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Finding AGN with wide-field VLBI observations

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VLBI observations are a reliable method to identify AGN, since they require high brightness temperatures for a detection to be made. However, because of the tiny fields of view it is unpractical to carry out VLBI observations of many sources using conventional methods. We used an extension of the DiFX software correlator to image with high sensitivity 96 sources in the Chandra Deep Field South, using only 9h of observing time with the VLBA. We detected 20 sources, 8 of which had not been identified as AGN at any other wavelength, despite the comprehensive coverage of this field. The lack of X-ray counterparts to 1/3 of the VLBI-detected sources, despite the sensitivity of co-located X-ray data, demonstrates that X-ray observations cannot be solely relied upon when searching for AGN activity. Surprisingly, we find that sources classified as type 1 QSOs using X-ray data are always detected, in contrast to the 10 % radio-loud objects which are found in optically-selected QSOs. We present the continuation of this project with the goal to image 1450 sources in the Lockman Hole/XMM region.

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1. Introduction

Extragalactic radio surveys are an increasingly popular method to investigate the evolution of star-forming and active galaxies. However, their resolution is of the order of arcseconds and hence not sufficient to separate the two emission processes. VLBI observations are only sensitive to brightness temperatures of around 10^6 K and can hence unambiguously identify AGN, provided the inferred luminosity exceeds 2×10^{21} W Hz^{-1} [5]. The high resolution and fringe rates of VLBI impose severe logistical constraints on wide-field imaging, however, and typical VLBI fields of view at cm wavelengths are around 10 arcseconds in diameter and hence unsuitable for surveying large numbers of objects. Here we report on the first use of a new multi-phase centre mode for the software correlator DiFX [1], which allows one to produce normal-sized VLBI data sets for a set of known target locations, and hence to image hundreds of objects with a single observing run.

2. The multi-phase centre mode of DiFX

The challenge in wide-field VLBI observations is to overcome the effects of time and bandwidth averaging, which reduce the amplitude of sources away from the phase centre. The obvious solution is to increase the temporal and spectral resolution at the correlation stage, but this results in TB-sized visibility data sets, which are difficult to process even on large computers. Whilst this approach has recently been used by Wucknitz et al. and Morgan et al. (these proceedings), we have developed an extension to the DiFX software correlator [2], which processes multiple phase centres in a single pass.

In this mode, the correlation is initially performed with high frequency resolution which is sufficient to minimise bandwidth smearing. Periodically, but still frequently enough to minimise time smearing, the phase centre of the correlated data is shifted from its initial location (which is usually the pointing centre) to a target source location. This shift requires rotating the visibility phases of each baseline by an amount equal to the difference in the geometric delay between the final and initial source directions, multiplied by the sky frequency. In effect, this corrects for the “unapplied" differential fringe rotation between the final and initial source directions. This phase shift is repeated for each desired source direction. After the phase shift is applied, the visibilities are averaged in frequency and continue to be averaged in time. Eventually, this results in an array of “normal–sized" visibility datasets, with one dataset per target source. The field of view of each of these datasets is of the order of $13''$, at which point bandwidth and time smearing would reduce the observed amplitudes by 5 %.

These data sets can be calibrated using standard methods. Furthermore, since the phase response of a parabolic telescope is constant within the primary beam, and since the geometric delays have been taken care of at the correlation stage, the amplitude, phase, and delay corrections can simply be copied from one data set to another.

3. Observations and calibration

On 3 July 2007 we have observed with the Very Long Baseline Array (VLBA) at 1.4 GHz a single pointing centred on the original CDFS [7]. We used 8 dual-polarisation IFs with 8 MHz

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bandwidth each and two-bit sampling, resulting in a recording bitrate of 512 Mbps, which was the highest possible bitrate of the VLBA at that time. The low declination of -27° allowed us to observe the target for 9 h only, yielding a total of 178 baseline-hours from which we expect image sensitivities of 50 μJy (note that the low elevations caused the system temperatures to be significantly higher than at zenith during substantial parts of the observations). A six-minute phase reference cycle time was used, with 5 min allocated to the target and 1 min to the nearby strong (600 mJy) calibrator source NVSS J034838$-$274914. The data were recorded on disk and shipped to the Max-Planck-Institut für Radioastronomie for correlation.

Correlation was carried out on a 22-node computer cluster with 176 compute cores using a development version of the DiFX software correlator. From previous ATCA observations [9] the positions of 96 sources within the VLBA's primary beam were known, and so 96 data sets were produced using the new multi-phase centre mode of DiFX. Calibration followed the standard steps for a phase-referencing VLBI observation. After phase-referencing, the target S503 was found to be bright enough for self-calibration, which improved the coherence of the data. The S503 calibration tables were then copied to the other data sets and all sources were imaged.

Unlike in compact-array interferometry, where the primary beam correction is carried out in the image plane, we have corrected for primary beam attenuation by calculating visibility gains. This is possible only because the fields of view are very small in our observations and so the attenuation due to the primary beam does not vary significantly across the images. We have calculated the primary beam attenuation at each station as a function of time and frequency (the primary beam size changes with frequency, and since the VLBA antennas have feeds offset from the optical axis they suffer from beam squint, which also scales with frequency).

4. Results

All sources were imaged using natural and uniform weighting (yielding restoring beams of 28.6×9.3 mas^2 and 20.8×5.9 mas^2, respectively), and using a 30 % Gaussian taper at a (u,v) distance of 10 Mλ, which resulted in a restoring beam of 55.5×22.1 mas^2.

Out of the 96 targets, 20 were detected reliably, and one more target was tentatively detected. We show here contour plots of three detected targets as an illustration of the image quality.

We have cross-identified the 96 targets with the deep X-ray data in the area [6, 7], to obtain as much evidence for AGN activity as possible. X-ray observations are claimed to be a very direct tracer of AGN activity [e.g., 8]. In the standard picture of AGN, the X-ray emission originates very close to the supermassive black hole, is relatively unabsorbed at energies of a few keV, and there is little contamination from other sources, such as stars. Where redshifts were available, we used the criteria by [10] to determine an object's nature using the X-ray data alone.

Surprisingly, we have detected with the VLBA 7 sources which have no X-ray counterparts. One of these sources is in a region covered by a 2 Ms Chandra exposure [7]. All these targets have redshifts exceeding 0.1, hence their radio luminosities suggest that they are AGN and not starbursts [5].

We also investigated the detection rate of those VLBI-detected targets with available X-ray counterparts, as a function of X-ray source type. We found that all sources classified as type 1

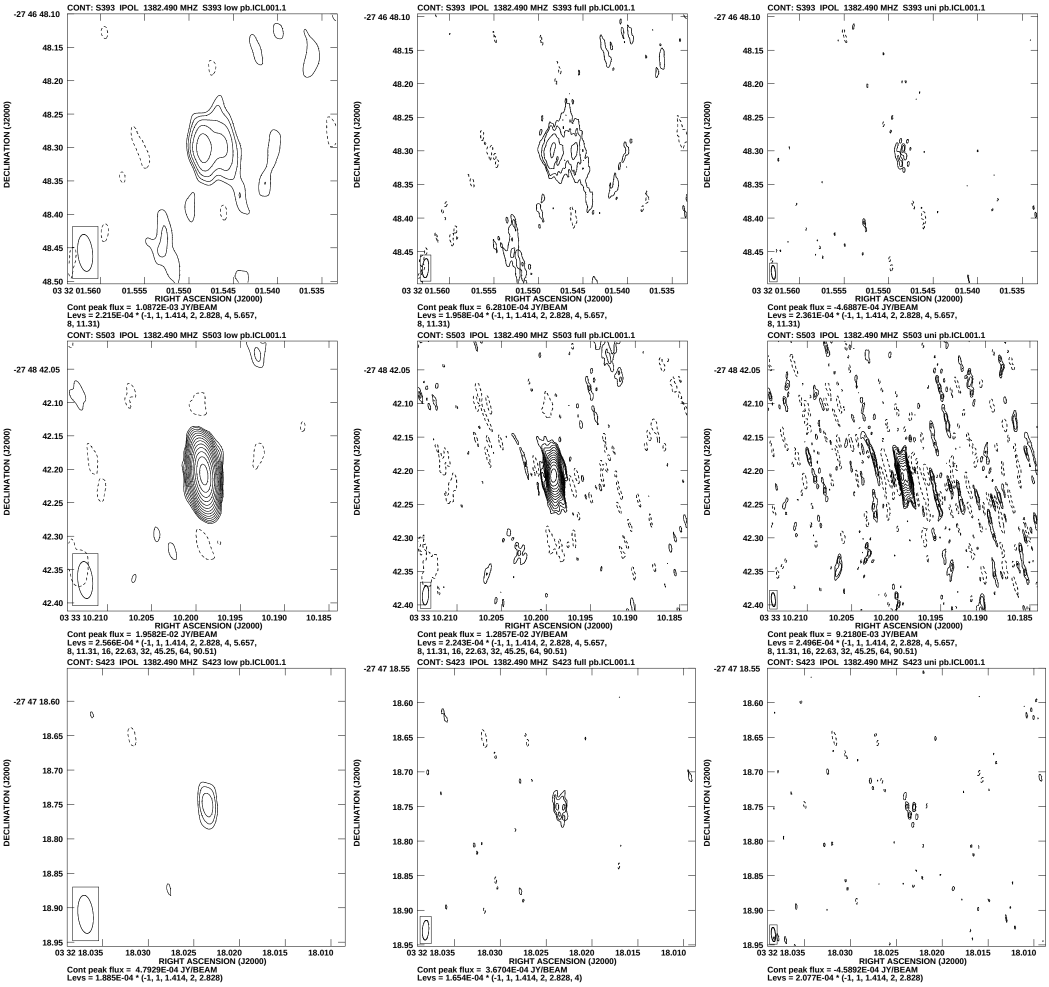

Figure 1: Contour plots of three of the detected sources. Three images per source are shown in a row. *Left column:* naturally-weighted images; *middle column:* untapered, naturally-weighted image; *right column:* uniformly-weighted image. Positive contours start at three times the rms level of the images and increase by factors of $\sqrt{2}$. One negative contour is shown at three times the rms.

QSOs by the criteria by [10] were detected (there were no type 2 QSOs in our sample). This is in stark contrast to optically selected QSOs, of which typically only a fraction of 10 % is radio-loud.

We investigated potential differences between VLBI-detected and undetected sources as a function of spectral index (using the data by [4]) and redshift, but found no significant differences.

One detected source in our sample, S423, shows no indication of AGN activity in optical and X-ray observations. However, it is clearly detected, and given its redshift of 0.73 it must contain an AGN. Another object, S443, has been tentatively detected. However, the VLBI core is offset from the centre of the galaxy and can therefore not be taken as evidence for an AGN. We note that the radio luminosity of this source, $5\times10^{21}\,\mathrm{W\,Hz^{-1}}$, is similar to one of the brightest radio supernovae, SN1986J. We therefore consider it possible that S443 is a radio supernova.

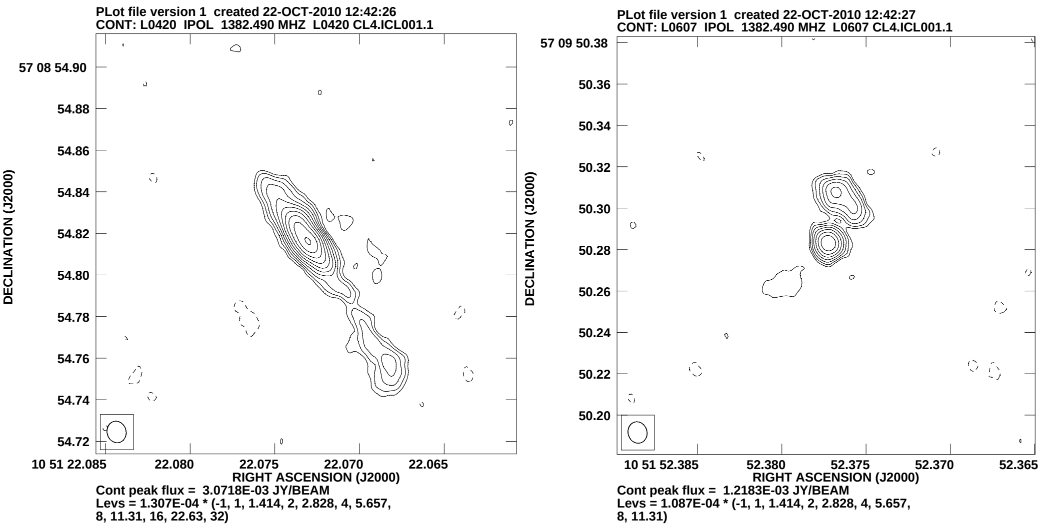

Figure 2: Contour plots of two targets detected in the Lockman Hole East. Contours are drawn at three times the rms level, and one negative contour is shown.

5. Conclusions and outlook

This pilot project can be regarded as a success, and the multi-phase centre mode is now publicly available at the VLBA. We have therefore embarked on a project to carry wide-field VLBI even further, using mosaicing of separate pointings, to increase the sensitivity of the observations over wide areas.

We have observed with the VLBA the three pointings observed by [3] with the VLA, resulting in an on-axis sensitivity of 23 uJy in each pointing. Around 330 phase centres were correlated in each run, targeting only those 508 sources with a 1.4 GHz flux density of more than 100 μJy. The observations resulted in a total of 1 TB of visibility data. In a follow-up project we will attempt to image all 1450 sources with a sensitivity on par with the VLA observations, when the VLBA recording rate has been increased to at least 2 Gbps.

The calibration of the centre pointing has been finished, but the images have not yet been analysed. We show in Fig. 2 two example images of interestingly-looking objects. The image fidelity is higher than that achieved with the CDFS observations, something we attribute to the higher elevation, and consequently better uv-coverage and calibration transfer, of the Lockman Hole East field.

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