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# Radio transients investigation with VLBI

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**Abstract.** The technique of Very Long Baseline Interferometry (VLBI) can provide accurate localization and unique physical information about radio transients. However, it is still underutilized due to the inherent difficulties of VLBI data analysis and practical difficulties of organizing observations on short notice. We present a brief overview of the currently available VLBI arrays and observing strategies used to study long- and short-duration radio transients.

**Keywords.** techniques: interferometric, radio continuum: general, stars: neutron

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## 1. Introduction

The Very Long Baseline Interferometry (VLBI; Walker, 1999) technique combines signals recorded at distant radio telescopes to achieve the highest angular resolution. A typical VLBI scale of 1 mas by definition corresponds to the linear size of 1 AU at the distance of 1 kpc and 1 pc at  $z \sim 0.05$ . The longer the baseline (distance) between the elements, the higher is the interferometer's angular resolution. Another way to increase angular resolution is to observe at a shorter wavelength. The measured interferometer response may be compared to a simple model in order to estimate the source size and flux density or, if measurements at many baselines are available, the source image may be reconstructed. The following features of VLBI may provide insights into the nature of various astrophysical transients:

- Superb angular resolution helps to measure the source size.
- Accurate localization of the radio emitting site is possible with VLBI.
- Imaging reveals the radio emitting region geometry (jet/shell/shock front) and allows us to follow its changes (proper motion, expansion).
- Full Stokes imaging may provide clues about the mechanism responsible for the transient's radio emission and, in the case of synchrotron transients, measure the magnetic field strength and structure.
- VLBI can separate the (small) transient source from the unrelated background emission that will be "resolved out", no matter how bright the background is.

In Section 2 we provide an overview of VLBI arrays performing astronomical observations. Section 3 lists the various types of radio transients and highlights selected observational

results. In Section 4 we discuss observing strategies suitable for transient source studies with VLBI. This is part two of the Workshop on radio transients. The first part of the workshop highlighting open questions in the transients science and how they may be addressed with non-VLBI techniques is presented by Anderson et al. (these proceedings).

## 2. An overview of VLBI arrays

The majority of arrays listed in this section offer at least part of their observing time as “open sky” (any astronomer can apply) and accept target of opportunity requests. A number of VLBI-capable telescopes are not part of these arrays: they are dedicated to either space geodesy (Schuh & Behrend, 2012) or deep space communication.

*The Very Long Baseline Array* (VLBA; Napier, 1994) is the first instrument fully dedicated to VLBI. It includes ten 25 m telescopes spread across the continental United States, US Virgin Islands and Hawaii. It operates full time at frequencies 0.3–96 GHz and is frequency agile, meaning that it may switch between the receivers in about a minute. The VLBA may be combined with the GBT 100 m, phased VLA 27x25 m, Arecibo 305 m, Effelsberg 100 m and/or the LMT 50 m to form *the High Sensitivity Array*.

*The European VLBI Network* (EVN; Zensus & Ros, 2015) is a collaboration of 10–15 diverse stations (including 60–100 m class telescopes). The number of participating stations depends on the observing band (1–43 GHz range) and station availability. Most EVN stations are not frequency agile. Observations are performed during three sessions per year. There is a limited number of pre-planned out-of-session observations. The EVN routinely includes stations from the regional VLBI arrays of Korea, Italy, China and Russia. The EVN may be requested together with the US stations as *the Global array*.

*e-EVN* is a subset of the EVN capable of real time correlation. This feature was specifically introduced for transient observations (Paragi, 2016). There is one 24 hr e-EVN observing session per month. Additional ToO observations are possible.

*The Global mm-VLBI Array* (GMVA; Hodgson et al., 2014) includes Effelsberg 100 m, GBT 100 m, NOEMA interferometer 7x15 m, VLBA and other mm-band telescopes in Europe. The observations are performed at 86 GHz during two sessions per year.

*The Event Horizon Telescope* (EHT; e.g. Lu et al., 2014) is a heterogeneous VLBI array observing at 230 GHz. The EHT has one observing session per year. The first open call for proposals for VLBI observations with the EHT together with the Atacama Large Millimeter/submillimeter Array is issued in 2018.

*RadioAstron* (Kardashev et al., 2013) combines ground stations with the 10 m radio telescope aboard the dedicated satellite in a high elliptical orbit (apogee – 326000 km) to form a Space-VLBI array. The observing frequencies are 0.3, 1.7, 4.8, 22 GHz. Observations at 22 GHz may reach a higher angular resolution (Gómez et al., 2016) than the EHT at 230 GHz. The first observation of a transient source with RadioAstron was the search for radio emission from SN2014J in M82 (Sokolovsky et al., 2014).

*The Long Baseline Array* (LBA; Edwards & Phillips, 2015) has its core stations in Australia (the largest are the ATCA interferometer 6x22 m, Parkes 64 m, and Tidbinbilla 70 m) but also provides intercontinental baselines to Hartebeesthoek 26 m in South Africa. This is the only VLBI array operating in Southern hemisphere. The observing frequency range is 1.4–22 GHz, but not all telescopes are available at all bands. The observations are conducted in 3–4 sessions per year. Test observations of GRB 080409 combining a few LBA stations with the telescopes in China and Japan in the e-VLBI mode were performed by Moin et al., 2016.

*The Korean VLBI Network* (KVN; Lee et al., 2014) consists of three dedicated 21 m stations capable of observing simultaneously at 22–43–86–130 GHz (Han et al., 2013, Rioja et al., 2015).

Possibilities of installing similar receiving systems at VLBI stations outside Korea are investigated by Jung et al. (2015).

*The VLBI Exploration of Radio Astrometry* (VERA; Kobayashi et al., 2003, Honma et al., 2012) array includes four 20 m telescopes in Japan. Its main focus is on parallax and proper motions measurements of Galactic maser sources. VERA observes at 6.7 (methanol), 22 (water) and 43 GHz (SiO masers) using the unique dual-beam system that allows simultaneous observations of the target maser source and an extragalactic continuum source serving as the phase calibrator.

*KaVa* combines KVN and VERA observing at 22 and 43 GHz (e.g. Hada et al., 2017).

*The Italian VLBI network* (Stagni et al., 2016) includes the Sardinia 64m and the two 32 m telescopes at Medicina and Noto. It is capable of observing in the 1–22 GHz range. Sokolovsky et al. (2013) searched for radio emission from SN2013ej in M74, using Medicina and Noto as a two-element VLBI.

*The Japanese VLBI Network* (JVN; Doi et al., 2006) combines VERA with other VLBI-capable telescopes including Usuda 64 m deep space communication antenna. No call for observing proposals from outside the JVN collaboration.

*The Russian VLBI Network “Quasar”* (Finkelstein, Ipatov, & Smolentsev, 2008) includes three 32 m telescopes in Svetloe, Zelenchukskaya and Badary observing in the 1–22 GHz range. The main focus of the network is on geodetic VLBI, but it also performs astronomical observations with EVN and RadioAstron. There is no open call for proposals, but proposals for astronomical observations submitted directly to the director may be considered.

*The Chinese VLBI Network* (CVN; Zheng, 2015) includes Tianma 65 m, Miyun 50 m, Kunming 30 m and the 25 m telescopes in Seshan and Urumqi. The network is used for spacecraft navigation, geodesy and astronomy. No open call for proposals.

Future facilities include *the East Asia VLBI Network* (Wajima et al., 2016, An, Sohn, & Imai, 2018) that will combine the national networks of China, Japan and Korea and the African VLBI Network (Gaylard et al., 2011, Copley et al., 2016).

*LOFAR* with its international stations is a VLBI array operating at frequencies  $\sim 50$  (Morabito et al., 2016) and  $\sim 150$  MHz (Varenius et al., 2016). Its angular resolution is comparable to that of connected interferometers operating at GHz frequencies.

*e-MERLIN* (Spencer, 2009) is a 7-station (including Lovell 76 m) array observing at 1–22 GHz providing baselines approaching those of regional VLBI arrays, while technically being a connected interferometer. It was recently used to study Galactic transients, among others, by Chomiuk et al. (2014), Healy et al. (2017).

### 3. Types of radio transients

Radio-transients can be divided in two broad classes (Bhat, 2011): *fast* transients likely related to neutron stars (and flares on low-mass stars) appear on sub-second timescales and *slow* transients related to various explosive astrophysical events that evolve on a timescale of days to months. The fast transients include:

The enigmatic *Fast Radio Bursts* (FRB; Petroff et al., 2016). Recent EVN+Arecibo observations allowed Marcote et al. (2017) to establish spatial coincidence of the repeating FRB 121102 with a persistent extragalactic radio source providing new constraints on the physical interpretation of the (repeating) FRB phenomenon. VLBI was used to investigate the suspected host of FRB 150418 (Giroletti et al., 2016, Bassa et al., 2016).

*Rotating radio transients* (RRATs; Karako-Argaman et al., 2015).

*Giant pulses from pulsars* (Mickaliger et al., 2012, Takefuji et al., 2016). The connec-

tion between the above three classes of fast transients is suspected (Popov, Postnov, & Pshirkov, 2018), but not yet established.

*Flare stars* produce outbursts of non-thermal radio emission (Osten & Bastian, 2008).

The following types of events may produce slow radio-transients:

*Supernovae* are the most studied class of radio-transients (Bartel, Karimi, & Bietenholz, 2017).

Over 50 radio supernovae are known (Lien et al., 2011). VLBI observations provide shell expansion velocity measurements independent of optical spectroscopy and reveal the mass-loss history of the progenitor star (e.g. Bietenholz et al., 2018).

$\gamma$ -ray bursts produce afterglows that may be detected (e.g. Moin et al., 2013, Michałowski et al., 2016, Nappo et al., 2017) and resolved (Pihlström et al., 2007) with VLBI.

*Novae and symbiotic stars* may appear as radio sources observable with VLBI, e.g. Sokoloski, Rupen, & Mioduszewski (2008), Giroletti et al. (2012). The source of radio emission may be the nova shell and possibly non-relativistic synchrotron-emitting jet (Rupen, Mioduszewski, & Sokoloski, 2008). VLBI imaging of the  $\gamma$ -ray emitting classical nova V959 Mon by Chomiuk et al. (2014) suggested the synchrotron emission is produced at the interface between the fast polar outflow and the slow thermally-emitting outflow escaping the binary system in the orbital plane. Understanding the structure of the shocks in nova ejecta is important as the shocks are found to be responsible not only for  $\gamma$ -ray, X-ray and radio (Weston et al., 2016) but also contribute significantly to optical emission of novae (Li et al., 2017).

*Dwarf novae* may also be transient radio sources (Körding et al., 2008). The mechanism of their radio emission is unclear.

*Tidal disruption events (TDE)* in galactic nuclei, such as Swift J164449.3+573451, may be detected in radio. This is interpreted as an evidence of a relativistic jet forming from the matter lost by the disrupted star (Berger et al., 2012). Surprisingly, Yang et al. (2016) were able to place the upper limit of 0.3 c on the ejection speed in this source.

*Active galactic nuclei (AGN)* are known sources of variable radio emission and may appear as transients rising above the threshold of previous radio observations.

*Microquasars* (Gallo, 2010) can flare by several orders of magnitude within days. Some of them are sources of radio emission also in the quiet state. Recent VLBI results include observations of the expanding jets in XTE J1908+094 by Rushton et al. (2017) and the giant flare of Cygnus X-3 by Eggen et al. (2017).

*Maser sources* associated with star forming regions and late-type stars may show flares by orders of magnitude (Matveenko, Graham, & Diamond, 1988, Rudnitskij et al., 2007).

*Other events.* Sometimes, even a combination of radio and multi-wavelength observations is not sufficient to determine the nature of a transient (e.g., Hyman et al., 2005). Such cases demand detailed investigation and can potentially lead to the understanding of novel astrophysical phenomena.

#### 4. Observing strategies

While, in principle, wide-field VLBI imaging (Morgan et al., 2013) may be used to search for slow transients, the most popular observing strategy so far is the *follow-up* of transients discovered at other wavelengths. The two key points to consider when planning observations are the array sensitivity and the possibility of rapid response. A sensitive array includes big dishes and is capable of performing phase-referencing observations. Phase referencing makes the integration time (and hence the sensitivity) limited by the experiment duration rather than the atmosphere coherence time. Dedicated full-time arrays like VLBA and KVN, as well as ad hoc arrays including only two to three telescopes can respond within days to a trigger (if the corresponding observing proposal is already

in place). VLBI observations often rely on the Earth rotation to probe more spatial frequencies as the array elements move and improve the resulting image. This technique cannot be used for rapidly evolving transients. A “snapshot” observation will result in a degraded image (compared to a “full track” image) or may be suitable only for modeling, not image reconstruction. The quality of a snapshot image may be improved by adding more elements to the array. Another point to consider for Galactic transients is their expected angular size. An explosive transient may take hours to days to reach the angular size of a few mas and become “too big” to be observed with VLBI. Unless it has a structure on smaller angular scales, it may be completely “resolved-out” by the interferometer. The choice of observing frequency is less important than other considerations when observing synchrotron transients as they tend to have nearly flat spectra.

With the exception of repeating events like FRB 121102 or the ones possessing a long-term “afterglow”, triggered observations of fast transients are not possible. Instead, the fast transients have to be found in the same data used to investigate them. Raw VLBI data (before being averaged in time and frequency by the correlator) are suitable for a fast transient search (Liu et al., 2018). The V-FASTR project is running a commensal survey for fast transients at the VLBA (Wayth et al., 2011, Wagstaff et al., 2016). One interesting possibility is shadowing a large single-dish telescope with a VLBI array, extending the observing strategy of Marcote et al. (2017) to a blind survey.

*The Square Kilometre Array* (SKA) will detect transients in real time providing targets for a VLBI follow-up. Including the phased SKA into an existing VLBI network will boost the network sensitivity by more than an order of magnitude. This will enable detailed VLBI studies of the classes of sources that are now just barely detectable. Studies of classical VLBI targets such as AGNs will also benefit from access to a larger sample of observable sources and its extension towards low-luminosity objects. An overview of VLBI prospects for the SKA is presented by Paragi et al. (2015), while Corbel et al. (2015) highlights perspectives for Galactic synchrotron transient studies.

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