The Deepest & Widest VLBI Survey yet: VLBA+GBT 1.4 GHz observations in Bootes.

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Abstract

We present preliminary results from the deepest VLBI observations yet conducted. VLBA+GBT 1.4 GHz observations of a region within NOAO-N, reach an r.m.s. noise level of 9 microJy per beam. Three sources are clearly detected ($>7\sigma$) within the inner 2 arcmins of the GBT primary beam, including two sub-mJy sources and the “in-beam” calibrator. In addition, by tapering the data, we map out a much larger area of sky, reaching well beyond the half-power point of the GBT primary beam. An additional 6 sources are detected in the extended field. We comment briefly on the scientific motivation for even deeper and wider VLBI surveys, and note that the summed response of sources in the field will permit self-calibration techniques to be employed in \textit{any} region of the radio sky, including so-called “blank” fields.

\textit{Key words:} galaxies: active – galaxies: radio continuum – galaxies: starburst

1 Introduction

Very Long Baseline Interferometry (VLBI) observations, and VLBI surveys in particular, have made a significant contribution to our understanding of radio galaxies and AGN quite generally. For example, the discovery of superluminal motion in these systems provided the first clue that orientation and viewing angle was an important parameter in interpreting and eventually unifying different classes of AGN, including radio galaxies and quasars (see Barthel & van Bemmel this volume). More recently, VLBI has provided direct evidence for an evolutionary scenario in which very young compact radio sources are the precursors of the giant extended radio sources associated with radio galaxies.
VLBI centimeter radio source surveys are usually “targeted”, that is to say, that the sources observed are distributed randomly across the sky and they are often pre-selected to be both bright ($S_T > 200$ mJy) and flat-spectrum ($\alpha < -0.5$) e.g. (1)). Not surprisingly such samples are largely dominated by moderate redshift ($z \sim 1 - 2$), intrinsically luminous AGN. In addition, the limited field-of-view adopted by most observers, ensures that only one source is detected in any given (snapshot) observation. VLBI surveying, is thus a slow business and the biases introduced are substantial.

Over the past few years attempts have been made to survey much fainter sources ($S_T > 10$ mJy) using phase-reference techniques. Such surveys take advantage of the huge catalogue of sources now available via the FIRST VLA survey. These faint VLBI surveys are still targeted but they are usually localised to one area of sky - a few square degrees that includes a bright reference source surrounded by much fainter targets (2; 3). In this sense the surveys are quite efficient (they minimize telescope slewing), and the pre-selection criteria can be relaxed (often targets are only pre-selected on their measured VLA size). The results of these surveys are encouraging but one potential problem is that since the observations are still targeted, the images are not very deep (the total integration time per source is still only $\sim 15$ minutes). Since the sources are not very bright (a peak flux of a few mJy is typical) the dynamic range ($S_{\text{peak}}/S_{\text{noise}}$) is often $\sim 10$ or less. For brighter sources ($S_{\text{peak}} > 10$ mJy) the dynamic range is often limited by errors introduced by conventional phase-referencing (switching) techniques. Under these circumstances its usually difficult to classify the sources detected – jets and other features can easily be missed. In addition, it is quite clear that at these mJy flux levels we are still probing, essentially the same radio source population that the brighter surveys target too.

How can we make progress in this area? The fundamental problem is that the field-of-view of most VLBI images is quite limited, often only a few hundred milliarcseconds in extent. In this paper, we present very preliminary results of the first deep, wide-field VLBI surveys that attempt to expand the VLBI field-of-view by many orders of magnitude, so that it is only limited by the response of the primary beam of the individual VLBI antennas. The idea is to demonstrate the feasibility of imaging many dozens of target sources simultaneously (just like short-baseline connected arrays) but with milliarcsecond resolution and full sensitivity.

2 Deep, Wide-field, VLBI Imaging

For a short baseline, connected element array, the field-of-view is often set by the primary beam size of the individual telescope elements. For VLBI this
is hardly ever the case. In VLBI, a more demanding limitation is set by the spectral resolution and time sampling that are employed during data correlation. The resolution and sampling must be fine enough to circumvent both bandwidth smearing and time averaging effects, at later stages of the processing (imaging) chain. In addition, since preserving the field-of-view scales (computationally) with baseline length squared, the generation of wide-field VLBI images is often limited by the off-line computing resources available to the astronomer. This latter restriction, has introduced another (psychological) barrier which is simply that most VLBI practitioners are inclined to (over) average their data (both in the time and frequency domains), in order to make even standard continuum VLBI data sets more manageable. Data averaging collapses both the field of view and thus the total information content, and
leaves us with the “postage stamp” VLBI images that we are all so familiar
with...

Recent attempts have been made to maintain the natural field-of-view pro-
vided by VLBI correlators in order to image out much wider areas of sky. Im-
ages a few arcminutes in extent can now be generated, and since the full
sensitivity of the array is brought to bear over a relatively large field-of-view,
several sources can be detected simultaneously. Figure 1 shows the first, deep
field VLBI observation of (what is essentially) a blank (radio) field - the Hub-
ble Deep Field-North [5]. In this paper, we report on a new attempts to make
deeper VLBI images, over a much wider area of sky.

3 Deep, wide-field VLBA+GBT 1.4 GHz observations in Bootes
(NOAO-N)

The rms noise levels achieved by the EVN HDF-N observations were limited
by phase errors introduced via conventional, external phase-referencing tech-
niques. Some recent VLBA+GBT deep field observations illustrate the gains
to be made in employing “in-beam” phase referencing. Figure 2 shows the
deepest VLBI images made to date (Garrett, Wrobel & Morganti in prep).
The images (with an rms noise of 9 microJy/beam in the centre of the field)
were made from a 1.4 GHz VLBA+GBT observing run (3×8 hours, employing
a sustained recording data rate of 256 Mbps). In-beam phase-referencing was
used to provide essentially perfect phase corrections for this data set, and eight
sources are simultaneously detected (> 7σ) within and outside the half-power
point of the GBT primary beam. The response of the “in-beam” calibrator
was subtracted from the full data set. Of the eight sources detected, two sub-
mJy sources are located within the primary beam of the GBT, in addition to
the in-beam phase reference calibrator (a compact 20 mJy source [3]). The
images of sources far from the field centre are tapered – the temporal and
spectral resolution of the data is only adequate for sources that lie within the
inner 2 arcmins of the primary beam of the GBT.

The total (target) data set size is 60 Gbytes (0.5 secs integration, 1024 ×
62.5 kHz channels). Images were made with the AIPS task IMAGR - dirty
maps/beams of each sub-band (IF) for each of the three epochs were generated
blindly, and then simply co-added together. Many “small” patches (6′′ × 6′′)
of the field were imaged, based on the positions of a deep, complimentary
WSRT 1.4 GHz survey [4]. The latter survey uses the upgraded WSRT system
and reaches an r.m.s. noise level of ∼ 13 µJy/beam in a 12 hour observing
run. The computational task of generating a map of each patch of sky is
considerable – about 8 hours was required to produce each dirty image (a dual
processor, 2 GHz, Linux box was employed). The analysis of these data is on-

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Fig. 2. Deep VLBA+GBT 1.4 GHz observations of a small portion of the NOAO-N Bootes deep field. The VLBI detections are shown inset. Radio line contours (produced by the WSRT) are superimposed on the NOAO optical field). One non-detection is also shown (bottom left) - a bright, presumably nearby (star forming) spiral galaxy that is well detected by the WSRT. These are the deepest images made with VLBI to date (Garrett, Wrobel & Morganti in preparation) with an r.m.s. noise of 9\mu Jy/beam.

going. For sources that were bright enough, CLEAN maps were produced by simply subtracting the dirty beam from the dirty image (AIPS task APCLN). More complicated tasks (e.g. IMAGR) involving a visibility based CLEAN are currently prohibitively expensive in terms of CPU requirements.

4 The Nature of the high-z, obscured sub-mm/radio source population and Future technical advances in VLBI

At full resolution and maximum sensitivity, our 1.4 GHz VLBA+GBT observations, can detect radio sources with a brightness temperature in excess of
$5 \times 10^5$K. The sources we detect must therefore be powered by AGN activity, rather than extended star formation processes [6]. For example, we do not detect compact emission from a nearby spiral galaxy (NGC 5646, $z \approx 0.03$), although it is one of the brightest ($S_T \sim 3$ mJy) sources in the GBT primary beam (see bottom left hand corner of Figure 2). The fact that the WSRT radio emission follows the optical isophotes, and that this source obeys the FIR/radio correlation, strongly suggests the radio emission arises mainly from star formation. All VLBI detections presented in Figure 2, represent direct evidence for AGN activity.

The long term motivation for these deep VLBI surveys is to determine a lower limit to the contribution AGN make to the faint radio source population in general, and the optically faint (obscured) radio and sub-mm (SCUBA) source population in particular. In order to make any impact in this area, it is essential that many sources are surveyed over large areas of sky, to $(1\sigma)$ depths of a few microJy. In principle, global VLBI arrays, employing disk-based recording[7] can reach these kind of sensitivity levels. A programme to harness the full capacity of the EVN correlator at JIVE (PCInt) will lead this year, to a remarkable expansion in the field-of-view accessible to VLBI observers. Output data rates of up to 160 MBytes/sec, will permit milliarcsecond imaging of huge swathes of sky, limited only by the primary beam of individual VLBI telescope elements. Since it will be possible to simultaneously sample the summed response of all compact radio sources within (and indeed beyond) the half-power point of the VLBI telescope primary beam, simple self-calibration of the target field will always be possible! Access to GRID like computing resources may be the best way to analyse the huge data sets generated. PCInt will permit dozens of sources to be detected simultaneously, and imaged at milliarcsecond resolution with full sensitivity. In this way, huge, unbiased VLBI surveys will be conducted, the bulk of the targets being faint sources with flux densities of only a few tens of microJy. Some of these will include the distant, high-z population of dust obscured systems.

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