*Proceedings of the 6th European VLBI Network Symposium*
*Ros, E., Porcas, R.W., Lobanov, A.P., & Zensus, J.A. (eds.)*
*June 25th-28th 2002, Bonn, Germany*

# VLBI observations at 147 GHz: first detection of transatlantic fringes in bright AGN

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**Abstract.** At 147 GHz (2 mm wavelength), we detected three prominent AGN (NRAO 150, 3C 279, 1633+382) with Very Long Baseline Interferometry (VLBI) with an angular resolution of only $\sim$ 18 micro-arcseconds. This is a new world record in radio interferometry and astronomical imaging and opens fascinating future possibilities to directly image and study the innermost regions in quasars and other active galactic nuclei.

## 1. Introduction

Even after more than 40 years of comprehensive astrophysical research on Active Galactic Nuclei (AGN) made since after Marten Schmidt's discovery of the cosmological redshift of the hydrogen lines in 3C 273, the enigma of the origin of the extreme luminosity of AGN (ranging from radio to Gamma-ray bands) and the creation mechanism for the highly relativistic plasma jets (often extending over many hundreds of kiloparsecs) is still not solved. Although the majority of the scientific community regards accretion onto supermassive Black Holes as the most plausible explanation for the 'quasar phenomenon', many details of the astrophysical processes taking place in the centers of these most luminous objects in the Universe still remain unexplained. In particular, it remains unanswered how the relativistic jets are made, accelerated and confined. In order to test the existing theories, most of which try to explain energy release and jet production via coupling to the accretion process onto a supermassive Black Hole (e.g. the Blandford-Payne magnetic sling-shot mechanism), the direct imaging of the innermost regions of AGN becomes of great importance. The technique of interferometry is the only astronomical observing method, that leads to such direct images.

In VLBI the angular resolution can be improved, either by increasing the distance between the radio telescopes or by observing at shorter wavelengths. The first approach leads to VLBI with orbiting radio antennas in space (e.g. VSOP, Hirabayashi et al. 2000), which however at present gives only an angular resolution of 0.2–0.3 mas (1 mas = $10^{-3}$ arcsec) at 5 GHz. The second approach leads to VLBI at millimeter wavelengths (mm-VLBI), which furthermore facilitates the imaging of compact structures, which are self-absorbed (opaque), and therefore not directly observable, at the longer centimeter wavelengths.

Nowadays, mm-VLBI observations are regularly performed at 86 GHz ($\lambda$ = 3.5 mm), where images with angular resolutions of up to $\sim 50\mu$as ($1\mu$as $= 10^{-6}$ arcsec) are obtained (e.g. Rantakyro et al. 1998, Lobanov et al. 2000).

VLBI observations at even shorter wavelengths are technically more difficult and have not yet passed the stage of test experiments on relatively short continental baselines. In 1989 the quasar 3C 273 was marginally detected at the so far highest VLBI frequency of 223 GHz, (with SNR $\leq$ 7), on the baselines Owens Valley to Kitt Peak (845 km, 0.65G$\lambda$) (Padin et al. 1990). In 1994, first fringes were seen at 215 GHz between the IRAM 30 m antenna on Pico Veleta (Spain) and a single antenna of the IRAM interferometer on Plateau de Bure (France) (Greve et al. 1995). A second experiment on this 1147 km long baseline in 1995, resulted in the successful (SNR$\leq$35) VLBI detection of 8 out of 9 observed compact flat spectrum sources, including the source in the Galactic Center Sgr A* (Krichbaum et al. 1997). This experiment lead to a number of conclusions, which are important for the future: (i) a large fraction of the known cm-VLBI sources are compact enough, so that they can be observed with VLBI at short millimeter wavelengths, (ii) the VLBI jets can be traced to sub-parsec scales, however, the curvature of the jets usu-

**Table 1.** Antenna properties: tabulated are the name (col.1), the altitude (col.2), the antenna diameter (col. 3), and the typical system temperature (col. 4), aperture efficiency (col.5) and system equivalent flux density at 147 GHz.

| Telescope | h [m] | D [m] | $T_{sys}$ [K] | $\eta$ | SEFD [Jy] |
|---|---|---|---|---|---|
| Pico Veleta | 2900 | 30 | 200 | 0.50 | 1600 |
| Heinrich-Hertz | 3200 | 10 | 200 | 0.60 | 11700 |
| Kitt Peak | 1900 | 12 | 250 | 0.45 | 13600 |
| Metsähovi | 40 | 14 | $\sim$1000 | 0.13 | 140000 |
| SEST | 2300 | 15 | 350 | 0.45 | 12200 |

ally increases towards the nucleus, and (iii) the internal structure of the Galactic Center source Sgr A* becomes visible through the foreground scattering IGM, and the size of Sgr A* must be smaller than $\sim$ 20 Schwarzschild radii (Krichbaum et al. 1998).

In 1995–2000 several attempts with various telescopes were made to achieve VLBI detections on the longer transatlantic baselines. These experiments were performed in the 2 mm and 1.3 mm bands, but failed due to technical difficulties. The recent promising detection of 3C 273 and 3C 279 at 147 GHz on the 3100 km (1.5G$\lambda$) baseline between Pico Veleta and Metsähovi (Finland) in March/April 2001 (Greve et al. 2002), and the availability of VLBI equipment and a new 2 mm receiver at the Heinrich Hertz telescope (HHT) on Mt. Graham (Arizona), stimulated a transatlantic VLBI experiment at 147 GHz, which we will describe in the following.

## 2. The Experiment, Data Analysis, Transatlantic Fringe Detection

The VLBI experiment was performed at 147 GHz and in coordination with a spectral line VLBI experiment at 129 GHz (see Doeleman et al. , this conference). The 147 GHz observations were done on April 18, 15 UT - April 19, 6 UT. Participating telescopes were the 30 m IRAM antenna on Pico Veleta (PV) in Spain, the 10 m Heinrich-Hertz telescope (HHT) on Mt. Graham (Arizona), the 12 m telescope on Kitt Peak (KP) (Arizona), the 14 m antenna at Metsähovi (MET) (Finland) and the 15 m SEST telescope in La Silla (Chile). Table 1 summarizes the antenna properties.

The observations were performed at a reference frequency of 147028.99 MHz. The data were recorded with the MkIV VLBI system at 224 Mbit/sec at 2 bit mode (256-8-2). Due to the limited number of only 4 video converters at HHT and KP, the frequency synthesis was made by recording upper and lower side band in each of the four base band converters (BBC's). The total observing bandwidth was 56 MHz, since the lower sideband in the first BBC was not recorded. To produce left circular polarization (LCP) quarter-wave plates were inserted in front of each receiver (single sideband tuned 4 K cooled SIS systems). Special care was taken for the tuning and stability of the LO-systems. Test tones were injected and

**Table 2.** Signal to noise ratios of VLBI detections at 147 GHz

| Source | HHT - KP | | HHT - PV | | KP - PV | |
|---|---|---|---|---|---|---|
| | cov1[a] | cov2[b] | cov1 | cov2 | cov1 | cov2 |
| 0133+476 | –[c] | 7–10 | – | – | – | – |
| NRAO150 | 7–10 | 9–14 | – | 7 | – | – |
| 0420-014 | 7–11 | 8–13 | – | – | – | – |
| 3C273B | 8 | 6.4? | – | – | – | – |
| 3C279 | 22–37 | 12–49 | 14–40 | 20–75 | 8–18 | 7–20 |
| 1633+382 | 10–20 | 10–22 | 11–17 | 22–23 | 9–13 | 10–12 |
| 3C345 | 7 | | 6.1? | | – | |
| MWC349 | – | | – | | – | |
| NRAO530 | – | 11–19 | | | | |
| SGR A* | 6.7? | | | | | |
| 1921-293 | 9 | | | | | |
| 3C454.3 | 10–15 | | – | | – | |
| BL LAC | 7 | | – | | – | |
| 2255-282 | – | 12–16 | | | | |

[a]: Coverage on day 109/110. [b]: Coverage on day 110/111. [c]: A dash means "no detection"; no entry means "not observed"

round-trip phase stability tests were performed before the VLBI run started (for details see Doeleman, this conference, and Greve et al. 2002). The data were recorded on thin tapes, except at SEST and Metsähovi, where thick tapes were used. In 10–15 min gaps between consecutive VLBI scans (each of $\sim$ 7 min duration), pointing checks, antenna temperature and atmospheric opacity measurements (skydips) were performed. At HHT, KP and PV typical opacities ranged between $\tau = 0.08 - 0.3$. The flux densities of the VLBI target sources were calibrated by using the planets as primary calibrators. Where possible, these flux density measurements were later used to determine elevation-gain curves for the antennas.

Immediately after the observations, selected recorded VLBI tapes from HHT and KP were shipped to Haystack for a first fringe verification. The final correlation of the 147 GHz experiment was done at the MPIfR in Bonn. The fringe fitting was done in two steps, initially with the MkIV software (FOURFIT, baseline-based fringe fitting) over the full scan length (440 sec). The data were then imported into AIPS using the new tasks MK4IN and GLAPP (for details, see Alef et al. this conference). The final fringe fit was done with shorter solution intervals (0.5 - 3 min) using the AIPS task FRING (station-based global fringe fitting). The amplitude calibration of the fringe fitted data is based on the system temperature and antenna gain and opacity measurements recorded during the observations. The data were then exported from AIPS to the DIFMAP-package, where the incoherent averaging (10 sec) and imaging was done. At the present stage of the data reduction, uncorrected antenna pointing errors and poorly known Kelvin to Jansky conversion factors limit the overall accuracy of the amplitude calibration to about 20-30 %.

In Table 2, we summarize for all observed sources the signal-noise-ratios of the VLBI detections obtained so far

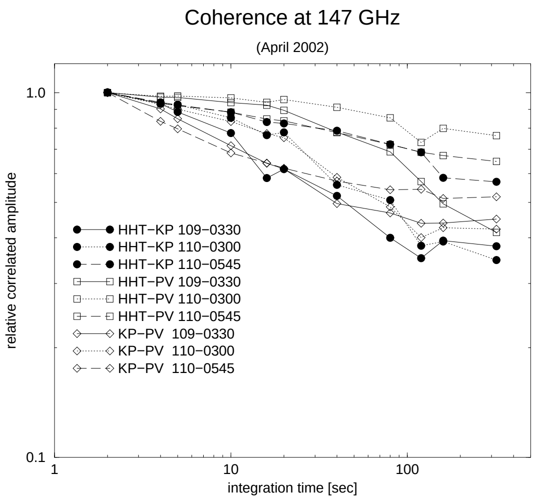


**Fig. 1.** Normalized correlated visibility amplitude plotted versus coherent integration time for the 3 different baselines and for 3 different times (dd-hhmm). The coherence varies with time and depends mainly on atmospherical conditions. Typically, a 10–20 % amplitude loss is reached after 10 seconds.

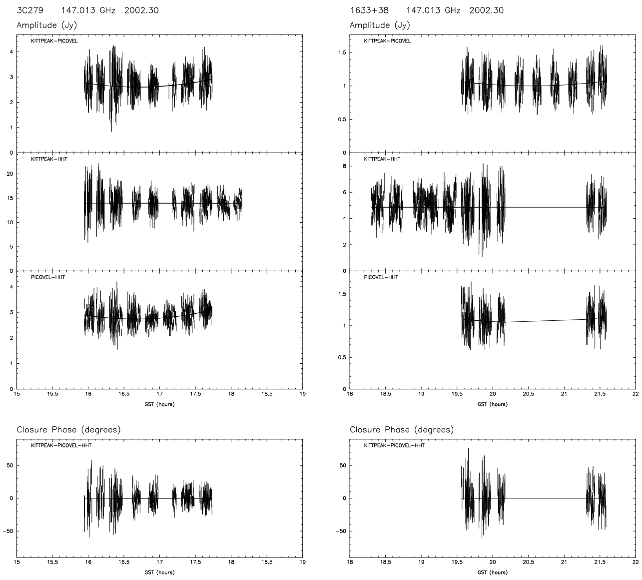


**Fig. 2.** Visibility amplitudes and closure phases for 3C 279 (left) and 1633+382 (right) at 147 GHz for the station triangle HHT – KP – PV. The solid line is a fit of a circular Gaussian model with the flux and size given in Table 3. For a few VLBI scans additional corrections of order 30–50 % were necessary, to remove obvious pointing errors.

on the individual interferometer baselines[1]. The SNR's correspond to incoherent integration over the full scan lengths. We expect some more detections after the correlation will be completed and after a fringe search with more restricted search windows in delay and rate. We note that we have detected 3 sources (NRAO150, 3C279, 1633+382) on the transatlantic baselines from Arizona (HHT, KP) to Pico Veleta at a fringe spacing of 4.2G$\lambda$ (corresponding to $\sim 24\,\mu$as resolution). This is, as far as we know, the highest angular resolution, ever achieved in astronomical radio interferometry. The SNR of the detections on the HHT – PV baseline are higher (SNR $\leq 75$) than on the KP – PV baseline (SNR $\leq 20$), indicating a very good sensitivity and phase stability of the HHT, which was never used in VLBI before. In Figure 1 we plot the loss of the correlated visibility amplitude as function of integration time (coherence plot). The atmospheric phase fluctuations limit the integration time to about 10 sec, but occasionally allows also much longer integrations.

So far we analyzed only the data for the two sources, which are detected with SNR > 7 on all of the 3 baselines (3C 279, 1633+382) and for which closure phases could be measured (see Fig. 2). For both sources the closure phases are close to zero, indicating either a point-like, or a symmetrical source structure (within the limitations given by the uv-coverage). In the present preliminary calibration, residual variations of the visibility amplitudes are still relatively large (of order of 30 %). We therefore adopted the simplest approach and fitted just one single circular Gaussian component to the data. In Figure 3 we show an example of such a model for 1633+382. The map is convolved with an elliptical restoring beam derived from the uniformly weighted data with the DIFMAP software. In Table 3, we show the parameters of the Gaussian fits and the derived brightness temperatures and linear sizes for both quasars.

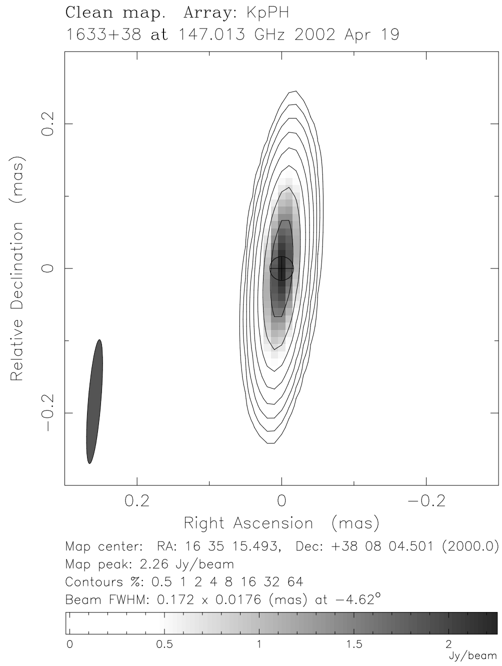


**Fig. 3.** Gaussian model of 1633+382 at 147 GHz. Data from HHT – KP – PV are shown in Figure 2. The elongated observing beam reflects the mostly east-west orientation of the VLB-interferometer. The minor axis of the observing beam is only 18 $\mu$as.

The estimate of the source sizes depends critically on the gain calibration of the 30 m antenna on Pico Veleta

[1] Metsähovi showed SNR $\leq 7$ fringes only with PV due to a problem in VLBI recording. Fringes to SEST are not yet found

**Table 3.** Results from the transatlantic VLBI detection for 3C279 and 1633+382. Successive columns give source name, redshift, total flux density, flux density and size ($FWHM$) of the compact VLBI component from the Gaussian model, its brightness temperature and its linear size (assuming $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$, $q_0 = 0.3$).

| Source | z | $S_{\rm tot}$ [Jy] | S [Jy] | $\theta$ [$\mu$as] | $T_B$ [K] | size [pc] |
|---|---|---|---|---|---|---|
| 3C279 | 0.536 | 21.1 | 14.0 | 34 | $7 \cdot 10^{11}$ | $\simeq 0.20$ |
| 1633+382 | 1.814 | 7.3 | 4.9 | 33 | $3 \cdot 10^{11}$ | $\leq 0.24$ |

(accurate within $\sim 20$ %), to which the long uv-spacings are formed. Larger correlated flux densities on baselines with this station would yield smaller source sizes. At the moment, it is therefore not completely clear, if the two sources shown in Table 3 are in fact marginally resolved along the minor axis of the beam, or if they are still unresolved. (The sizes from the Gaussian fits are about a factor of 1.9 larger than the minor axis of the beam and a factor of 1.3 larger than $0.5(u_{max}^2 + v_{max}^2)^{-0.5}$ ). If the sources were unresolved, the size estimates shown in Table 3 must be regarded as upper limits to the true source size. With the usual assumption of the brightness temperature being limited by the inverse Compton effect ($T_B \leq 10^{12}$ K), an interesting *lower* limit to the source size of $\geq 17\,\mu$as for 1633+382 and $\geq 27\,\mu$as for 3C 279 is obtained (from $\theta_{[\rm mas]} \geq [1.22 S_{[\rm Jy]}/\nu^2_{[\rm GHz]}]^{0.5}$). These lower limits indicate, that at least for 3C279, for which it is larger than the beam size, 2 mm-VLBI starts to measure the true spatial extent of this quasar nucleus and this despite of its large cosmological redshift of $z = 0.536$ !

## 3. Outlook

It is obvious that with better uv-coverage and more antennas participating in future VLBI at $\leq 2$ mm, the calibration uncertainties can be removed and 'true maps' rather than simple Gaussian model fits can be made. From our experience with global 3 mm-VLBI, we would like to point out that many of the radio sources observed so far show a considerable amount of sub-structure on the mas- to submas scale (c.f. Krichbaum et al. 1999). Imaging of such complex brightness distributions requires a very regular and dense uv-coverage and at least $\sim 8 - 10$ VLBI antennas (the more the better). Present day mm-VLBI suffers severely from the lack of short uv-spacings. As a consequence of this, it is presently not possible to reliably image about $30 - 50$ % of the total source flux. The relatively high surface brightness of the sources on 10–500 km long baselines, thus gives room also for less sensitive and smaller antennas to play a significant role in future high resolution imaging. This experiment has demonstrated that the combination of two closely spaced smaller antennas (HHT-10m & KP-12m) with a more distant large antenna (PV-30m), resulted in promising new science.

The addition of more collecting area by adding sensitive antennas designed for millimeter and sub-millimeter research will always be most important for mm-VLBI. This includes existing antennas, which are not yet participating in mm-VLBI (eg. JCMT, SMA, NRO), but also new antennas like eg. the 50 m LMT in Mexico and the ALMA prototype antenna APEX. Owing to their outstanding sensitivity, phased interferometers will play a particularly important role in future mm-VLBI. For the near future, the participation of the IRAM interferometer at Plateau de Bure (France) is planned (first at 3 & 1 mm, later also at 2 mm). This will increase the present sensitivity by a factor of $\sim 2 - 3$ to the $\sim 0.1$ Jy level. In the more distant future, CARMA —the merger of the BIMA and OVRO interferometers— and ALMA should lower the detection threshold to 1–10 mJy and by this tremendously improve the observational possibilities (cf. Krichbaum et al., 1996). In parallel, higher data recording rates and larger observing bandwidths (GBit/sec using the future MKV system) and the possibility of atmospheric phase corrections (via water vapor radiometry and/or phase referencing) will also help to further improve the sensitivity.

All this will facilitate the imaging of quasars, nearby radio-galaxies and of the Galactic Center source with the fascinating angular resolution of only ~10–20 microarcseconds! In nearby galaxies, structures of a few light days in size could then be seen. If the Galactic Center source Sgr A* would be detected with mm-VLBI at $\geq 4\,{\rm G}\lambda$ resolution, the direct imaging of a region as small as $\sim 2-4$ Schwarzschild radii would become possible. It is therefore not completely unrealistic that in 10–20 yrs, general relativistic effects caused by the distortion of the space-time in nearby supermassive Black Holes would become directly observable.

*Acknowledgements.* We thank all the personnel from the observatories who participated in this experiment for their efforts and enthusiasm, without which this success would not have been possible.

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