outlined elsewhere (Wilkinson 1987) there is no reason why



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images of the sensitivity and quality now produced by the VLA should not be achieved by VLBI arrays in the 1990's. The major problems involved are to acquire data good enough (residual phase errors $< 0^\circ.01$, residual amplitude errors $< 0.02\%$) to yield a dynamic range of $10^5 : 1$; and, for weak sources, to calibrate the phase accurately (see section 3.6). To achieve the quality goals many current sources of error will have to be overcome.

## 2.1 Current Problems

Primary amplitude calibration is poor. Even at 1.6 GHz the initial calibration of an array is never better than a few percent rms (see also Jones *et al.* 1986). At other frequencies errors of tens of percent are quite common. Not enough systematic investigations have been made (or at least reported) of calibration errors and how time-variable they are. Clearly they must be affecting the quality of our images, but it is hard to say by how much.

There are baseline-related offsets of several percent in amplitude and several degrees of phase in many data sets. Such effects are the enemy of self-calibration algorithms (Wilkinson 1983; Perley 1986) and there are many ways in which they can arise (see *e.g.* Cornwell 1986a); specific to VLBI is poor recording and playback. With Mk2 systems significant amplitude errors can certainly be introduced in this way although the situation is improving as new correlators come into use (S. Unwin, private communication). We do not know the facts about Mk3 recording/playback repeatability. Excellent quality control throughout the data transmission path is a *sine qua non* if our $10^5 : 1$ goal is to be achieved.

The final passband-defining filters must be well-matched or baseline offsets will occur (see *e.g.* Thompson 1980). In the recent 'world array' observations the amplitude and phase responses of the final 1.8 MHz video filters showed a wide variation in performance relative to the ideal. Calculations of the effect on the correlation coefficients (J. Benson, private communication) showed baseline offsets ranging from 0% to 8% in amplitude and 0° to 13° of phase, with the errors predominantly at the low end of these ranges. We compared these calculated offsets with those determined empirically (see below) from the "world array" data on M87 (W. Junor and T. Muxlow, private communication). There is a reasonable correlation between the phase offsets but no correlation between the amplitude offsets - it appears that non-matched passbands are only part of the problem in this data set.

Polarisation impurity in the front-ends is another potential source of baseline-related errors. If LCP channels from the two antennas contributing to a baseline contain an RCP impurity *i.e.* $L_1 = L_1 + aR_1$ and $L_2 = L_2 + bR_2$ then $L_1L_2 = I(1 + ab) + mI(a + b)$. If the impurities are very bad *i.e.* $a = b = 0.1$ and the compact source is overall 10% polarised (as is commonly observed, see the review by Wardle in this volume) then $\sim 1\%$ complex gain errors are introduced per baseline. These will vary with parallactic angle and hence with time. This represents very much a worst case but this effect may become important as other sources of error are eliminated.

Finally not much has been reported about hardware problems (*e.g.* Wilkinson 1983; Cornwell 1986a) which may give rise to offsets in VLBI correlators. Overall we stress that much more attention should be given to identifying and eliminating sources of non-closing errors in VLBI data.

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## 3. DATA CORRECTION

After correlation many stages of data correction are needed before the final map is produced. Typically this now involves delay/rate estimation (global fringe fitting), data editing, self-calibration and a final deconvolution step. Some observers even iterate around this loop. A case study has recently been presented by Jones *et al.* (1986).

### 3.1 Global Fringe Fitting

The idea of estimating residual fringe rate and delay offsets on a station-by-station basis was introduced by Schwab and Cotton (1983, SC). More recently Alef and Porcas (1986, AP) have described a simpler approach which may yield comparable results in practice. These algorithms are intended to overcome the problem of non-closing delay estimates, and hence non-closing phase errors, which arise when fringe fitting is performed on a baseline-by-baseline basis as was the case for the first 17 years of VLBI.

Utilising current algorithms to their best advantage is, by common consent, quite tricky. There is no simple recipe which works under all circumstances given the several different timescales and signal-to-noise ratios which are inherent to the problem. A good introduction to the practical aspects of using the SC algorithm has been given by Walker (1986), while Jones *et al.* (1986) also pass on some useful experience. M. Cohen (private communication) has compiled (and is continually updating) a "users guide" to the AIPS implementation of the SC algorithm.

### 3.2 Data Editing

For high dynamic range work one should ruthlessly discard bad data including whole baselines where there is no signal to be seen above the $\sim 1\sigma$ level. Such data seem only to add unwanted noise to the image (see for example Jones *et al.* 1986, although other observers have come to the same conclusion). Ruthless editing means point-by-point editing on each baseline and not merely "global" editing via, for example, "UVSUB" and "CLIP" in AIPS package. The latter approach is clearly inadequate. R.C. Walker (private communication) reports that the inclusion of data from UTs where there is no closure information (typically at the start and finish of intercontinental runs) can also degrade the final image.

### 3.3 Self-calibration

Self-calibration is basically the reason for the success of VLBI imaging. Useful practical discussions regarding its use have recently been given by Cornwell (1986a) (in a VLA context) and by Walker (1986). Despite its success there are circumstances in which imprudent application of the method can lead to an imperfect image—even to the extent of inventing spurious components and/or eliminating real components. However we stress that such cases are a) rare and b) invariably associated with data sets possessing limited closure information or low signal-to-noise ratio or large amplitude errors or a combination of all three.

Spurious symmetrisation can occur in a one-sided source if the starting model is symmetric (*e.g.* a point source). Usually the algorithm will converge to the correct solution (see for example the test presented by Readhead and Wilkinson 1978) but one should always be suspicious of "ghost" components on the opposite side of a bright core. Linfield (1986) points out that symmetrisation is most likely to be a problem when the array is not well-mixed, for example if it contains an outrigger antenna. Linfield describes a lengthy procedure to help convergence in tricky cases, however it may by quicker to use a different starting model. The "difference mapping" technique is ideal for rejecting suspicious components and hence overcoming this particular problem.

Poorly-mixed arrays can also cause problems with amplitude self-calibration. Since the amplitude of the visibility function falls off as a function of baseline length, part of the true structure can be "telescope factorisable" and it is possible to "lose" real flux from extended components by injudicious (too early, too vigorous) amplitude correction. Always examine the fit to the *observed* data as well as to the corrected data after the "final" map has been obtained. If the fit on the short baselines is systematically low the intermediate maps have been insufficiently cleaned and hence the trial maps used in the data correction stage do not contain enough flux. If the array is sparse and poorly mixed the algorithm can systematically "correct" (downwards) the amplitude scale on telescopes involved in shorter baselines. A simple trick to preserve the *overall* flux scale is to rescale the mean of the amplitude correction factors to unity before each data correction stage.

Amplitude correction is notoriously more tricky than phase correction. Excluding negative image components always helps to correct phase errors (antisymmetric) but is less effective in reducing amplitude errors (symmetric) which can be largely positive. Careful image plane windowing can drive the algorithm towards the correct solution but great care is needed if the windows are the strongest constraints. As an example, the data from MERLIN at 151 MHz can be badly affected by radio frequency interference which in turn causes major (tens of percent) amplitude calibration problems. Because MERLIN is a sparse, relatively ill-mixed array, obtaining good maps at 151 MHz demands great care on the part of the astronomer, even though the source is apparently simple enough for the method to converge easily when the amplitude errors are small. However, many reliable MERLIN maps have been made at 151 MHz using the "difference mapping" technique.

### 3.4 Removal of baseline-related errors

Empirical correction of simple baseline-related offsets is now becoming common. The transform of the "almost-final" image is compared with the self-calibrated data; the offsets in amplitude and phase are summed for each baseline and the mean subtracted from the data. This is an inherently dangerous procedure which can be justified pragmatically by the reduction of spurious sidelobes after application. It should be used very sparingly and it is obviously crucial that the "almost final" image be a good representation of the true source.

### 3.5 Example

In Figs. 1, 2, and 3, we show images made by one of us (JB) at different stages of the data correction cycle. The data are those from the 'world-array' at 1.66 GHz on M87 (see also Biretta *et al.*, this volume). The data reduction was performed mostly with the NRAO AIPS package, save for the detailed editing, for which the CIT VLBI package was used.

Fig. 1 shows the result of a standard ASCAL+MX iteration where the data were weighted by the square root of the standard weights. (There is conflicting opinion about the usefulness of such weights). The dynamic range in Fig. 1 is 800:1. To produce the image in Fig. 2, negative CLEAN components were deleted prior to self-calibration, the normal AIPS weights were used and smaller windows were employed in CLEAN. The dynamic range in Fig. 2 is 1500:1. Finally, to produce Fig. 3 the baseline-related errors were removed by the empirical method described above. The effect on the north-south sidelobe level is clear and the dynamic range at this stage of the reconstruction is 2300:1. The noise level in Fig. 3 is $\sim$ 0.4 mJy/beam, and is roughly equal to that expected from thermal noise (*cf.* Wilkinson 1983).

### 3.6 Phase referencing

For self-calibration the signal-to-noise ratio on individual baselines must typically be of order unity or greater in a coherence time. This places a lower limit on the flux density of the target source even if it is compact. The weakest sources so far imaged with the EVN using fringe-fitting (AP) and self-calibration have peak flux densities of $\sim$ 6 mJy per synthesised beam (with the thermal noise level ranging from $<$ 1 mJy to $\sim$ 10 mJy in a 60 second integration depending on the baseline). Using a nearby source to determine the telescope-related errors is becoming possible as sensitivities improve to the extent that suitable reference sources (*e.g.* flat spectrum, $S > 100$ mJy at 5 GHz) can be found within a few degrees of any target source. Alef and Lestrade *et al.* (this volume) indicate what is currently being achieved. Note that neither do the source positions need to be known perfectly, nor does the reference source need to be unresolved for the technique to be useful for structure work (*e.g.* Wilkinson 1983). One can expect to see many useful images of mJy sources in the next five years.

## 4. DECONVOLUTION

Non-linear deconvolution algorithms (see *e.g.* Cornwell 1986b) attempt to interpolate across the unmeasured parts of the $(u, v)$ plane or, equivalently to suppress the sidelobes in the 'principal' solution. As has been pointed out many times (*e.g.* Wilkinson 1983, 1987; Dulk *et al.* 1984, Perley 1986) the on-source fidelity of the resulting image can be very much less than suggested by the dynamic range. The tests described by Dulk *et al.* and Readhead (1984) show that the on-source errors induced by CLEAN can be $>$ 10 times worse than the thermal noise level especially on and around a bright core. Note that no work has been done in quantifying image fidelity when using self-calibration. There will inevitably be an interaction between deconvolution-induced artefacts and the determination of the complex gains.

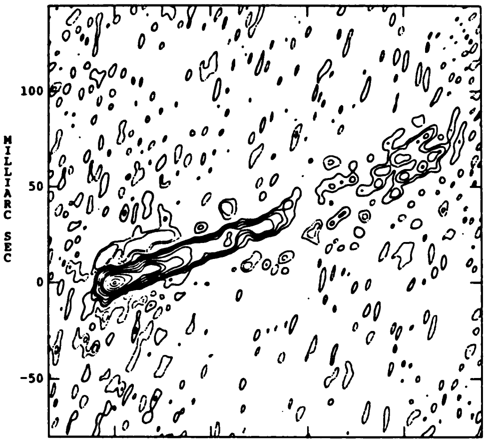



Fig.1 M87 at 1.6 GHz

(for explanation see section 3.5)

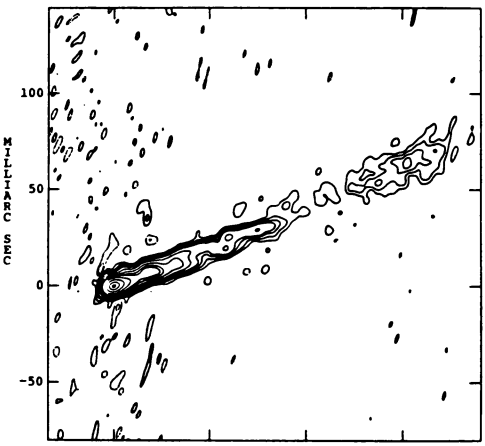



Fig.2

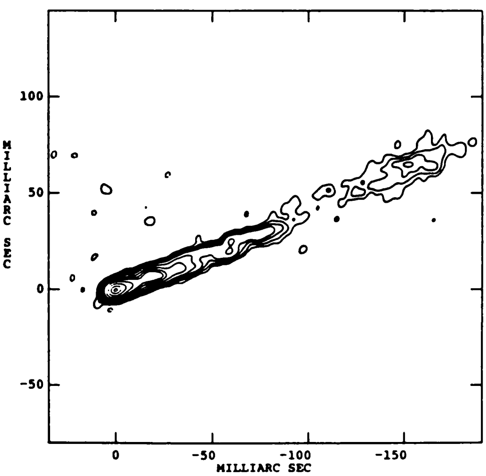



Fig.3

Recently the MEM algorithm, of Cornwell and Evans (1985) has been used to reconstruct VLBI images from the 'world array' (see *e.g.* Muxlow *et al.* this volume) *after* self-calibration (it is too slow to use in the loop) and subjectively superior images to those produced by CLEAN have resulted. We expect that, in line with VLA practice, steadily more use will be made of MEM for this final deconvolution step. For current VLBI data sets it can be tricky to get the algorithm to converge reliably (see Cornwell 1986b). "Pre-convolution" of the dirty map, removal of strong point sources with CLEAN, and a good knowledge of the expected noise level in the outer parts of the map are often required (T. Muxlow, private communication).

## 5. THE STATE OF THE ART

The weakest source for which a true image (by which we mean one utilising phase information) has been made is probably the nucleus of NGC 4151 (total flux density $\sim$ 15 mJy; Preuss *et al.* 1987). Like many of the images of weak objects now being produced this was made with the large EVN telescopes and Mk3 recording terminals; it still involved self-calibration and not phase-referencing. As far as dynamic range is concerned the current record is probably the $\approx 8000:1$ (rms noise to peak flux) achieved in the map of 3C273 made by Unwin and Davis (this volume). The most complex images made so far are certainly those resulting from the 18 station 'world array' (M87: Muxlow *et al.* and Biretta *et al.*; 3C236: Schilizzi *et al.*; 3C120: Walker *et al.*, all in this volume). However the maps of 3C236, for example, are rather similar in quality to the 6 station MERLIN map of 3C249.1 at 408 MHz produced in 1981 (Lonsdale and Morison 1981). There is still much untapped potential in current VLBI arrays. Higher quality data is the key to releasing it.

## 6. MULTI FREQUENCY SYNTHESIS

The only way to improve the coverage of the aperture plane for a given VLBI array is to observe at different frequencies. This idea has already been used at the VLA (*e.g.* Braun *et al.* 1987) to improve the image of Cas A. Even for arrays consisting of 8 stations observations in different frequency bands, covering a range $\Delta\nu = \pm 10\%$ often fill in the synthesised aperture very satisfactorily.

The fact that the source structure is different in each frequency channel has so far been ignored. However, following Cornwell's (1984) pioneering analysis of the problem, a new technique has been developed which takes account of spectral variations if the intensity follows a power law at each pixel (Conway, Cornwell and Wilkinson, in preparation). To a good approximation the "dirty map" (DM) derived from multi-frequency data is a superposition of two distributions. One of them is the true distribution at a specific "reference frequency" $\nu_0$, convolved with a "composite dirty beam" obtained in the usual way from all the $(u, v)$ points assuming that there are no differential spectral index variations across the face of the source. The second distribution contains the effects of these variations. It is the true distribution (weighted by a differential spectral index at each pixel) convolved with a "spectral dirty beam" which is the Fourier transform of the aperture coverage but now with each $(u, v)$ point weighted by $(\Delta\nu/\nu_0)$. These weights are positive or negative depending on the sign of $\Delta\nu$.

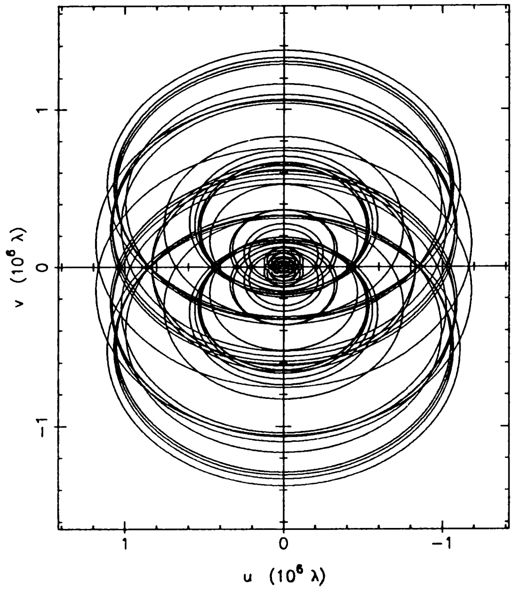



Fig.4

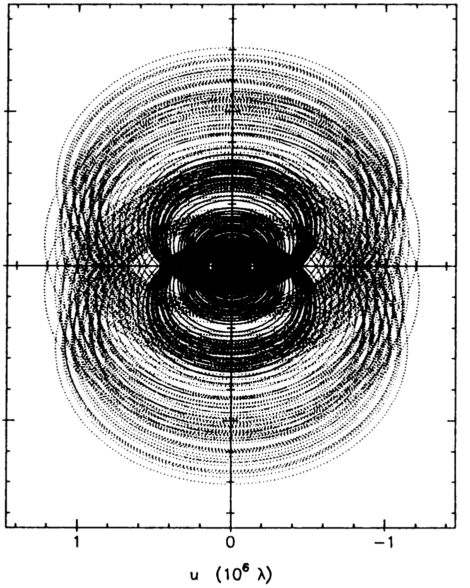



Fig.5

Fig.6

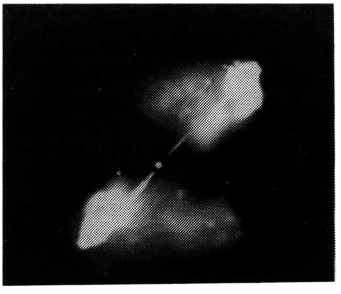


Fig.7

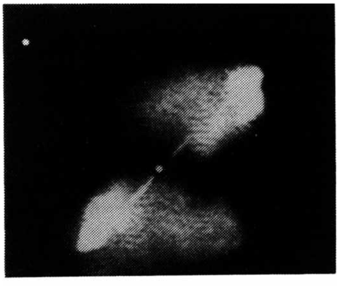


Fig.8

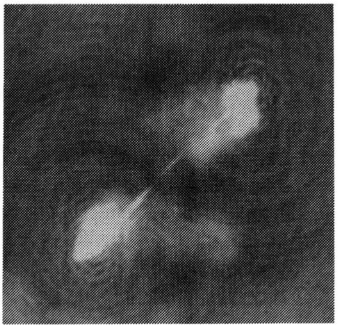
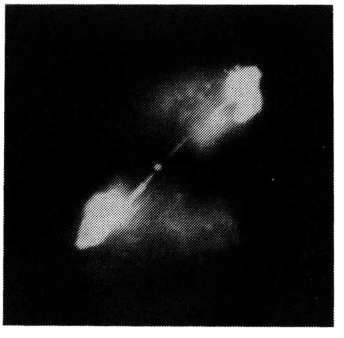


Fig.9



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One of us (JEC) has developed a scheme, dubbed "double deconvolution," to separate out these two distributions. Here we show the results of one of the tests which have been run to prove the method. Fig. 4 show the aperture plane coverage of MERLIN at $\delta = 50°$ as it would be if the current 6 telescope array were enhanced by the addition of telescopes in Cambridge and Chilbolton. Fig. 5 shows the greatly improved coverage which would result from observing in 5 separate bands over a $\pm 12\%$ range in frequency (*viz.* 1350 to 1710 MHz). The effect is similar to increasing the number of MERLIN telescopes to 17. Fig. 6 shows a model intensity distribution; not shown is the assumed spectral index distribution which varies from $-0.5$ in the "hot spots" to $-2$ in the "lobes." Fig. 7 shows the reconstruction of the source from simulated data at only a single frequency—note in passing the obvious CLEAN artefacts in the faint "lobes" and the subsequently poor on-source fidelity in these regions (*cf.* section 4). Fig. 8 shows the effect of using five-frequency data without taking account of the spectral index variations— note that the clear "spectral sidelobes" are primarily associated with the "hot spots." Finally Fig. 9 shows the image after the application of double deconvolution—virtually all of the subtle details in the model are recovered. The technique appears to be a very promising way of improving VLBI maps in the next few years. The major problems will be amplitude calibration and radio frequency interference.

## 7. POSTSCRIPT

There is now an awareness that thermal-noise-limited imaging should be the norm in VLBI. To achieve it regularly more understanding is urgently needed regarding: i) baseline-related errors; ii) the utilisation of arrays in which the baselines have markedly different sensitivities; iii) the effect of poor initial amplitude calibration on an image—this is important for mm-wavelengths and we may need larger arrays than we think merely to ensure reliable self-calibration.

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