mm VLBI

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Abstract. Very Long Baseline Interferometry (VLBI) has now made its break-through into the mm wavelength regime. A global VLBI array has produced maps of radio sources at $\lambda 3$ mm since 1988 and development is under way to improve the sensitivity for VLBI also at $\lambda 1$ mm. This contribution discusses the present state of mm VLBI and the future developments.

1. Introduction

It is now more than 20 years since the very first intercontinental VLBI experiment was made between USA and Europe. The quest to further improve the techniques and to improve the resolution has been going on since then. It took some 10 years to improve the resolution with the first $\lambda 13$ mm VLBI experiment in 1977 and 1978 (Bååth *et al.* 1981) when maps of the quasar 3C345 were made for the first time with a resolution of less than 1 mas. It took another 10 years, until 1988, to further improve the resolution when the first hybrid maps at $\lambda 3$ mm could be made.

The success of mm VLBI is mainly due to a long series of test experiments during 1982–87, and to the development of better receivers and local oscillator systems as well as to the improvement in data reduction techniques which took place during the late 1980's. The first VLBI experiments at $\lambda 3$ mm resulted in detections of the strongest sources on trans-USA baselines only. Models of 3C273B (Moffet and Readhead, 1988) and 3C84 (Readhead *et al.*, 1983) could be made. Other papers describing the first efforts of mm VLBI are Rogers *et al.* (1984), Backer (1984a, 1984b, 1988), Backer *et al.* (1987), and Wright *et al.* (1988). The models presented in these early papers did contain data from the baseline OVRO to Quabbin, across the USA, so it seemed possible that also fringes on intercontinental baselines could be found. These fringes were difficult to find though, mainly due to the low signal-to-noise ratio on long baselines. Finally, in 1988 we did a test using global fringe fitting technique which showed to be successful on also the longest baselines. There were, however, also some fringes on the longest baselines from USA to Nobeyama and Onsala with the traditional single baseline fringe fitting technique. The technique of global fringe fitting which we used in this experiment is described in Bååth *et al.* (1992).

2. The Antennas

The antennas used for mm VLBI are summarized in Table 1. The first set of experiments were made with Nobeyama, Onsala, Hat Creek, Owens Valley, Kitt Peak, and Quabbin, the original and pioneering sites of mm VLBI. In 1990 the SEST telescope in Chile participated for the first time. The inclusion of a southern hemisphere telescope is important in order to observe low declination sources. In 1993 Haystack, Effelsberg, and Pico Veleta participated for the first time, adding significant amount of (u,v)-coverage and collecting area to the VLBI array. Haystack has contributed a large part to the development with the Mk3 processor where all the data processing have been made. The Haystack Observatory has therefore played a major, probably a crucial, role in the development and success of mm VLBI even at the time when the telescope itself could not be used at these short wavelength. This clearly shows that a VLBI array is *one* instrument, and that this instrument is much more than the sum of its parts. It is our hope that VLBI at $\lambda 3$ mm soon shall be made available for the general VLBI observer via a proposal system to a loosely formed mm VLBI network. We also hope that a few of the VLBA antennas and some of the AT telescopes soon can participate in the mm VLBI sessions. The large antennas of the mm-array of IRAM would naturally be a significant and important addition to the VLBI array.

It is important to notice that at mm wavelength the troposphere is the limiting factor and that therefore the relevant system temperature has to be calculated at the outside of the atmosphere. Thus small telescopes at high altitudes can compete very well with large telescopes at low altitudes. A high altitude is also important in that the weather there is usually much more stable and calibration is made easier. Some

Table 1. Available antennas for $\lambda 3$ mm and $\lambda 1$ mm VLBI. $S_{\rm sys}$ refers to the system temperature in Jansky at the top of the atmosphere.

Antenna	diam. (m)	$\lambda 3$ mm eff.	$\lambda 3$ mm $S_{\rm sys}$	$\lambda 1$ mm eff.	$\lambda 1$ mm $S_{\rm sys}$	VLBI backend
Nobeyama	45	0.30	1500	0.10	10000	K4/VLBA/Mk3A
Onsala	20	0.48	5400	—	—	Mk3A
Owens Valley	3 × 10.4	0.60	2700	0.45	9600	cable to VLBA
Hat Creek	3 × 6.1	0.60	13000	?	?	none at present
Kitt Peak	12	0.60	8000	0.40	36000	cable to VLBA
Quabbin	14	0.50	8700	—	—	Mk3A Haystack
SEST	15	0.60	3900	0.50	12400	VLBA/Mk3A
JCMT	15	0.60	—	0.60	8700	K4 Nobeyama
Pico Veleta	30	0.50	1200	0.27	5600	VLBA/Mk3A
Haystack	37	0.15	4200	—	—	Mk3A
Effelsberg	60	0.10	2500	—	—	VLBA/Mk3A
Metsähovi	14	0.30	18000	—	—	VLBA/Mk3A
Quing Hai	14	0.30	15000	—	—	Mk3A Shanghai?

of the high system noises in Table 1 are due to not so good receivers, e.g. SEST could do with a much better SIS mixer at both $\lambda 3$ mm and $\lambda 1$ mm.

Note also in Table 1 the large scatter in available backends. OVRO and Kitt Peak have fibre optic cables laid from the mm antenna to the VLBA site, transporting the signal from the frequency standard to the telescope and the IF signal to the VLBA terminal. This procedure means that mm VLBI can only be performed at these sites when the VLBA backend is not in use by the VLBA. So far we have had no difficulties in negotiating times on the terminals. SEST has previously had a Mk3A terminal on loan from the Peldehue VLBI station in Santiago de Chile. A permanent VLBA/Mk3A terminal is now being built for SEST. JCMT has been borrowing a K4 terminal from Nobeyama and the data have then been translated to Mk3A tape at Nobeyama for further processing. It is also noteworthy that OVRO and Kitt Peak are limited in bandwidth to 64 MHz since only 8 videoconverters are available in the VLBA terminals there.

3. The Sources

A number of sources have now been mapped with VLBI at $\lambda 3$ mm. Table 2 presents a summary of the sources observed by us. The major results from our observations are:

- The core component is much more dominant at mm wavelengths than at cm wavelength.
- The linear diameter of the core is typically 10^{16}–10^{17} cm.
- The jet is more curved closer to the core than has been observed at cm wavelengths further away.
- In the one case where we have a $\lambda 3$ mm VLBI hybrid map observed very close in time to a major outburst the new component was elongated across the jet and very thin along the jet in proportions 10:1.
- In some cases, 3C84 and BL Lac, we have observed structural velocities of the order 20000 km sec^{-1}, much smaller than has been observed further out in the jet.

These results are consistent with a model of AGNs where the jet originates from a region of a disc accreting to a massive black hole of some 10^8–10^9 $M_\odot$ (REES, 1986; BAND and MALKAN, 1989). The size scale observed by us implies that we are seeing the very start of the jet, and are looking into a volume inside the Broad Line Region only some 50–500 Schwarzschild radius from the central black hole. The slowly moving components in the jets are well explained by the model of HARDEE (1990) where components are formed at the intersection point of two modes of reflective Kelvin-Helmholz instability shocks. In addition to these shocks we also have a more violent phenomena. In 3C273B we did observe a thin component very close in time to a major outburst which was simultaneous at all frequencies. Such a component can be explained with the "Blazar shock" model of MARSCHER and GEAR (1985) where the radiation originates from a thin region just behind a thin shock travelling down through the plasma flow of the jet. Further observations of such "Blazar" type components are needed to fully develop this theory. The major problem for such

Table 2. Sources mapped with $\lambda3$ mm VLBI. $D_{40\mu\text{as}}$ refers to the linear diameter in cm of the full width half maximum of the synthesized antenna beam for global VLBI at $\lambda3$ mm (40 μas). S_{corr} is the correlation coefficient for the most compact feature of the source at $\lambda3$ mm in 1989, except for 3C273B (1988) and 3C446 (1990).

Source	z	$D_{40\mu\text{as}}$ (cm)	S_{corr} (%)	References
3C84	0.0172	$3\cdot10^{16}$	19	READHEAD *et al.*, 1983 WRIGHT, 1984 BACKER *et al.*, 1987 BÅÅTH *et al.*, 1992
OJ287	0.306	$4\cdot10^{17}$	72	BÅÅTH *et al.*, 1992 INOUE, 1994
3C274	0.004	$7\cdot10^{15}$	29	BÅÅTH *et al.*, 1992
3C273B	0.158	$2\cdot10^{17}$	25	MOFFET and READHEAD, 1988 PADIN *et al.*, 1990 ($\lambda1$ mm) BÅÅTH *et al.*, 1991
3C279	0.538	$5\cdot10^{17}$	16	PADIN *et al.*, 1990 ($\lambda1$ mm) BÅÅTH *et al.*, 1992
3C345	0.595	$5\cdot10^{17}$	67	BÅÅTH *et al.*, 1992
BL Lac	0.070	$1\cdot10^{17}$	92	BÅÅTH *et al.*, 1992 INOUE, 1994
3C446	1.404	$7\cdot10^{17}$	31	LERNER *et al.*, 1994

observations is the long planning time of sessions which is necessary for the very oversubscribed telescopes of the mm VLBI array. We have submitted a proposal for an opportunity mm VLBI project where telescopes should be made ready to start observing with mm VLBI in just a week after an outburst has been reported.

4. The Future

The major future development in the area of mm VLBI I foresee are:

- Open up the proposal system at $\lambda3$ mm for the more general VLBI observer.
- Add more and larger antennas to the $\lambda3$ mm array.
- Record with larger bandwidth to increase the sensitivity.
- Continue the development towards even higher frequencies.

Development is under way towards wider bandwidth recording systems. Haystack Observatory and the European VLBI Network (JIVE) are together developing recording systems and processor for the next generation VLBI system (Mk4). The development of "burst mode" recording which is under way at Nobeyama will have a very important impact at very high frequencies, probably 350 GHz and up, where the tropospheric fluctuations are very severe indeed. A 2 GHz bandwidth system will be crucial for VLBI observations at the very highest frequencies.

Several test experiments have been tried at $\lambda1.3$ mm. So far only marginal fringes have been detected on the shortest baseline OVRO to Kitt Peak (PADIN *et al.*, 1990). There are two possible ways to improve the sensitivity at $\lambda1$ mm. The first is to increase the recording bandwidth as discussed above, but that may be some time into the future. The second possibility is to record simultaneously at $\lambda 3$ mm and $\lambda 1$ mm and use the fringes found at the longer wavelength to predict the delays and rates at the shorter wavelength. This would narrow the search windows at $\lambda 1$ mm to such an extent that fringes should be found given the signal to noise ratios we obtain at $\lambda 3$ mm. Both SEST and Pico Veleta can observe at both wavelengths simultaneously and through the same beam. OVRO can naturally do the same by using two antennas of the array. We plan to do such a test experiment during 1994.

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