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Detecting sub-mJy sources with the EVN

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Abstract Some microquasars are permanently bright radio sources while others are faint but produce powerful radio outbursts. Most of the X-ray binaries (XRB) however are very faint or undetected in the radio regime. The European VLBI Network (EVN) recently introduced the Mark5 recording system which allows data rates of up to 1 Gbit s^{-1}. This increases the sensitivity of the array significantly. We briefly describe recent developments in the EVN in terms of reliability of the network and also data quality. We demonstrate the power of the EVN in detecting sub-mJy radio sources with modest integration times (order of hours). This high sensitivity capability will permit the study of variable Galactic sources at milli-arcsecond resolution. An estimate is given for the lowest detectable mass of hypothetical intermediate-mass black holes (IMBH) in nearby galaxies, provided these are located in radio-jet systems analogous to microquasars and active galactic nuclei.

Key words: techniques: interferometry

1 THE EUROPEAN VLBI NETWORK

The European VLBI Network (EVN) consists of telescopes in Europe, South Africa, and China. The network includes some of the largest telescopes in the world, for example the 100 m Effelsberg antenna, the 76 m Lovell Telescope, and the Westerbork Synthesis Radio Telescope. There are in general three observing sessions in a year. The data are normally correlated at the EVN MkIV Data Processor at JIVE. Recent developments in the EVN (*http://www.evlbi.org*) improved the data quality as well as the operational reliability of the array, as summarised below.

1.1 The Mark5 recording system

As from 2004, all EVN stations are equipped with the Mark5 disk-based recording system (*http://web.haystack.mit.edu/mark5/Mark5.htm*). This greatly improves the EVN reliability. Quick fringe tests are possible by ftp-ing some data from the stations to the correlator. The processing is done in an automated fashion using a software correlator developed in the Kashima Space Research Center, NICT (formerly CRL), Japan (Kondo et al. 2003). With the Mark5 recording system it is also possible to send the data in realtime to the EVN MkIV Correlator via optical fibres. The first realtime EVN eVLBI map was made on 2004 April

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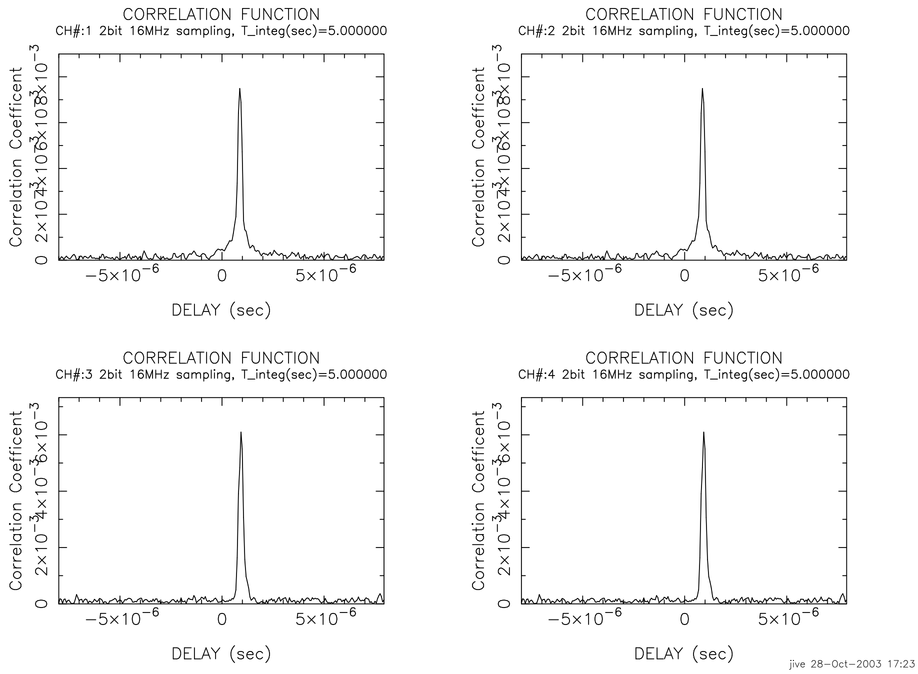

Fig. 1 Fringes produced from data files ftp-d over the Internet. Ftp fringe-tests are very useful for early realisation of telescope failures. The data are processed by the NICT Software Correlator on a Cluster computer at ASTRON/JIVE.

26 using a three-station network of telescopes including Onsala, the WSRT and Jodrell Bank (*http://www.evlbi.org/evlbi/te017/te017.html*). Recently a fourth antenna came on-line – the 32 m Torun telescope in Poland.

These technical developments provide not only a better calibrated and more reliable array, but also the possibility of increasing the sensitivity. From 2002, two headstack recording has been available allowing 512 Mbit s^{-1} data rate, but mechanical and logistical limitations meant it was used rarely. With the Mark5 system, 1024 Mbit s^{-1} became a reality in the EVN in 2004.

1.2 Data calibration pipeline

All experiments are processed by a data calibration pipeline (Reynolds, Garrett & Paragi 2002). This is especially useful for users that have little experience with VLBI data reduction. This reduces the time needed for post-processing significantly. The pipeline also produces rough maps of the calibrators, and, upon request, the target source. It cannot be stressed how important this may be for quick response science projects, to see whether the target is detected or not, without the user touching the data.

The pipeline results, the correlation FITS file, and any information related to the observations are stored in the EVN Data Archive (*http://archive.jive.nl/scripts/listarch.php*).

1.3 Amplitude calibration

The EVN is an inhomogeneous array with a variety of dishes with different sizes and receivers with different characteristics. In the past, $T_{\rm sys}$ measurements were sparse, and the calibration diode temperatures were occasionally ill determined which caused difficulties in processing the data.

Since 2002, the EVN introduced continuous $T_{\rm sys}$ monitoring. The data are provided to the user in a format (so-called ANTAB file) which can be directly applied by the user without further editing. In each observing session the calibration diode temperatures are determined at the stations, and frequency dependent variations are also corrected for.

1.4 Correlator upgrade

The field of view of VLBI images is usually limited to the order of 0.1 arcsec. This is because the data are averaged in frequency and time during processing, to reduce the data size, in order to match the capacity of the correlator and the post-processing hardware. Currently the EVN MarkIV Correlator is being upgraded to be able to handle sub-second integration times (0.25 s already possible) and an increased number of frequency channels.

It is now possible to image a field of view of many arcminutes at 1.6 GHz (18 cm), and the limitation is becoming the primary beam (field of view) of phased arrays (like Westerbork) and big dishes (Effelsberg, Lovell Telescope). Surveying projects of, for example nearby galaxies ($< 10'$ in size) can be carried out in a single observation without observing with different pointings or recorrelating with different positions.

2 FAINT SOURCE DETECTION WITH THE EVN

The thermal noise on VLBI images depends on the antenna sensitivities, the noise characteristics of the receivers of each interferometer element, and on additional noise sources (like the electronics and the target source itself). The noise can be reduced by observing the target source longer or increasing the recorded data rate. With tape recording, 256 Mbit s^{-1} was available using one recording head, and this was extended to 512 Mbit/s using two recording heads (see a two-head recording result in Fig. 2.).

With the Mark5 disk recording system, introduced at the EVN in 2004, it is possible to record at 1024 Mbit s^{-1}. For two bit sampling and dual (RCP+LCP) polarization this results in 128 MHz bandwidth in each polarization. The theoretical noise in the L- and C-bands (18 cm and 6 cm) at this high recording rate is about 10 μJy per beam with 5 hours on-source integration time.

Detecting sub-mJy sources requires a special observing mode, so-called phase-referencing. In this technique the target and a nearby calibrator ($\sim$ 1 Jy source within 3–4 degrees) are observed alternately in short cycles. The atmospheric phase errors are corrected for using the calibrator data. Phase-referencing is able to correct the phases to some extent, but residual errors remain in the data. For this reason, a phase calibrator is needed (order of 5–100 mJy, within $\sim$1 arcminute from the target) to reach the required noise level. Alternatively, one could use the summed response of all detected sources in the field, so-called "full-beam" VLBI self-calibration (Garrett et al. 2003). By correlating the observations with wide field of view mode (see above), we have a better chance of having an in-beam phase reference. To conclude, the EVN has the potential of detecting 40-50 μJy sources if the data are sufficiently well calibrated.

3 MICROQUASARS AND ULXS: POTENTIAL EVN TARGETS

Some of the microquasars are permanently bright in the radio (like SS433), others produce strong outbursts but are quite dim during quiescent periods (e.g. GRS 1915+105). The majority of XRBs are not detected in the radio regime. Another consideration for Galactic sources is that these are often variable on timescales of hours. With the EVN at 1 Gbit s^{-1} recording rate, a 2 mJy target can be imaged at 100:1 dynamic range within only an hour of observation.

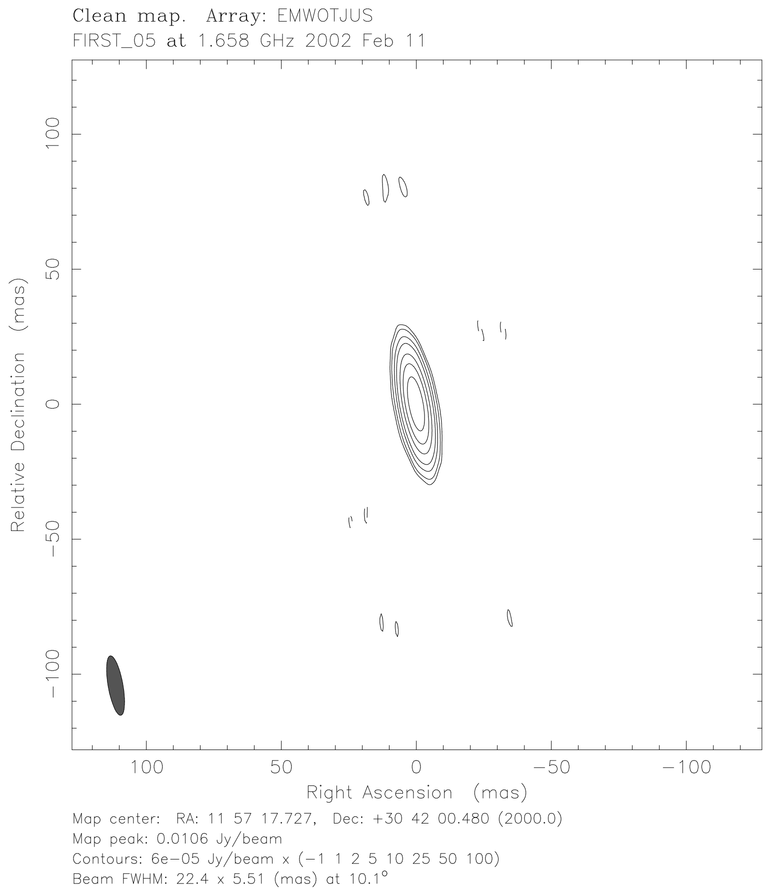

Fig. 2 The 10 mJy source FIRST 051 observed in a phase-referenced Network Monitoring Experiment (Paragi et al. 2002). The rms noise on the map is 18 μJy per beam, achieved by 150 minutes on-source integration time with the EVN, using 512 Mbit s^{-1} recording rate.

Potential candidates are the Ultra-Luminous X-ray (ULX) sources that may have radio counterparts. Some of these might be powered by Intermediate-Mass Black Holes (IMBH, Colbert & Miller 2004). Observation at milliarcsecond resolution could tell us whether these radio sources have a compact jet structure or not. The existence of a jet would confirm the presence of an accreting compact object in ULX sources.

One can speculate whether radio-loud IMBHs could be detected in nearby galaxies, if these have a jet analogous to microquasars and active galactic nuclei. By scaling the radio flux density of SS433 (probably hiding a 10 $M_\odot$ black hole), and assuming the $L_\mathrm{r} \propto M_\mathrm{BH}^{17/12}$ relation (Heinz & Sunyaev 2003), one could make such an estimate. On Fig. 3a we plot the minimum detectable black hole mass with the EVN with different on-source integration times. The results are shown with respect to the source distance, and some galaxies are also indicated.

Note that there is no well established relation between the black hole mass and the radio luminosity. Heinz and Sunyaev (2003) proposed $L_\mathrm{r} \propto M_\mathrm{BH}^{17/12}$ for optically thick flat spectrum core-dominated jets. Earlier Falcke and Biermann (1995, 1996) came to similar conclusions, and found that this seems to be consistent with the observations. Merloni et al. (2003) looked for correlation between L_r, L_x, and M_BH, and showed that the Heinz and Sunyaev (2003)

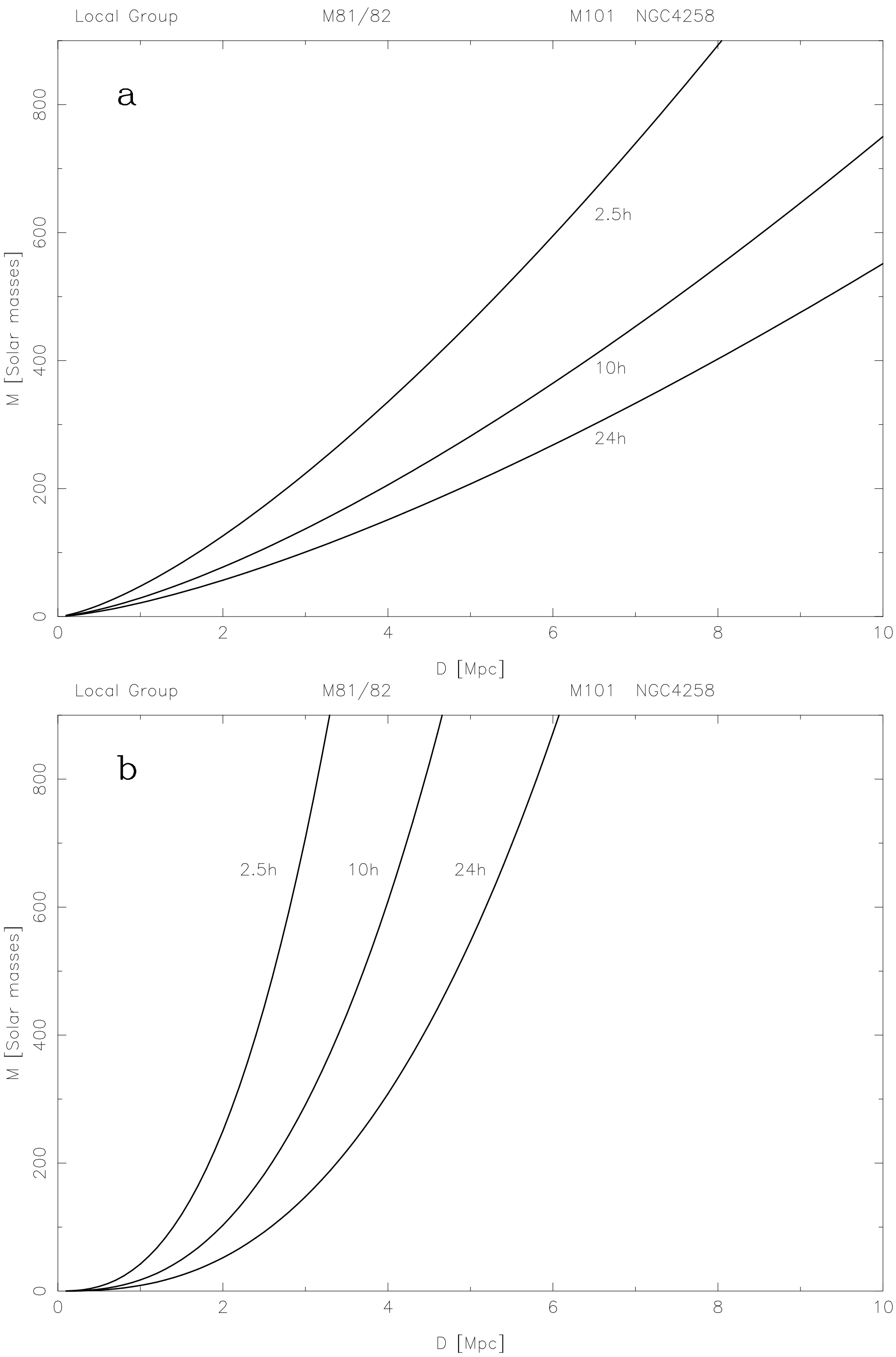

Fig. 3 The minimum detectable mass of an IMBH ($5\,\sigma$ detection at 5 GHz) in nearby galaxies, using different on-source integration times with the EVN. a) scaling up SS433 (300 mJy at 5 GHz, located at a distance of 5 kpc, BH mass is about 10 $M_\odot$) using $L_{\rm r} \propto M_{\rm BH}^{17/12}$ (Heinz & Sunyaev 2003), and b) using the formula given by Maccarone (2004) and assuming an ULX luminosity of $L_{\rm x} = 10^{40}\,{\rm erg\,s^{-1}}$.

model is consistent with the observed properties of Galactic and supermassive black holes if the accretion flows are radiatively inefficient. Maccarone et al. (2004) achieved similar results but by excluding sources in the high/soft state. Finally, Maccarone (2004) used the Merloni et al. (2003) correlation, $L_{\rm r} \propto L_{\rm x}^{0.6} M_{\rm BH}^{0.78}$, to express the radio flux of an accreting black hole system. He showed that deep radio surveys may be useful for studying ULX sources. In Fig. 3b we plot the minimum detectable black hole mass, corresponding to this latter relation. Both approaches agree that IMBHs could be detected in the closest galaxies with the EVN.

4 CONCLUSIONS

The operational reliability and general performance of the EVN has improved greatly in the past couple of years. New users not familiar with VLBI data reduction are particularly encouraged to use the EVN. A data calibration pipeline is available for users (especially useful for beginners), and support scientists are also available to support EVN users at all stages of their observations. The sensitivity of the array has improved by a factor of two recently with the introduction of the Mark5 recording system. Faint, variable Galactic sources as well as extragalactic objects can be detected at the 40-50 μJy level. According to our estimates, IMBHs, if they exist, can be safely detected with the EVN in nearby galaxies.

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