Imaging of Nuclei of Active Galaxies

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Introduction

Very Long Baseline Interferometry at millimetre wavelengths (mm-VLBI) allows the detailed imaging of compact galactic and extragalactic radio sources with angular resolutions unreached by any other astronomical observing techniques. This technique offers a unique possibility to image the direct vicinity of the Super Massive Black Holes (SMBH) thought to be located in the centres of powerful radio galaxies and other Active Galactic Nuclei (AGN), including the SMBH in our Galaxy (SgrA*). The highest possible angular and spatial resolution is also required to answer the still unsolved and fundamental question of how the powerful radio jets of AGN are launched and how they are accelerated and collimated.

In radio interferometry the angular resolution can be improved either by increasing the separation between the radio telescopes, or by observing at shorter wavelengths. The first possibility leads to VLBI with orbiting radio antennas in space (e.g. VSOP, ARISE).The second alternative leads to mm-VLBI, in which ground-based radio telescopes observe at frequencies above ~80 GHz. The resolution of a global mm-VLBI array at 230 GHz would be about 25-30 micro-arcseconds ($1\ \mu as = 10^{-6}$ arcsec), similar to the resolution of space-VLBI at 43 GHz. Since the innermost region of an AGN is invisible at centimetre wavelengths (due to intrinsic self-absorption), mm-VLBI offers the additional advantage to penetrate this opacity barrier, opening the direct view onto the "central engine".
Here we report on recent developments in mm-VLBI, with particular emphasis on VLBI experiments performed at the highest accessible VLBI frequencies of 86, 150 and 230 GHz. We demonstrate that global VLBI at 230 GHz now is technically feasible and provides the angular resolution of 25-30 µas quoted before. When combined with additional future antennas (like CARMA, ALMA, see Table 3), mm-VLBI at and above 230 GHz therefore bears the realistic potential to image and study the direct vicinity of galactic and extragalactic (super massive) Black Holes.

Imaging the Jet Base of M87 with 20 R_s

The Global mm-VLBI Array has been operational since 2002 (*www.mpifr-bonn.mpg.de/globalmm*, see the poster of I.Agudo et al., this conference). At 86 GHz, the combination of large European antennas with the VLBA has considerably improved the imaging capabilities of global VLBI at this frequency. With the addition of the two IRAM telescopes (the 30m telescope on Pico Veleta, Spain, and the 6x15m interferometer on Plateau de Bure, France), the imaging sensitivity is improved by a factor of 3-4, when compared to the VLBA alone. As an example, we show in Figure 1 a new 86 GHz VLBI image of the inner jet of M87 with an angular resolution of 300 x 60 µas. At a distance of the source of 18.7 Mpc, this corresponds to a spatial scale of 30 x 6 light days, or 100 x 20 Schwarzschild -radii (assuming a $3 \times 10^6\ M_\odot$ BH). The existence of a fully developed jet on these small spatial scales gives important new constraints to the theory of jet formation and may indicate rotation of the central SMBH (via the size of the light cylinder).

Towards Shorter Wavelengths - VLBI at 2 and 1 mm

In order to demonstrate the technical feasibility of VLBI at wavelengths shorter than 3mm and in order to find out, if the known compact radio sources can be detected also on long transatlantic baselines, several VLBI experiments were performed during recent years. In Figure 2 and Tables 1-3 we summarize the results from the recent global VLBI observations performed at 150 and 230 GHz. It is seen that at both frequencies many sources are detected on the short (100-3000 km long) continental baselines. Mainly due to sensitivity limitations, the number of sources detected on the long transatlantic baselines still is small. The 230 GHz detection of the blazars 3C454.3 and 0716+714 on the Pico Veleta to HHT baseline (Tab.3) marks a new "world record" in angular resolution in Astronomy (size < 30 µas). These detections confirm the existence of ultra compact emission regions even at these high frequencies. The brightness temperatures of the VLBI cores appear not to be significantly lower than at cm-wavelengths. There are indications that the compactness of the sources varies (between sources and for a given source with time). This is not unexpected considering the known and often dramatic flux density and spectral variabilty in quasars, which is much more pronounced at mm- than at cm-wavelengths.

Future Outlook

For the future, it is expected that the imaging capabilities of mm-VLBI can be substantially increased and that sub-mm VLBI will become possible. With new mm-telescopes, the overall collecting area and the uv-coverage of the global array will be improved. The addition of large instruments like CARMA, the LMT and ALMA to global VLBI will be essential. Without sensitive telescopes, one could not reach the sensitivity (mJy level), which is required for the detailed imaging of the "event horizon" of SMBHs and the study of the coupling between Black Hole and jet (sub-mm polarimetry will be necessary to test magneto-hydrodynamical (MHD) jet models).
The demand for higher sensitivity is already supported by the ongoing development of the VLBI recording systems towards higher sampling rates and larger bandwidth (several Gbit/s). At mm- and sub-mm wavelengths, it will be also important to correct for the phase noise introduced by the atmosphere. Dual frequency observations or observations using water vapor radiometry will prolong phase coherence and integration times and thus further enhancing the sensitivity.

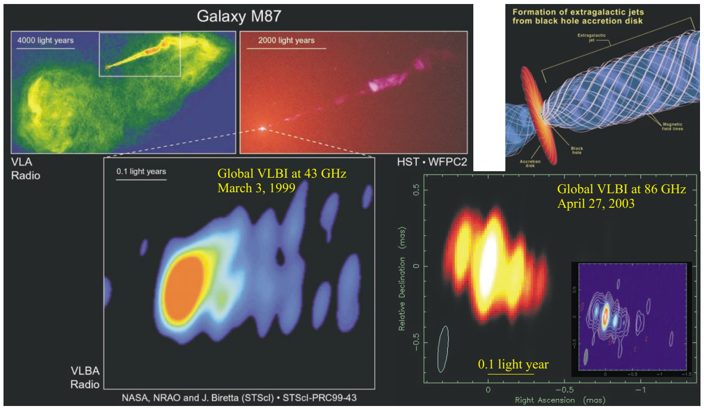


Figure 1: The jet of the giant elliptical galaxy M87 (Virgo A, 3C274, NGC4486). On the left a VLA radio map and a HST image of the arcsecond scale jet are shown (credit: F. Owen et al., NRAO, J. Biretta et al., STScI). The global VLBI image below shows the innermost region of the jet with an angular resolution of 0.33 x 0.12 mas as observed in March 1999 at 43 GHz by Junor et al., 1999. On the right, we show a new and so far unpublished 86 GHz VLBI image observed in April 2003. The beam size is only 0.3 x 0.06 mas. This image shows details near the jet base as small as 6 light-days or 20 Schwarzschild radii.

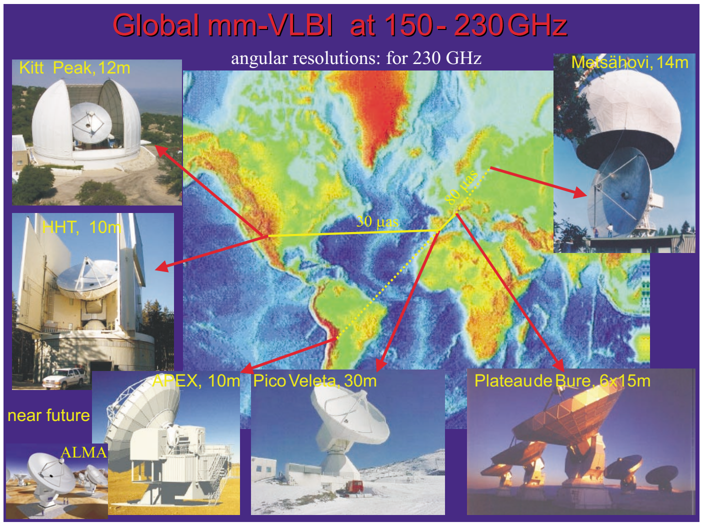
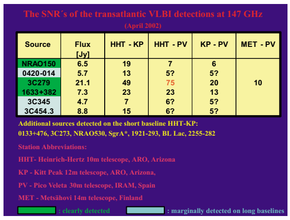


Figure 2: World map with the locations of the observatories which participated in recent VLBI experiments at 150 GHz and 230 GHz. In the near future, the 12m APEX antenna, located at the Chajnantor site in Chile, could provide important VLBI baselines for observations of southern sources, like Sgr A*.



The SNR´s of the transatlantic VLBI detections at 147 GHz
(April 2002)

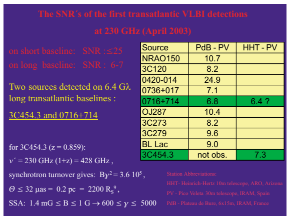
Source	Flux [Jy]	HHT - KP	HHT - PV	KP - PV	MET - PV
NRAO150	6.5	19	7	6	
0420-014	5.7	13	5?	5?	
3C279	21.1	49	75	20	10
1633+382	7.3	23	23	13	
3C345	4.7	7	6?	5?	
3C454.3	8.8	15	6?	5?	

Additional sources detected on the short baseline HHT-KP:
0133+476, 3C273, NRAO530, SgrA*, 1921-293, BL Lac, 2255-282

Station Abbreviations:
HHT- Heinrich-Hertz 10m telescope, ARO, Arizona
KP - Kitt Peak 12m telescope, ARO, Arizona,
PV - Pico Veleta 30m telescope, IRAM, Spain
MET - Metsähovi 14m telescope, Finland

🟩 : clearly detected
▨ : marginally detected on long baselines

Table 1& 2: Summary of detected radio sources in VLBI experiments performed at 150 GHz (Table 1, left) and 230 GHz (Table 2, right).



The SNR´s of the first transatlantic VLBI detections
at 230 GHz (April 2003)

on short baseline: SNR : ≤25
on long baseline: SNR : 6-7

Two sources detected on 6.4 Gλ long transatlantic baselines :

3C454.3 and 0716+714

Source	PdB - PV	HHT - PV
NRAO150	10.7	
3C120	8.2	
0420-014	24.9	
0736+017	7.1	
0716+714	6.8	6.4 ?
OJ287	10.4	
3C273	8.2	
3C279	9.6	
BL Lac	9.0	
3C454.3	not obs.	7.3

for 3C454.3 ($z = 0.859$):
$\nu' = 230\ \mathrm{GHz}\ (1+z) = 428\ \mathrm{GHz}$,
synchrotron turnover gives: $B\gamma^2 = 3.6\ 10^5$,
$\Theta \leq 32\ \mu as = 0.2\ pc = 2200\ R_S{}^9$,
SSA: $1.4\ mG \leq B \leq 1\ G \rightarrow 600 \leq \gamma \leq 5000$

Station Abbreviations:
HHT- Heinrich-Hertz 10m telescope, ARO, Arizona
PV - Pico Veleta 30m telescope, IRAM, Spain
PdB - Plateau de Bure, 6x15m, IRAM, France

Table 3: A selection of radio telescopes, which at least in principle can participate in future VLBI experiments at wavelengths shorter than 2mm (ν >150 GHz). The telescopes in the upper part of the table already participated in recent VLBI experiments at 150 and 230 GHz. The antennas with a surface rms < 50-70 µm would be able to perform VLBI observations at 230 GHz and possibly also at 345 GHz. At the highest frequencies and for sensitivity reasons, the participation of large telescopes like CARMA, the LMT and ALMA in future VLBI experiments will be essential.

Selection of Antennas for VLBI above 150 GHz

Observatory	Location	Diameter [m]	surface [microns]	Altitude [m]	Comment
Plateau de Bure	France	6 x 15	60	2100	
Pico Veleta	Spain	30	50	2900	
Kitt Peak	AZ, USA	12	75	2000	
Heinrich-Hertz Telescope	AZ, USA	10	15	3100	
Sest	Chile	15	70	2300	
Metsähovi	Finland	14	100	100	only >2mm
existing antennas, potential future candidates					
NRO	Japan	6 x 10	30	1300	
JCMT	Hawai, USA	15	25	4000	
CSO	Hawai, USA	10.4	25	4000	
Onsala	Sweden	20	130	sea level	only >2mm
Taeduk	Korea	14	130	200	only >2mm
under construction or planned					
ALMA	Chile	64 x 12	25	5000	
LMT	Mexico	50	70	4600	
CARMA	CA, USA	6x10.4+10x6.1	30	2400	
SMA	Hawai, USA	8 x 6	15	4000	
APEX	Chile	12	18	5000	
KVN	Korea	3 x 21 + 14	100	200	only >2mm

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