Proceedings of the 7th European VLBI Network Symposium
Bachiller, R. Colomer, F., Desmurs, J.F., de Vicente, P. (eds.)
October 12th-15th 2004, Toledo, Spain

Discovering the microJy Radio VLBI Sky via "Full-beam" Self-calibration

M.A. Garrett[1], J.M. Wrobel[2] and R. Morganti[3]

[1] Joint Institute for VLBI in Europe, Postbus 2, 7990 AA, Dwingeloo, The Netherlands (garrett@jive.nl)
[2] National Radio Astronomy Observatory, P.O. Box O, Socorro, NM 87801.
[3] Netherlands Foundation for Research in Astronomy, Postbus 2, 7990 AA, Dwingeloo, The Netherlands.

Abstract.
We demonstrate that at 1.4 GHz the combined response of sources detected serendipitously in deep, wide-field VLBI images is sufficient to permit self-calibration techniques to be employed. This technique of "full-beam" VLBI self-calibration permits coherent VLBI observations to be successfully conducted in any random direction on the sky, thereby enabling very faint radio sources to be detected. Via full-beam self-calibration, Global VLBI observations can equal and indeed surpass the level of sensitivity achieved by connected arrays. This technique will enable large-scale VLBI surveys of the faint radio source population to be conducted, in addition to targeted observations of faint sources of special interest (e.g. GRBs, SNe, SNR and low-luminosity AGN).

1. Introduction

Until recently the study of the sub-mJy and microJy radio sources at milliarcsecond resolution has been limited by the phase stability of VLBI arrays. While the technique of phase-referencing is often used to improve the stability and thus coherence time of VLBI data, the results are often non-optimal, especially in poor observing conditions or for reference-target separations that are greater than a few degrees. In this paper, we present a new calibration technique for VLBI - *full-beam* self-calibration. In this case, the self-calibration process is driven by the response of *multiple faint sources*, *i.e.* sources that serendipitously lie close to the target source, within the confines of the FWHM of a typical VLBI antenna's primary beam. While individually these faint sources may not be strong enough for self-calibration techniques to be employed, their *summed response* will often be more than sufficient. The technique relies on being able to detect all these faint sources simultaneously, and thus requires the employment of wide-field VLBI imaging techniques. In this paper we demonstrate the feasibility of applying full-beam self-calibration techniques to (wide-field) VLBI data.

2. Deep, Wide-field VLBA-GBT Imaging of the Bootes Field in NOAO-N

We have recently completed a deep 1.4 GHz VLBA-GBT wide-field survey of a region located within the NOAO-N Boötes field. The observing programme employed both traditional external and "in-beam" phase-reference techniques (see Garrett, Wrobel & Morganti 2004, for the gory details). Applying wide-field VLBI techniques, a total of 61 sources, selected from a Westerbork Synthesis Radio Telescope (WSRT) image, were surveyed simultaneously with a range of different sensitivities and resolution. A total of 9 sources were detected over a field of 1017 arcmin^2 = 0.28 deg^2. The inner few arcmins of the field reaches unprecedented VLBI noise levels of $\sim 9\mu$Jy/beam, rising to $\sim 55\mu$Jy/beam at the edge of the field. The field and the detections obtained from the full 24 hr data set are shown in Fig. 1. Each of the VLBI detections has a brightness temperature in excess of 10^5 K and morphology that strongly suggests that their radio emission is powered by AGN processes. For a full scientific discussion of the nature of the sources, see Garrett, Wrobel & Morganti (2004).

The VLBI detection rate for sub-mJy WSRT radio sources in the Boötes field is 8^{+4}_{-5}%. As expected, the VLBI detection rate for mJy WSRT sources is higher, 29^{+11}_{-12}%. Our VLBI results suggest, that a significant fraction ($\sim 1/3$) of the sub-mJy AGN radio sources (> 100 microJy) are sufficiently compact to be detectable with VLBI.

3. Full-beam Self-calibration

The simultaneous detection of several sub-mJy and mJy radio sources in a single observation, suggests that their combined response may be used to self-calibrate wide-field VLBI data. We have attempted to investigate this possibility by self-calibrating a *subset* of the full Boötes VLBI data with all the sources detected in the field, excluding the bright (20 mJy) "in-beam" calibrator (the response of which was already subtracted from the data as part of the deep field analysis process). A subset of the data were selected (8 hr of the 24 hr total) with a further constraint that the uv-distance be restricted to $< 3\mathrm{M}\lambda$. This sub-set was chosen in order that the self-calibration process be tractable on reasonable time-scales, using a standard (Linux) dual-processor PC. The uv-data limit was also required in order to reduce time and bandwidth smearing effects for sources at the edge of the field. Of the 8 sources detected in the original analysis, 2 of the fainter sources could not be detected in the restricted (and thus less sensitive) $3\mathrm{M}\lambda$ data set. However, the remaining six sources provide a summed (CLEANed) flux density response of ~ 20 mJy across the field.

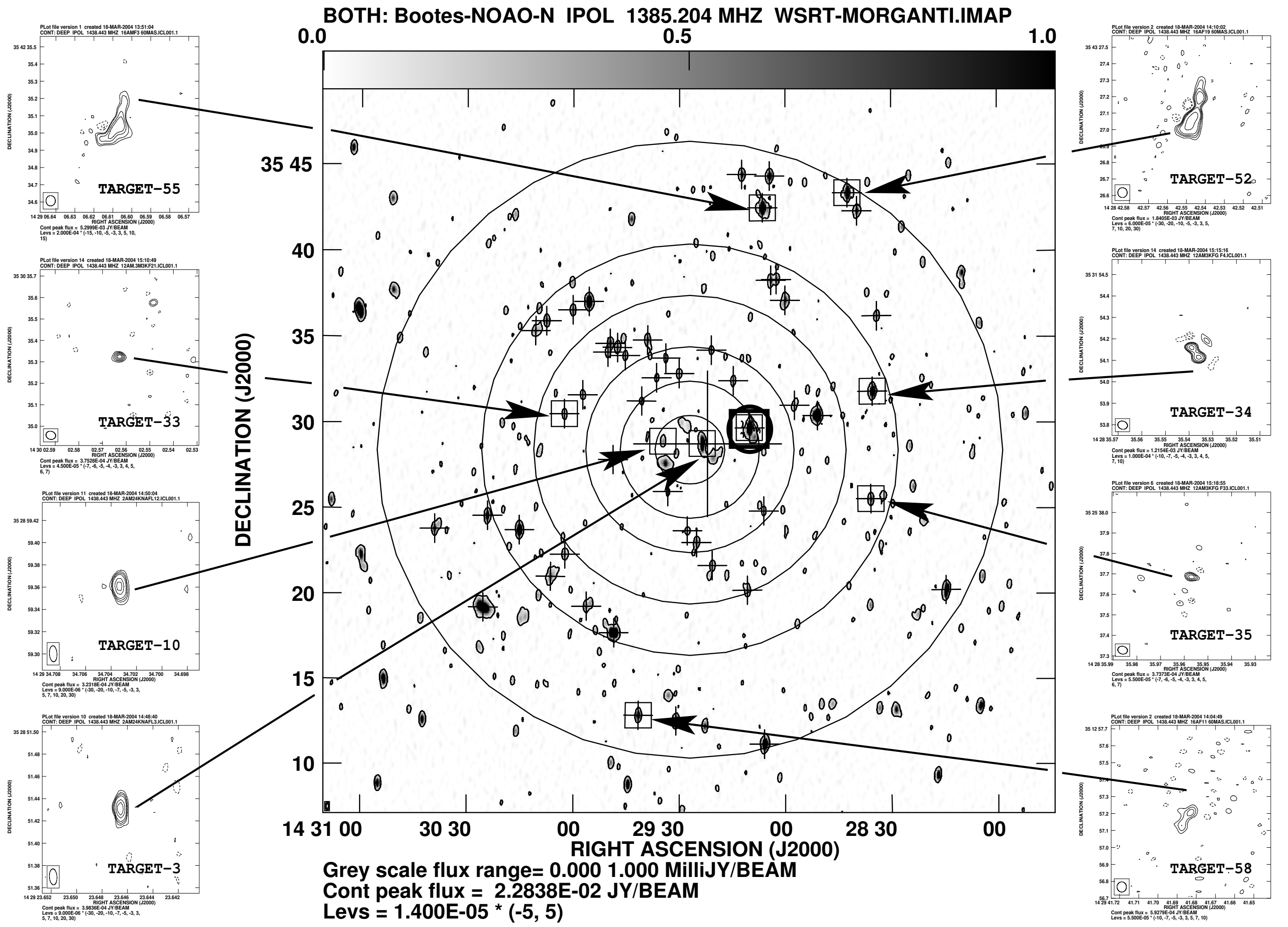

Fig. 1. Nine of the compact radio source targets detected simultaneously by VLBI in the Boötes field (contour maps) and boxed in the WSRT finding image. The "in-beam" calibrator lies ~ 4 arcmins from the phase centre and is thickly circled and boxed.

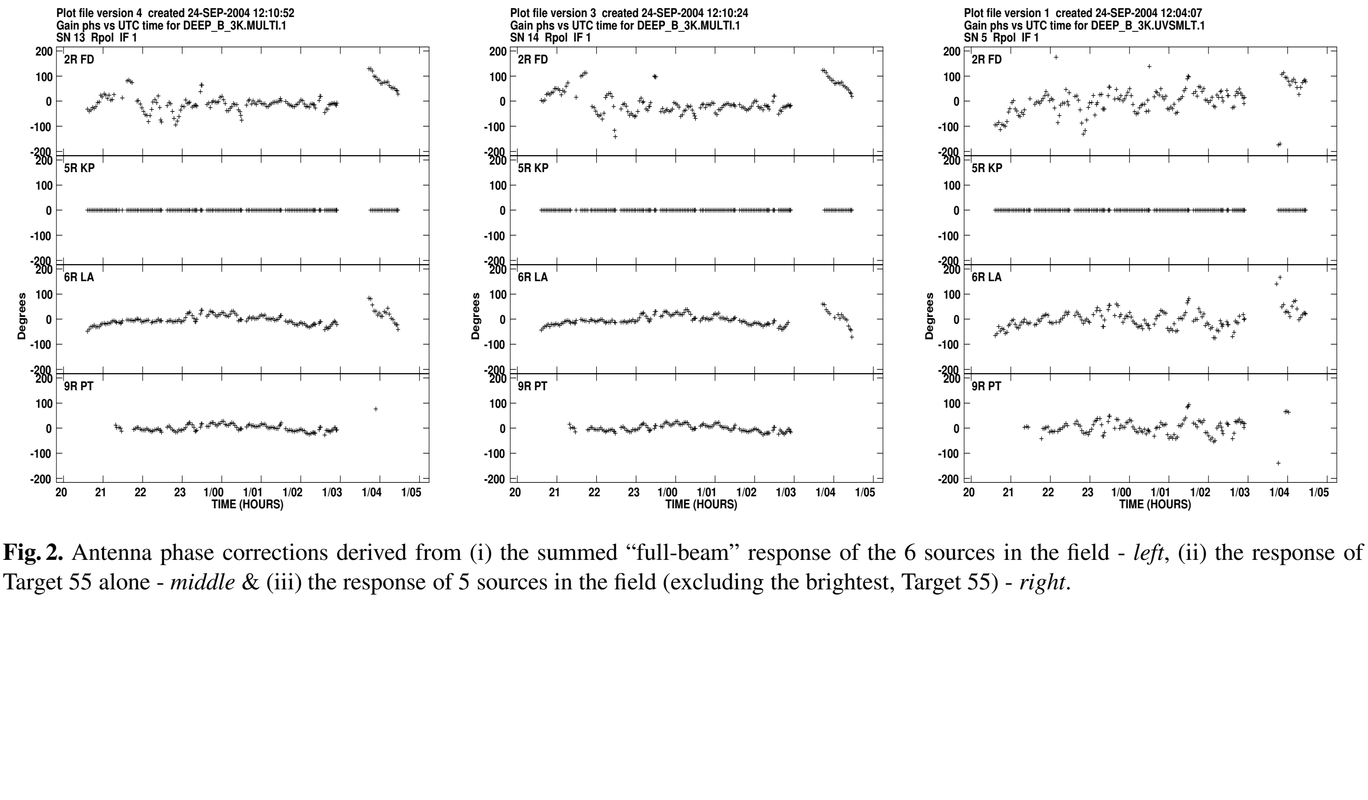

Fig. 2. Antenna phase corrections derived from (i) the summed "full-beam" response of the 6 sources in the field - *left*, (ii) the response of Target 55 alone - *middle* & (iii) the response of 5 sources in the field (excluding the brightest, Target 55) - *right*.

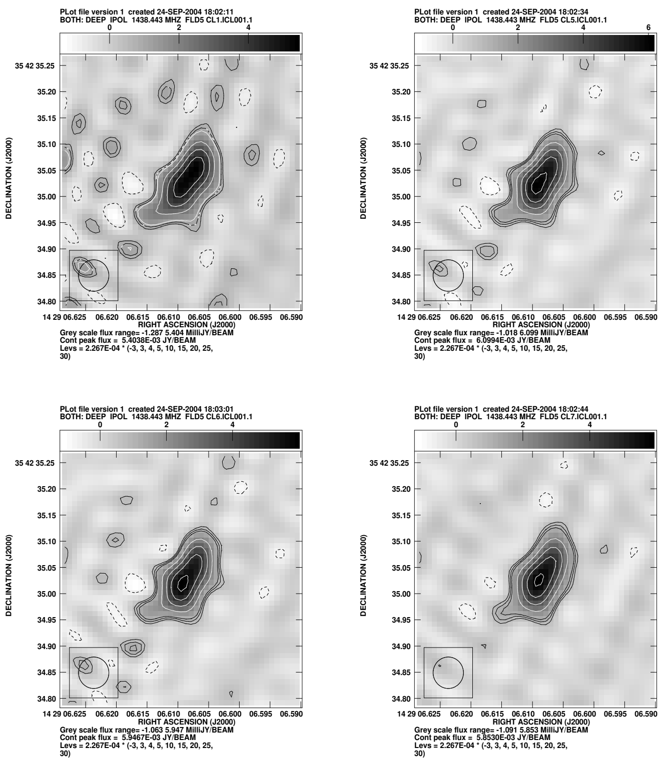

Fig. 3. Images of Target 55 with phase corrections derived from: (i) the original in-beam calibrator - *top left*, (ii) the full-beam response of 6 sources in the field - *top right*, (iii) the response of Target 55 alone - *bottom left* and (iv) the full-beam response of 5 sources in the field, excluding Target 55 itself - *bottom right*.

Combined solutions across the full 64 MHz band were obtained with a solution interval of ~ 600 seconds using the AIPS task, CALIB. The source model for the self-calibration process, included all 6 maps associated with the sources detected in the field. Phase solutions were obtained (see Fig. 2, left) with good signal-to-noise. The solutions are centred around 0° phase but there are clear deviations from this, reflecting changes in the phase corrections derived from the original "in-beam" calibrator (located close to the centre of the field, see Fig. 1) and those derived via the "full-beam" technique.

In Figs. 3 we present images of the brightest source (Target 55, $S_T \sim 13$ mJy) in the field (excluding the ~ 20 mJy in-beam calibrator) made with the original "in-beam" corrections (Fig. 3, top left) and "full-beam" corrections (also Fig. 3, top right). The similarity of the maps suggest that the "full-beam" approach has worked well. We also determined phase corrections using the response of this bright source (Target 55) alone. The corresponding image is also shown in Fig. 3 (bottom left). Again this image is similar to the images obtained via the original "in-beam" calibrator and "full beam" approach.

We also made an additional "full-beam" calibrated image, but this time the response of the brightest source (Target 55) itself was excluded from the self-calibration process. The total summed flux density of the remaining 5 sources was ~ 6.5 mJy and the self-calibration was conducted on a data set for which the response of Target 55 had already been subtracted. The phase corrections are presented in Fig. 2 (right). These corrections are noisier than the previous solutions but are still very similar to those obtained from the response of Target 55 only. The similarity is probably due to the fact that the phase solutions are weighted towards the second brightest source in the field (Target 52) which lies very close to Target 55 - at the edge of the field, due north of the phase-centre (see Fig. 1). The solutions were copied back to the original data set (that included the response of Target 55) and the associated image is presented in Fig. 3 (bottom right). The image is similar to the other images presented in Fig. 3, suggesting that the full-beam technique has worked well.

All images of Target 55 were made with the AIPS task APCLN using the same CLEAN parameters in each case. Note that corrections for ionospheric Faraday rotation and dispersive delay were not made to this data set.

We have also made a very preliminary study of the effect of the various "in-beam" and "full-beam" corrections, on the detectability of fainter sources in the field, lying far from the original "in-beam" calibrator and Targets 55 and 52. In particular, in Fig. 4 we present images of Target 58 using the original "in-beam" calibration, and various flavours of "full-beam" calibration. Target 58 is located far from the field centre, almost 0.5° away from Target 55 and 52, on the opposite side of the primary beam (see Fig. 1). The images in Fig. 4 show that Target 58 is detected using all flavours of full-beam calibration, the maps are all very similar and the 1 mJy source is detected with SNR > 13.

4. Conclusions

Our study demonstrates that at 1.4 GHz the combined response of sources detected serendipitously in deep, wide-field VLBI images will often be sufficient to permit full-beam self-calibration techniques to be employed. The implication is profound: the application of full-beam self-calibration permits VLBI observations to be conducted in any random direction on the sky, thereby enabling large-area, unbiased surveys of the faint radio source population to be conducted. In addition, the technique of full-beam calibration can also be used to improve traditional (nodding) phase reference observations where the target-calibrator separation is often several degrees and the resulting images are usually dynamic range limited. Full-beam VLBI self-calibration techniques are particularly appropriate for observations of specific (faint) sources of special interest (e.g. GRBs, SNe, SNR, low-luminosity AGN *etc*).

As the major VLBI networks upgrade to Mk5 recording systems (permitting data rates of 1 Gbps), EVN and Global VLBI observations can expect to reach 1 σ rms noise levels of a few microJy/beam. Sources brighter than ~ 10μ Jy will be legitimate VLBI targets. Fig. 5 presents a simulated view of the faint microJy sky. Up to 10% of the faint sources presented in this figure may be detectable with VLBI and the summed response of these will enable full-beam calibration to be employed at frequencies of a few GHz and perhaps as high as 5 GHz for very deep observations. For next generation instruments like e-MERLIN, e-EVN/e-VLBI and the SKA, there will

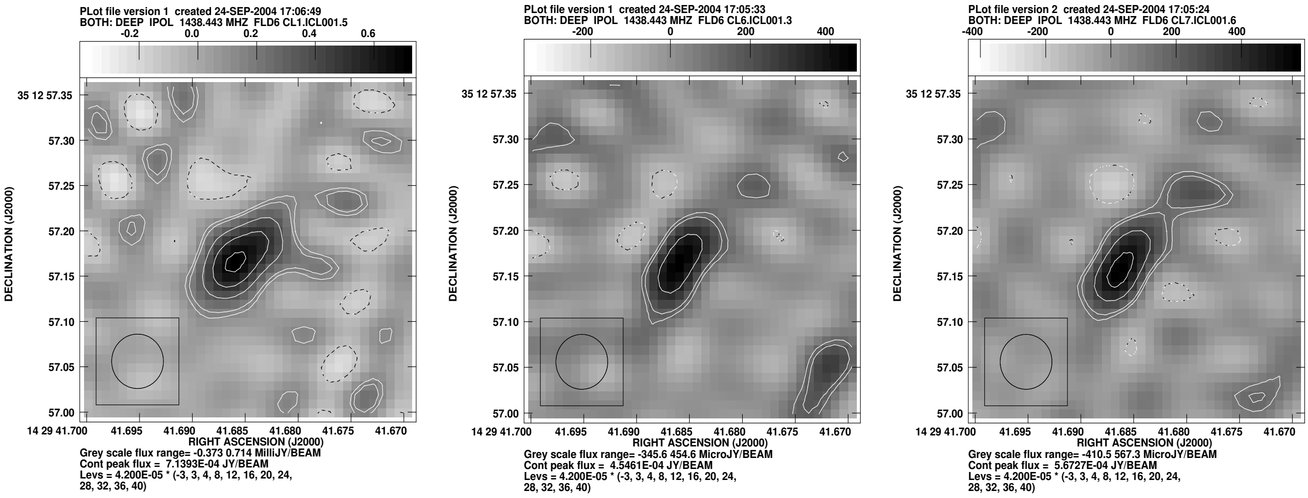

Fig. 4. Images of the faint radio source, Target 58, with phase corrections derived from: (i) the original in-beam calibrator - *top left*, (ii) the full-beam response of 6 sources in the field - *top right*, (iii) the full-beam response of 5 sources in the field, excluding Target 55 itself - *bottom left*.

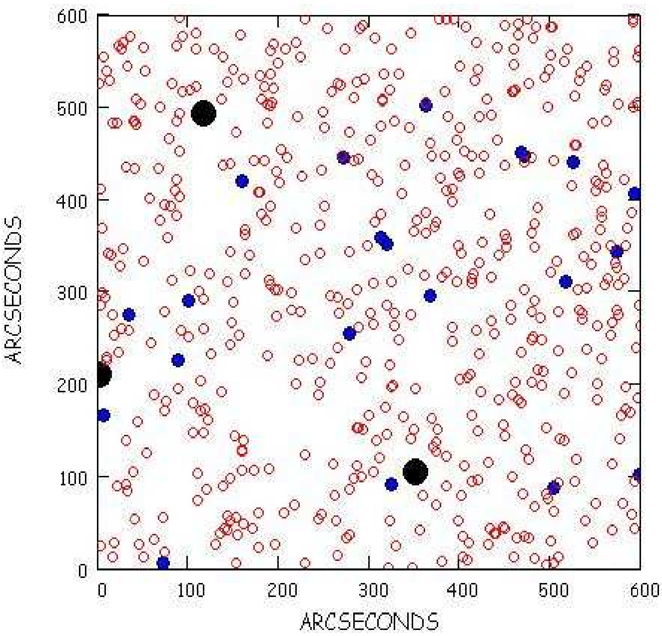

Fig. 5. A simulated view of the faint microJy sky as viewed by a wide-field VLBI array. There are several hundred potential targets in the field of which $\sim$ 10% will be compact enough to be detected at milliarcsecond resolution. The summed response of these sources will enable full-beam self-calibration to be employed in all cases. The radio sources are represented by open circles ($S \sim 10 - 100\mu$Jy), small filled circles ($S \sim 0.1 - 1$ mJy) and large filled circles ($S > 1$ mJy).

be a wealth of calibration sources available at almost all frequencies (0.1-25 GHz).

At the levels of sensitivity about to be explored by VLBI, a comprehensive census of active galaxies associated with sub-mJy radio sources will be possible, including studies of the optically faint microJy radio source population. At microJy noise levels, radio-loud active galaxies are detectable at the very earliest cosmic epochs, when the first active galaxies and their energising massive black holes began to form. In addition, hypernova such as those already detected in local starburst galaxies (e.g. Arp 220) will be detectable at cosmological distances, as will GRB after-glows. Full-beam self-calibration can play an important role in realising these prime scientific goals.

Acknowledgements. This research was supported by the European Commission's I3 Programme "RadioNet", under contract No. 505818. NRAO is a facility of the NSF operated under cooperative agreement by Associated Universities, Inc. The WSRT is operated by the ASTRON (Netherlands Foundation for Research in Astronomy) with support from the Netherlands Foundation for Scientific Research (NWO).

References

Garrett, M. A., Wrobel, J.M. & Morganti, R. 2004, ApJ in press (see astro-ph)