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e-VLBI observations of GRB 080409 afterglow with an Australasian radio telescope network

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Abstract Transcontinental e-VLBI observations were conducted in June 2008 with telescopes in Australia, China and Japan. Detections were made of the radio-loud quasar PKS B0727−115, which shows superluminal motion, and the intra-day variable quasar PKS B0524+034. The latter source was used as a phase reference calibrator for observations at the position of the gamma-ray burst GRB 080409, for which an upper limit to the radio emission is set. Australia Telescope Compact Array data were also used to derive a limit on the radio flux density of the GRB afterglow. These observations demonstrate the capability to form a large Australasian radio telescope network for e-VLBI, with data transported and processed in real-time over high capacity networks. This campaign represents the first step towards more regular e-VLBI observations in this region.

Key words: techniques: interferometric — galaxies: active — gamma rays: bursts

1 INTRODUCTION

Very Long Baseline Interferometry (VLBI) is a well-established technique enabling milli-arcsecond (mas) to sub-mas angular scales to be studied in compact radio sources. The development of electronic-VLBI (e-VLBI) for observations with geographically distributed telescopes, where data are transferred over high-speed data networks and correlated in real time, has provided a number of advantages over traditional VLBI, where the data are recorded on-site and transferred to the correlator some time later.

e-VLBI provides logistical advantages in reliability, especially for “part-time” VLBI arrays, and scientific advantages in the rapid availability of results (see, e.g., Conway 2009; van Langevelde 2013). e-VLBI observations have been carried out with a subset of the Long Baseline Array (LBA) within Australia since 2007 (Phillips et al. 2007; Hancock et al. 2009; Tingay et al. 2009; Moin et al. 2011) and China, when high-speed internet links between the telescopes were established. e-VLBI within a country is generally more straightforward, as telescopes and the network are usually operated by a single agency. Transcontinental e-VLBI is more challenging as a greater degree of cooperation and collaboration is required to establish the light-paths between the telescopes and the correlator.

This was illustrated by observations in 2007, coordinated by the Joint Institute for VLBI in Europe (JIVE) as part of the Express Production Real-time e-VLBI Service[1] (EXPReS) project. e-VLBI observations of 3C 273 were made using Chinese (Sheshan 25 m), Australian (Mopra 22 m), and European telescopes with data correlated in real-time using a software correlator (e.g. Kettenis et al. 2009) at JIVE in the Netherlands. Data were transferred to JIVE at a rate of 256 Mbps per telescope. The Sheshan telescope was connected for the first time via the Chinese CSTNET[2] and CERNET[3] to the then new high-speed route

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[1] *http://www.expres-eu.org*
[2] *http://english.cnic.cas.cn/rh/div/cstnet/cstnetintro/*
[3] *http://www.edu.cn/HomePage/english/cernet/*

across Siberia provided by the EC-sponsored ORIENT[4] and TEIN2[5] networks, the pan-European GEANT2[6] network and finally SURFnet[7]. Mopra was connected directly to JIVE through a dedicated 1 Gbps light-path set up by the Australian, Canadian and Dutch national research and education networks AARNet[8], CANARIE[9] and SURFnet, respectively. The success of this program encouraged further testing and development, with even higher observing bandwidths, and here we describe observations made in June 2008, establishing a transcontinental Australasian e-VLBI network for the first time.

2 OBSERVATIONS

The 8.4 GHz observations were undertaken as a demonstration of the e-VLBI technique and were presented in real-time to participants of the seventh International e-VLBI workshop, held at Shanghai Astronomical Observatory, Shanghai, China in June 2008. The participating radio telescopes were the Kashima 34 m of the National Institute of Information and Communications Technology, Japan, the Sheshan 25 m of Shanghai Astronomical Observatory, and the Parkes 64 m, Mopra 22 m and five 22 m elements of the Australia Telescope Compact Array (ATCA), which were phased together to form a single "tied" array, of the CSIRO Astronomy and Space Science (CASS). Data from all telescopes were streamed to the Parkes Observatory in Australia for real-time correlation using the DiFX software correlator (Deller et al. 2011).

Dedicated "light paths" were established from Kashima and Shanghai to the Parkes Observatory with the help of AARNet, CSTNET, JGN2[10] and other National Research and Education Networks (NRENs[11]) that provisioned a non-routed "point to point" 622 Mbps circuit from both Shanghai and Kashima directly to Parkes. Data from Mopra and ATCA were streamed over existing 1 Gbps circuits between the observatories. Data were streamed at 512 Mbps from all telescopes except Shanghai, which ran at 256 Mbps due to a problem later identified as being with the setup of DiFX. Data transfer from Shanghai over the network at 512 Mbps presented no problems. Fringes were observed on all baselines.

The networks performed flawlessly for the entire 12 h period of the demonstration, during which observations of two active galactic nuclei (AGNs) and a newly-discovered gamma ray burst (GRB) were made, with the choice of targets being dictated by the mutual sky visibility at the time. Data from the telescopes were two-bit sampled in eight 16 MHz bands, centred at 8409, 8425, 8441, and 8457 MHz in both left- and right-circular polarisation.

Observations commenced with short observations of the "fringe finders" (i.e., known bright compact sources) 2251+158, 0430+052 and 3C 273. As one of the target sources, six pairs of observations were made of GRB 080409 (J2000 RA = 05:37:19.14, Dec = 05:05:05.4) with the nearby phase-reference source PKS B0524+034. Following this, observations were made for $\sim$2 h of the radio-loud quasar PKS B0727$-$115.

Overall, the demonstration went very smoothly and was very well received by the workshop attendees. (Audience participation was entertained and a request was made to stop tracking on one of the telescopes: the fringes clearly disappeared when the telescope stopped and then came back when the tracking was resumed!)

3 DATA ANALYSIS AND RESULTS

The correlated data were reduced using the analysis package AIPS (Greisen 2003). First, the data quality was examined and bad data were discarded. Following this, data were fringe fitted (with FRING) to correct the delay and phase rate offsets using standard fringe finders. Following the fringe fitting, amplitude calibration was carried out using 3C 273 (assuming a correlated flux density of 10 Jy, VLBA Calibrator Survey) to set the flux density scale. We estimate a systematic uncertainty of about 10 per cent in the overall amplitude scale. After applying the calibration solutions, the data were exported to Difmap (Shepherd 1997) for imaging and model fitting.

Figure 1 shows the (u, v)-coverage obtained for one of the main target sources PKS B0727$-$115; it excludes all the unusable data that were flagged during data verification and reduction. As indicated by this figure, the (u, v) coverage for this ad hoc array is very one-dimensional, and has a large gap between the short and long baselines. This results in imaging being very challenging because the synthesized beam is highly elliptical and there is no spatial information available on the missing intermediate baselines.

Despite this, clear detections were made on all baselines of the radio emission from the AGN PKS B0727$-$115 (e.g. Kellermann et al. 2004) and the intraday variable source PKS B0524+034 (e.g. Gorshkov & Konnikova 1997; Kovalev et al. 2005). The latter was used as the phase-reference calibrator for GRB 080409, for which an upper limit to the radio emission was obtained. Table 1 presents the details of the observations of these sources.

We produced images of all of the target sources from our e-VLBI campaign, going out to at least $5''$ from the phase centre in each case. By retaining the maximum time resolution and a frequency resolution of 32 kHz, the effects of time and bandwidth smearing were kept to a minimum. No radio emission brighter than 5σ was detected away from the phase centre.

Figure 2 shows plots of the visibility amplitude and phase of PKS B0727$-$115 as a function of projected ra-

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[4] *http://geant2.archive.geant.net/server/show/ConWebDoc.2575.html*

[5] *http://tein2.archive.dante.net/server/show/nav.622.html*

[6] *http://geant2.archive.geant.net/server/show/nav.740.html*

[7] *https://www.surf.nl/en/about-surf/subsidiaries/surfnet*

[8] *https://www.aarnet.edu.au*

[9] *http://www.canarie.ca/*

[10] Research Test-bed Network operated by NICT (National Institute of Information and Communications Technology: *https://www.jgn.nict.go.jp/english/index.html (currently JGN-X))*

[11] *https://www.isoc.org/inet99/proceedings/3h/3h_1.htm*

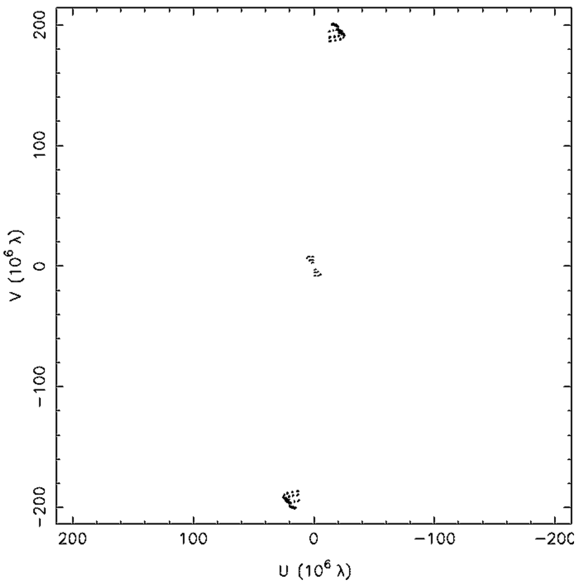

Fig. 1 e-VLBI (u, v)-coverage for the 2-hour observation of PKS 0727−115 at 8.4 GHz. Telescopes: ATCA, Mopra, Parkes, Kashima and Sheshan.

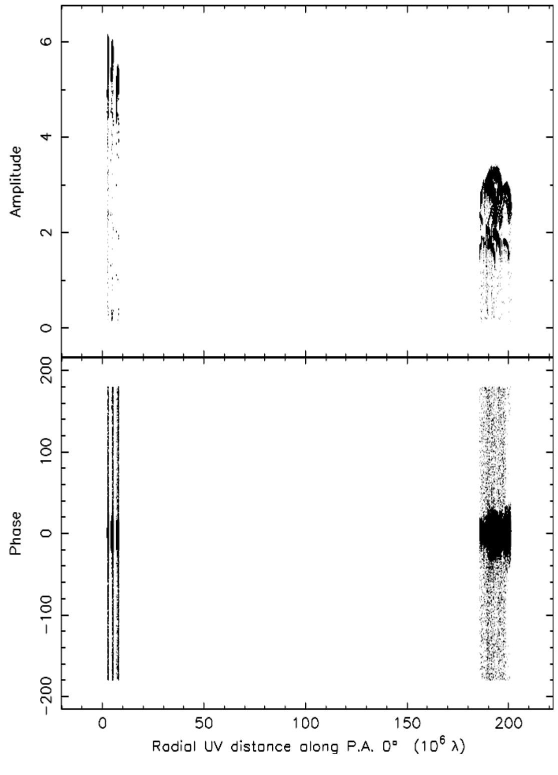

Fig. 2 Visibility amplitude (Jy) and phase (deg) for PKS 0727−115 as a function of radial (u, v) distance.

Table 1 Australasian e-VLBI demonstration observations at 8.4 GHz. In the case of non-detections, the flux densities reported are the 3σ upper limits.

Source	Duration (h)	Beam size (mas × mas)	Flux density	rms noise (mJy beam^{-1})
PKS B0727−115	2	18.1 × 0.4	2.54 Jy	63
PKS B0524+034	2	21.1 × 0.4	0.218 Jy	7.4
GRB 080409	5	21.1 × 0.4	<0.45 mJy	0.15

Table 2 Simultaneous ATCA 8.4 GHz observations of PKS B0727–115, PKS B0524+034 and GRB 080409 during the e-VLBI run. In the case of non-detections, the flux densities reported are the 3σ upper limits.

Source	Duration (h)	Beam size (arcsec × arcsec)	Flux density	rms noise (mJy beam^{-1})
PKS B0727–115	2	7.35×1.03	5.32 Jy	34
PKS B0524+034	2	30.3×0.9	0.79 Jy	3.7
GRB 080409	5	19.8×0.8	<0.66 mJy	0.22

dial (u, v) distance for all of the baselines in the network. Figure 3 and Figure 4 are the e-VLBI images of PKS B0727$-$115 and PKS B0524+034 respectively. Both the sources were unresolved down to the beamsize of the array. The geographical configuration of the array gave very long north-south baselines compared to the east-west baselines resulting in much coarser east-west resolution and the beams were elongated in the north-south direction.

In addition to the e-VLBI data, we also processed the ATCA internal baseline data that were simultaneously taken during the e-VLBI run. The ATCA data were reduced using the ATNF Miriad (Sault et al. 1995) package and standard techniques were employed for the data reduction. Amplitude calibration was done using the flux calibrator PKS 0823$-$500 and PKS B0524+034 was used as the phase calibrator for the GRB. The calibrated data were then exported to Difmap for model fitting and imaging. Both PKS B0727$-$115 and PKS B0524+034 were clearly detected and a radio flux density upper limit for the GRB 080409 was obtained. Table 2 reports the details of the ATCA observations.

4 DISCUSSION

Multi-epoch VLBI observations of PKS B0727$-$115 as part of the MOJAVE project have revealed that the source structure is dominated by a bright core and single jet component. This component is located ~5 mas to the west of the core and is moving with an apparent speed of $31.2 \pm 0.6\,c$ (Kellermann et al. 2004; Lister et al. 2009). The lack of longer east-west baselines in our e-VLBI observations resulted in a beam size of 18.1×0.4 mas at a position angle (PA) of 84.4° for PKS 0727$-$115, and as a result the observations could not resolve the jet component from the core.

GRB 080409 was detected by the Swift Burst Alert Telescope (BAT) on 2008 April 9 as a long GRB with a light curve showing a double-peaked structure with a duration of about 10 s. The peak count rate was ~5000 counts s^{-1} (15–350 keV) at ~0.7 s after the trigger (Holland et al. 2008). The position used for the VLBI observations was determined by Evans et al. (2008) using 91 s of overlapping XRT Photon Counting mode, with an uncertainty of $2.0''$ (radius, 90% confidence). No optical counterpart of this GRB was detected as an outcome of the subsequent optical follow-up. There were no reports of a supernova association either.

We tracked the position of the GRB 080409 with our e-VLBI array for about 5 h. The radio counterpart was not detected but we were able to obtain a 3σ upper limit of 0.45 mJy. The e-VLBI observation of this GRB was carried out about nine weeks after the prompt emission so the non-detection was not very surprising. In general, the GRB afterglow is produced when the fireball decelerates as it interacts with the circum-burst medium. The time evolution of the radio afterglow suffers from self-absorption, and it rises some time after the GRB prompt emission. The peak flux density of the radio afterglow is frequency dependent since synchrotron self-absorption frequency shifts across the observing band and it generally fades away over a timescale of a few days to weeks as the fireball continues to decelerate in the circum-burst medium. (e.g. Frail et al. 1997; Kulkarni et al. 1999; Frail et al. 2003; Piran 2004; Chandra & Frail 2012; Ghirlanda et al. 2013).

In case of very bright, exceptionally energetic and relatively closeby GRBs, it is normal that the radio afterglow remains detectable over several weeks or even months (e.g. GRB 030329: Taylor et al. 2004; Pihlström et al. 2007, GRB 100418A: Moin et al. 2013). GRB 080409 was chosen as one of the target sources for these observations primarily on the basis of the mutual sky visibility for the participating telescopes. Our non-detection 69 d after the detection of prompt emission is consistent with the fact that the radio flux must have dropped to values much lower than the upper limit achieved by our observations at 8.4 GHz. Although the energy output and source distance were not determined from the e-VLBI observations, it is likely that GRB 080409 was probably not at a comparatively small distance nor did it have a particularly large kinetic energy release.

5 CONCLUSIONS

The e-VLBI observations reported in this paper serve to demonstrate the e-VLBI capability of the participating radio telescopes. To conduct these observations, an Australasian e-VLBI array was formed using high-speed networks, which enabled the real-time monitoring of rapidly varying radio sources of interest. This initiative was part of the concerted efforts to establish e-VLBI as a more regular and efficient mode of operation for a VLBI array and was one of the initial steps taken in this direction. We were able to detect the radio-loud quasar PKS B0727$-$115 and the intra-day variable quasar PKS B0524+034, and obtained upper limits for the afterglow of GRB 080409.

This exercise successfully demonstrated the real-time, large-volume VLBI data transportation and correlation over the networks across Australasia. This mode of op-

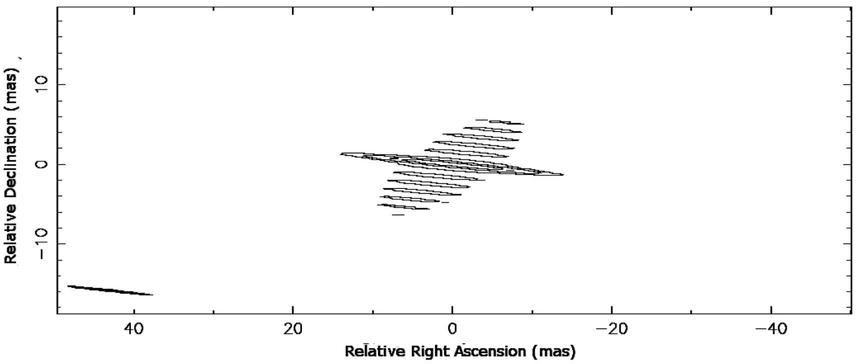

Fig. 3 e-VLBI image of the superluminal source PKS 0727−115 at 8.4 GHz. Image peak: 2.54 Jy; Image noise (1σ-rms): 63 mJy; Beam size: 18.1 × 0.4 mas. Contours: 19, 26.9, 38, 53.7, 76; PA: 84.4°.

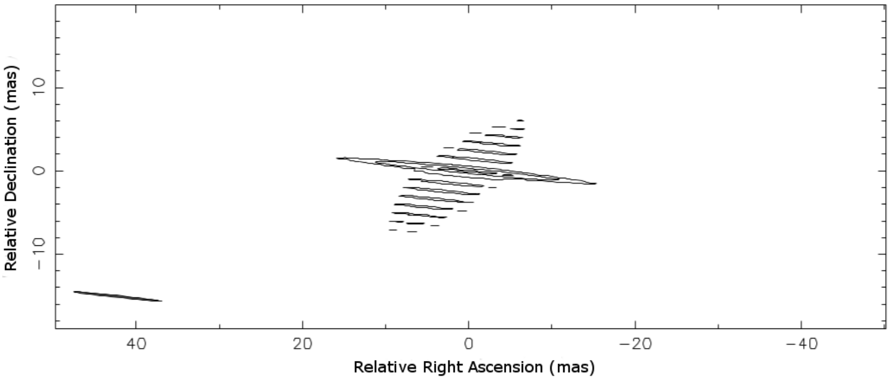

Fig. 4 e-VLBI image of the intraday variability (calibrator for GRB 080408) source 0524+034 at 8.4 GHz. Image Peak: 0.218 Jy; Image noise (1σ-rms): 7.4 mJy; Beam size: 21.1 × 0.4 mas. Contours: 19, 26.9, 38, 53.7, 76; PA: 84.3°.

eration is becoming of greater interest as we move towards the era of next generation instruments such as Australian Square Kilometre Array Pathfinder (ASKAP), Murchison Widefield Array (MWA) and Square Kilometre Array (SKA). A Southern Hemisphere GRB radio detection and monitoring program (led by A. Moin) is already in place, which will take advantage of e-VLBI follow-up for very high-resolution observations, should a potential GRB radio afterglow candidate meet the target selection criteria. In time, the program will be expanded to include next-generation telescopes with enhanced capabilities. These all-sky survey instruments are expected to detect a large number of transient sources. Rapid, real-time e-VLBI follow-up of such sources, with as many stations as possible, will be critical in order to learn about the finest structural details and dynamic astrophysical processes.

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