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Enhancing VLBI capabilities: recent achievements and future upgrades of the INAF radio telescopes

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Abstract. Small and flexible VLBI arrays, as exemplified by the successful EVN-lite operational model, can produce significant scientific outcomes. INAF, the Italian National Institute of Astrophysics, operates such an interferometer, comprising three dishes with a total collecting area equivalent to an 80m class radio telescope and baselines up to 950 km, supported by a software correlator in Bologna. This facility can serve as a complementary resource to the full-size EVN. I will present recent observational results in the areas of active galactic nuclei and astrophysical transients, showcasing the current capabilities. Additionally, I will discuss ongoing upgrades, including the installation of compact triple-band receivers for millimeter-wave observations and plans for broadband receivers. I will highlight the potential for multi-wavelength and multi-messenger studies, and especially the possible synergies with neutrino and gravitational wave detectors.

1. Introduction

The technique of VLBI has delivered high impact results over the past decades, and still continues to do so. Some of these results clearly benefit from the high sensitivity and image fidelity resulting from the combination of many telescopes, with Global VLBI being at the core of breakthrough discoveries (Spingola et al. 2018; Ghirlanda et al. 2019). In this framework, the activities of the Global VLBI Alliance (Colomer 2022)[1] are extremely important and needed for further progress and science discoveries.

However, also more limited arrays have delivered important results. This was the case in the beginning of the VLBI experiments, and still is relevant nowadays. For example, Nimmo et al. (2022) have discussed the localisation of FRB 20201124A showing that 8 out of 13 bursts have been detected with as few as four participating stations (6 effective baselines). Regional/national arrays with 3 or 4 stations such as the VLBI Exploration of Radio Astrometry (VERA[2]) and Korean VLBI Network (KVN[3]) are in operation and provide flexibility, ease of access, while delivering important results in multiple science areas, such as star formation (e.g. Kim et al. 2023) or active galactic nuclei (Takamura et al. 2023).

In Sect. 2, we introduce the current status of the INAF facilities (radio telescopes and correlator) and in Sect. 3 we present two examples of INAF-based VLBI projects. In Sect. 4 we describe the status of recent, current, and planned upgrades for the network. In Sect. 5 we give an outlook of how the INAF resources can complement the EVN and Global-VLBI activities in the science landscape of the next years.

[1] https://www.iau.org/science/scientific_bodies/working_groups/324/
[2] https://www.miz.nao.ac.jp/veraserver/
[3] https://radio.kasi.re.kr/kvn/main.php

2. The INAF facilities

The Italian National Institute for Astrophysics (INAF) operates three radio telescopes, the two 32-m Medicina and Noto antennas and the 64-m Sardinia Radio Telescope. Basic parameters are listed in Table 1. All the three telescopes can operate both in single dish mode and as elements of a VLBI array, as they are equipped with state-of-the-art receivers and digital backends. All the stations participate regularly in both disk-recorded and e-VLBI observations within the European VLBI Network.

When considered as a standalone array, the longest baseline is the one between Medicina and Noto (893 km), while the shorter baselines to Sardinia provide higher sensitivity and sample complementary spatial frequencies. A summary of the baseline lengths and reference sensitivities for the current available frequency bands is given in Table 2. The total collecting area of the three telescopes is $4825\,\mathrm{m}^2$, corresponding to 98% of that of the 10-stations VLBA, or to a single dish with equivalent diameter of 78.4 m. Correlation can be performed at the Institute of Radioastronomy headquarters in Bologna, where a software correlator running DiFX is operating.

Whereas time to observe as part of the EVN or Global-VLBI array can be obtained through the regular proposals for the full networks, observing time as a stand-alone interferometer or as part of other ad-hoc arrays needs to be arranged independently. Observing time is offered twice a year via open skies call for proposals[4] and additional elements can be included in the array at the principal investigator (PI) initiative. A Memorandum of Agreement between INAF and the Korean Space Science and Astronomy Institute (KASI) is in place, offering up to 30 hours per semester for projects with Italian- or Korean-affiliated PIs.

[4] published at https://www.radiotelescopes.inaf.it

Table 1. INAF radio telescopes characteristics as of November 2024.

Location	Code	Size	Year	Latitude	Longitude	Elevation	Receivers as of 2024/11[a]
Medicina	Mc	32 m	1983	44° 31′ 15″ N	11° 38′ 49″ E	25 m	L, S, C, C+, X, K
Noto	Nt	32 m	1988	36° 52′ 34″ N	14° 59′ 21″ E	78 m	L, S, C, C+, X, K
Sardinia	Sr	64 m	2013	39° 29′ 34″ N	9° 14′ 42″ E	600 m	P, L, C, C+, K

[a] - constantly-updated information is provided at `https://www.radiotelescopes.inaf.it/summary.html`

Table 2. INAF VLBI baseline length and sensitivity.

Baseline	Length [km]	Sensitivity [mJy min^{-1} Gbps^{-1}]			
		L	C	C+	K
Mc-Nt	893	5.9	1.7	7.8	6.1
Mc-Sr	592	1.8	0.7	1.7	2.5
Nt-Sr	580	1.8	0.8	1.9	2.7

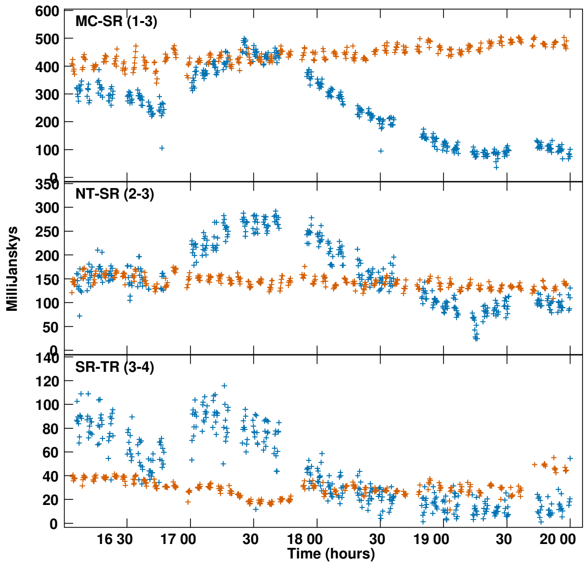

Fig. 1. Visibility amplitudes of Cyg X-3 (blue) and J2007+4029 (orange) during four hours of observation; variability is observed on the Mc-Sr, Nt-Sr, Sr-Tr baselines for Cyg X-3, in contrast with the stability of the comparison source.

3. Science results delivered by INAF-led VLBI observations

Observations based on arrays more limited than the EVN have delivered results in the context of several campaigns. The early steps of Pinpointing REpeating ChIme Sources with EVN dishes (PRECISE[5], now an EVN-lite project) are a prominent example. PRECISE started as a collaboration between a few 25-32m class radio telescopes in Europe to pinpoint repeating fast radio bursts (FRBs), exploiting the significant availability of observing time on these facilities. Exploiting just two ground station and the orbiting satellite Radioastron, the VLBI images of Popov et al. (2017) revealed a substructure in the scatter-broadened image of PSR B0329+54, constituting a new probe of the ionized interstellar material.

In most of these projects, high fidelity imaging and extreme sensitivities are not key features. The project science goals are well addressed with the simple detection of fringes on baselines of suitable length and simple modelling of the source structures. These can be relevant for the detection of compact features, pinpointing the presence and location of high brightness temperature components of non-thermal, coherent, or maser nature, and describing their evolution. In the present section, I will point out two such examples based on observations with the INAF radio telescopes.

The first example comes from the scientific field of microquasar studies. These accretion-powered binary systems can go into outburst and undergo a phase of ejection, with the launch of a pair of relativistic jets from the surroundings of the compact object (a black hole or a neutron star) member of the binary. Given the linear scales involved in these systems (the gravitational radius of a few solar mass black hole is of the order of $\sim 10\,\mathrm{km}$), the variability time scales are generally quite rapid (hours/days) allowing a "fast forward" view of the same processes occurring in radio loud active galactic nuclei. One of the most studied and brightest systems is Cygnus X-3 (Cygnus X-3), whose outbursts can reach up to a few Jy.

In Fig. 1 (Egron et al. 2017), we show the results of observations carried out during an episode of activity in 2016 by plotting the visibility amplitude of Cyg X-3 and of a reference source. The pattern exhibited on all baselines, irrespective of the orientation in the (u, v)-plane, and the lack of a matching evolution for the reference source, indicates that it was possible to trace genuine variability in the target. Moreover, by fitting a simple Gaussian model to the visibilities, it was possible to reveal an expansion of the emitting region at a rate of $0.075\,\mathrm{mas\,hr}^{-1}$, or $0.07(d/7\,\mathrm{kpc})c$, where d is the distance of the source.

Shifting to the extragalactic domain and to the connection to high energy observations, we can consider the case of the search for the counterparts to the unidentified gamma-ray sources detected by the *Fermi* Large Area Telescope (LAT). *Fermi* is regularly surveying the $E > 100$ MeV sky since 2008 and it has so far revealed over 7,000 sources (Ballet et al. 2023; Abdollahi et al. 2020). In every release of source catalogues, the vast majority of

[5] `http://www.ira.inaf.it/precise/`

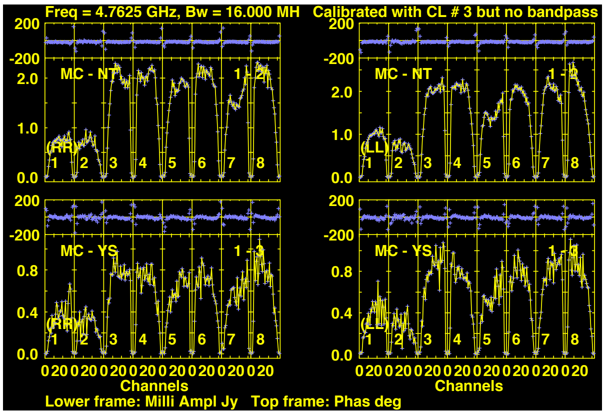

Fig. 2. Visibility phase and amplitude as a function of frequency for an eight minute scan on a candidate counterpart of one unidentified *Fermi* gamma-ray source on baselines from Medicina to Noto and Yebes, in the top and bottom pairs of panels, respectively.

objects are associated with blazars, with a significant population of pulsars and other galactic systems. However, a fraction of $\sim 30\%$ of unassociated sources has appeared consistently in the various catalogues. Unknown blazars likely constitute a significant number of these unidentified gamma-ray sources. However, pending a proper optical classification, it is difficult to tell them apart from other contaminating objects. The existence of a highly significant correlation between gamma-ray and radio emission (Ackermann et al. 2011) means that the counterpart of a weak gamma-ray source (as those that are entering the latest releases of the LAT catalogues) is likely to be also a weak radio source. Since weak radio sources have a high spatial density, finding one or more by chance in the localisation region of a gamma-ray source (which can have a radius of several arcminutes) prevents a statistically significant association between the gamma-ray source and the true counterpart. This can be significantly alleviated if we only focus on the objects with a compact (milliarcsecond) component, which are much less numerous than the whole population of radio sources. At the same time, the associated high brightness temperature is a strong indication of the blazar nature of the object, which therefore lends further physical support, not just statistical, to the association. Finding a compact high-brightness component is a task that can be effectively carried out with a two-station interferometer; additional stations and baselines provide redundancy and improve the reliability of the experiment, but significant conclusions can be drawn with very basic configurations (Fujinaga et al. 2016). We have undertaken one such campaign targeting 388 candidate counterparts of 157 gamma-ray unidentified sources, detecting ~ 90 VLBI sources. A sample case is shown in Fig. 2

4. Status of upgrades

Under the project "Enhancement of the Sardinia radio telescope for the study of the Universe at high radio frequencies", funding has been awarded to increase the performance of the Sardinia Radio Telescope not just as a stand-alone instrument but also as a part of a flexible array. In particular, given the success of the design, construction, and operation of the triple-band receivers on the KVN telescopes, and the science interest in the 20-90 GHz regime (Dodson et al. 2017), one of the work-packages of the project was dedicated to the purchase and installation of "Simultaneous microwave compact triple-band (CTR) receiving system for the three Italian radio telescopes (18-26; 35-50; 85-116 GHz)". Receiver specifications were given by INAF, design and construction were then performed by KASI. The CTR's have been delivered and are currently being installed on INAF telescopes. Significant mechanical work is also underway to adapt the structures of the radio telescopes for short-wavelength observations. In Medicina, replacement of the main reflector surface and installation of actuators is underway (as of September 2024); a new subreflector will also be installed as part of the ongoing refurbishment. Surface accuracy will be ≤ 60 and $40\,\mu$m for the main surface and the subreflector, respectively. In Noto, a new subreflector will be installed at the end of 2024. The surface accuracy of the mirror, better than $50\,\mu$m, will enable observations up to 100GHz. Taken together, these improvements will allow observations in the three bands, also simultaneously, and implementation of strategies such as source-frequency-phase-transfer. Global efforts in this area will enable a discovery potential with strong impact on a number of scientific fields ranging from fundamental cosmology and black hole physics to stellar astrophysics and studies of transient phenomena (Dodson et al. 2023).

At lower frequencies, the recent EVN Science Vision document (Venturi et al. 2020) has listed as top priority among upgrades of the network the development of broad-band EVN antenna/receiver systems that are compatible with SKA1-MID. This will increase sensitivity and provide the possibility of spectral index, polarisation, and Faraday rotation studies across a wide frequency range. INAF has thus started the procurement process for two C/X wideband receivers, operating in the $4.2 - 9.0$ GHz range, to be installed in secondary focus on the Medicina and Noto radio telescopes. The project is funded by the Italian National Recovery and Resilience Plan (PNRR) in particular to provide multi-wavelength support for the study of the physics of transients sources in the framework of the so-called Cherenkov Telescope Array Plus (CTA+) programme. The delivery of the units is expected by the end of 2025; a potential third unit for the Sardinia Radio Telescope could be considered as a follow up.

5. Outlook

The major upgrades described in the previous section are essential to improve the performance of the INAF telescopes both as standalone instruments and as elements of the EVN. In the coming years there will be many facilities coming online which will provide an immense number of targets across the bands of the electromagnetic spectrum and even studying other messengers, which are also discussed in other contributions at this conference. I would like to highlight in particular the following three cases:

- at very high energies (VHE), the Cherenkov Telescope Array Observatory (CTAO[6]) is planned to comprise 8 large-, 40 medium-, and 70 small-size telescopes over two sites in Chile and in the Canary islands. CTAO will provide unprecedented sensitivity at TeV energy, with an extremely broad science potential probing environments from black holes vicinity to large scale cosmic voids (Cherenkov Telescope Array Consortium et al. 2019). This design will be enhanced by up to 2 large and 5 small telescopes in the southern site, as part of the CTA+ programme mentioned above.
- after the detection of gravitational waves (Abbott et al. 2016), the identification of a short GRB as the electromagnetic counterpart to the GW 170817 event (Abbott et al. 2017), and the high angular resolution observations of the resulting relativistic jet (Mooley et al. 2018; Ghirlanda et al. 2019), there is an immense discovery potential for upgraded and next generation GW detectors, such as the Einstein Telescope (Maggiore et al. 2020)
- current and next generation of large volume detectors, such as IceCube and KM3NeT, allow the observation of neutrinos of cosmic origin; this has the potential to shed a new light on the most extreme particle acceleration processes in the Universe, requiring however a proper identification of the origin of the neutrinos and of their astrophysical characterisation (e.g. Nanci et al. 2022)

In all the above areas, and in many others, the number of sources of potential interest will be much larger than observable with full size arrays such as the EVN. Automated tools to prioritise the targets of interest will be fundamental. At the same time, the availability of a flexible facility able to screen the candidates of interest and narrow down further the most astrophysically worthwhile targets will be an essential asset. The possibility to monitor samples of sources for a systematic characterisation will also be useful in other field of interest for the Italian community, such as the study of maser sources or the search for gravitational lenses.

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[6] https://www.ctao.org/

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