whose main directions for science archives can be summarised as "findable, accessible, interoperable, re-usable" (FAIR). A better interface would make VLBI data more re-usable, saving the effort that EVN users make regularly to derive publishable data from the archive. Open science aims at making it easier and more transparent to verify and reproduce the data that led to a scientific conclusion. Thus, it could be considered beneficial if the EVN could offer a method to associate results from datasets (including intermediate steps, storing scripts and calibration) with publications. For these reasons, there is a pressing need to make the archive more integrated with VO methods, and also to provide technology and incentives that allows users to document their data processing efforts.

- The EVN should welcome the development of a data processing platform in common with other major facilities (e.g. VLBI capabilities in CASA), focusing on ways to define and maintain high level scripts and recipes that can also be used to drive observatory side computing. This recommendation is independent of the need of an inventory of the algorithmic processing functionality for all of the EVN science cases. Such efforts would align quite well with the big data challenges that the community is facing with the advent of the SKA. Presumably, SKA users will have to rely on observatory-side computing for anything but their image analysis. Similar data processing recipes would then have to be manipulated on-line for controlling the SKA or SKA data centre compute clusters; note that using the same recipes locally and interactively is very important for prototyping and optimising. In this sense, it must also be ensured that the existing archive is interoperable with future CASA processing.

7.3 Concluding remarks

The previous chapters have demonstrated the very broad range of science the EVN addresses. The distribution of the top-100 most cited publications with EVN data (including global VLBI and multi-messenger papers) per research area, organised based on which chapter they would fit the most, and the citation history to these papers have been shown earlier in this document in Fig. 1. This demonstrates how the EVN evolved to become a multi-disciplinary facility during its 40 years of existence. Almost 2/3 of the most cited papers appeared after 2000, and they show a much more balanced distribution between science areas. Past technological advances made this possible: at the end of 1990s and early 2000s the EVN introduced the Mark4 and then the Mark5 systems, allowing high data rates of 512-1024 Mbps, which resulted in a great increase in sensitivity. The EVN MkIV Data Processor and later the EVN Software Correlator at JIVE (SFXC) became operational, and the EVN Archive came online with pipeline data products.

The unique capabilities of the network resulted in high impact discoveries. The very sensitive short spacings compared to other VLBI networks were crucial to show that low-power radio galaxies can also produce relativistic jets (Giovannini et al. 2001), and that CSOs represent a class of very young radio sources (Owsianik & Conway 1998). The very sensitive baselines, especially when combined with sensitive telescopes in other networks have been fundamental to e.g. detecting outflows of neutral atomic hydrogen (H I) from active galactic nuclei, demonstrating jet-driven AGN feedback (Morganti et al. 2013). The advance in galactic science is related to the start of maser astrometry programmes. Observing the 6.7 GHz transition of the CH_3OH line (for a long time unique to the EVN), allowed studies of star formation and Galactic structure (e.g. Rygl et al. 2010, 2012). The introduction of real-time e-VLBI during the mid-2000s brought forward another revolution. The scope for transient science has increased and a number of high impact results followed, like revealing the likely origin of γ-rays in classical novae (Chomiuk et al. 2014), and eventually the first

10-mas scale localisation of FRB 121102, providing the ultimate evidence that fast radio bursts are indeed extragalactic and may reside in extreme astrophysical environments (Chatterjee et al. 2017; Marcote et al. 2017). The final peak marks the start of the gravitational-wave astronomy era as well (see Fig 1).

As we have seen earlier in this document, the scientific potential of very high angular resolution radio astronomy is still enormous. Emerging new facilities bring forward new synergies and actually strengthen the impact the EVN will have. The science case of the SKA as well as forthcoming facilities in other bands (e.g. CTA and ELT) overlaps with that of the EVN, but some of the highest priority science cases actually do depend on complementary VLBI observations. Furthermore, SKA-VLBI will bring forward new possibilities in the field of VLBI astrometry and in the study of the faint radio source populations[5]. *Gaia* is providing stellar astrometry comparable to what can be achieved with VLBI, but aligning the *Gaia* frame with ICRF and by studying individual sources brings forward interesting new science cases (e.g. Paragi et al. 2016; Kovalev, Petrov and Plavin 2017; van Langevelde et al. 2019).

In summary, the next revolution will be a very sensitive, broad-band, flexible EVN with a wide range of *uv*-spacings and archival/user services compatible with other instruments in the era of VO archives. This will also bring forward exciting synergies for the science addressed by future multi-messenger instruments. A technology roadmap for the EVN will detail the steps necessary to achieve the exciting science described in this document.

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Figure 7.3: THEZA is a space mm-VLBI concept to directly image supermassive black holes in the nearby Universe, and massive black hole binaries up to cosmological redshifts (Gurvits et al. 2019). Figure credits: BH simulations – Monika Mościbrodzka et al. (2014) & Freek Roelofs. Beabudai Design.

A. Appendices

A.1 Present and future VLBI arrays and other radio facilities

In the following we aim to capture the trajectory of technical capabilities of major radio astronomy facilities around the world and other instruments in other wavebands that are expected to play a major role in the evolution of VLBI science during the first half of the 2020s.

A.1.1 EVN and JIVE

The European VLBI Network (EVN) was formed in 1980 by leading radio astronomy institutes in Europe (see review by Schilizzi 1995). Today it is a joint facility of independent European, African, Asian, and North American radio astronomy institutes with 32 telescopes that cover a broad range of wavelengths from 92 cm to 0.7 cm. The EVN offers an angular resolution down to (sub-)milliarcsecond in the main observing bands 21/18 cm, 6/5 cm and 1.3 cm. It is the most sensitive regular VLBI array that employs a fully open skies policy. The total aggregate bit rate per telescope has increased from the initial 4 Mbit s^{-1} to 2 Gbit s^{-1} in the past four decades. Its collecting area is comparable to that of SKA1-MID.

It operates in three major observing sessions through the year, but a limited number of out of session observations are carried out to support Target of Opportunity (ToO) or other multi-band observing campaigns, and until quite recently, space-VLBI experiments carried out jointly with the *RadioAstron* mission (concluded in 2019). In addition to that, there are 10 days a year dedicated to real-time electronic-VLBI (e-VLBI) observations.

The EVN has a governing body formed by the Consortium Board of Directors (CBD), a Technical and Operations Group (TOG) and a time allocation committee referred to as Programme Committee (PC). The chairs of the two latter groups report to the CBD every 6 months. Beyond the chairs of the three groups mentioned before, there is a fourth officer, the scheduler, who is in charge of scheduling all EVN observations and coordinates with other arrays, like the global VLBI array, the GMVA and the IVS. The CBD is formed by the directors of the EVN institutes who set the technological and

Chapter image credit: The freshly refurbished and modernised 32m telescope in Irbene, Latvia during the inauguration ceremony in 2015. Photo by Zsolt Paragi.

scientific strategy of the network for the future. The TOG is in charge of the operations and technical developments of the network. It is composed by VLBI friends at the stations and personnel at the correlators. The composition of the PC is determined by the CBD who invites experts in different fields both from EVN and non-EVN institutes.

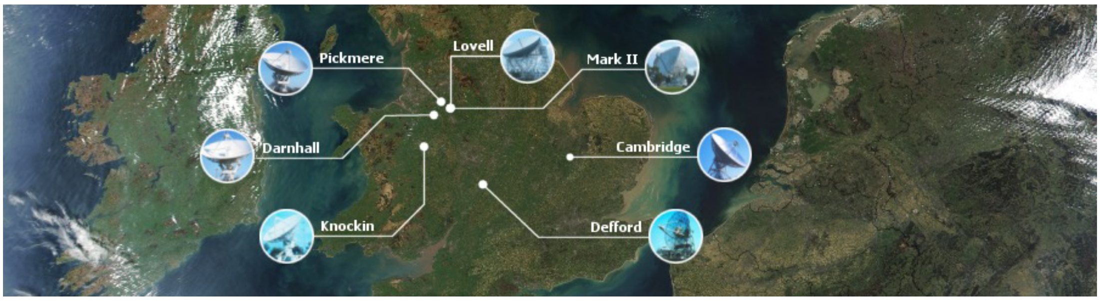
The EVN science is very broad, with the highest impact in the fields of radio galaxies, AGN, and studies of Galactic sources of methanol masers. The latter was a unique EVN capability at 5 cm until the mid-2010s (Zensus & Ros 2015). Since the development of e-VLBI, transient phenomena have become a very competitive EVN research field. The latest highlights are the milliarcsecond localisation of the repeating fast radio burst FRB 121102 (Chatterjee et al. 2017, Marcote et al. 2017), the EVN and the VLBA (see below) monitoring of a tidal disruption event in a nearby galaxy (Mattila et al. 2018), and the detection of the first electromagnetic counterpart to a gravitational wave source GW 170817, a merger of binary neutron stars (Abbott et al. 2017). Global VLBI data on the radio afterglow provided key insights to the nature of the explosion (Ghirlanda et al. 2019).

The current members of the EVN (various levels of membership). Image: `http://evlbi.org`.

From the 1980s until the end of 1990s the EVN data were correlated at the Max Planck Institute for Radio Astronomy (MPIfR) in Bonn. In 1993 the EVN established the Joint Institute for VLBI in Europe (JIVE) in Dwingeloo, the Netherlands (formally as a Dutch foundation). A new, broad-band, 16-station MarkIV correlator began operations in 1999. In 2015 JIVE became a new legal entity, a European Research Infrastructure Consortium (ERIC); first (and only so far) of its kind in the field of astronomy. The main mission of JIVE is to support EVN operations, support the EVN users, as well as develop next generation VLBI correlators and the VLBI technique in general. JIVE has led the e-VLBI developments in the early 2000s, and real-time e-EVN observations have been offered routinely since 2006 (Szomoru 2008). The MarkIV correlator has been replaced with the EVN Software Correlator (SFXC; Keimpema et al. 2015), which is very flexible for special VLBI applications (wide-fields of view, pulsar binning observations etc.). The network support includes regular network monitoring experiments, rapid (ftp-)fringe tests during observing sessions, and additional tests for new hardware/firmware and aspiring new EVN members. The user support is offered for all stages of the research from developing a proposal idea through scheduling observations to help with data processing. JIVE maintains the EVN Archive, where all data become available following a proprietary period of one year (half a year for ToOs). All the data are pipeline processed (Reynolds, Paragi & Garrett 2002); the latest version of the pipeline script makes use of ParselTongue, a scripting environment developed at JIVE (Kettenis et al. 2006).

The EVN has grown considerably during the past decade. The possible evolution of the EVN with regards to technologies and expansion by including new antennas, as well as the future possible relations with SKA1-MID and as a standalone very wide-band VLBI array on the long run are described later in the document.

A.1.2 *e*-MERLIN



The distribution of the *e*-MERLIN telescopes in the UK. Image: `http://www.e-merlin.ac.uk/`.

In the UK, *e*-MERLIN with baselines ranging from 10 km to 220 km in length provides imaging capability covering a unique range of spatial scales, overlapping with the JVLA (see later) at lower angular resolution and extending up to the EVN with ultimate angular resolution < 1 mas. In addition to being a dedicated compact VLBI imaging array with sub-arcsecond angular resolution and μJy sensitivity, *e*-MERLIN is used in combination with the JVLA for increased angular resolution whilst retaining superb surface brightness sensitivity—and in combination with the EVN to provide short-spacing coverage to the EVN to both place the mas-scale VLBI images in context with regard to any extended radio structure present. Also, *e*-MERLIN has the capability to directly image such structures at intermediate angular resolutions through integrated high fidelity combination imaging over a range of angular resolutions and spatial scales between 5 mas and 150 mas, providing a unique region of radio imaging capabilities at centimetre wavelengths which have not been available before. This new capability will enable transformational scientific investigations of planetary formation around nearby young Galactic stars at the shorter wavelengths, and probe detailed AGN jet feedback and its interplay with surrounding host galaxies at higher redshifts, including the role of feedback in those systems with intense nuclear starbursts at longer wavelengths where the superb surface brightness sensitivity of EVN+*e*-MERLIN combined can detect and image this steep-spectrum emission to high redshifts.

The additional short baselines for high fidelity imaging at angular resolutions between *e*-MERLIN and the EVN has long been promised and is now finally achieved. Recent tests have confirmed that data for the *e*-MERLIN antennas can now be output in VLBI Data Interchange Format (VDIF) and stored locally at JBO enabling 2×128 MHz of data (e.g. both circular polarisation states) for 6 *e*-MERLIN antennas to be recorded for correlation with other EVN telescopes at JIVE. In March, 2018, a successful test demonstrated interferometric fringes between Cambridge and Effelsberg (Germany), later followed by participation of other *e*-MERLIN outstations in e-VLBI mode with the EVN in September 2018.

The addition of telescopes at Goonhilly Earth Station in Cornwall to *e*-MERLIN at both L- and C-Band is planned. The benefit of this additional antenna site to *e*-MERLIN and to the integrated EVN+*e*-MERLIN has been well described by Heywood et al. (2011) and Kloeckner et al. (2011) respectively. For *e*-MERLIN in standalone mode Goonhilly nearly doubles the angular resolution in fields at northern declinations, and for equatorial fields significantly circularises the beam and improves image fidelity. In combination with the EVN and *e*-MERLIN, Goonhilly adds additional intermediate spatial frequency coverage to ensure seamless integration of *e*-MERLIN with the EVN over a wide declination range, which will be enhanced still further in the southern skies by the addition of telescopes in the AVN in the next few years. Initial data tests to Goonhilly are expected in the early 2020s.

A.1.3 CVN

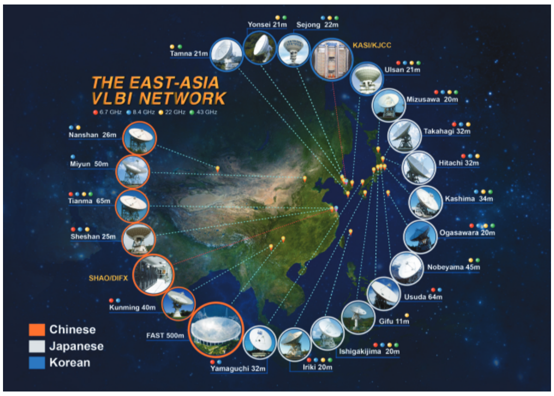
The proposal to build the Chinese VLBI network (CVN) was first raised by Prof. Shuhua Ye of the Shanghai Astronomical Observatory in the 1970s (Ye, Wan & Qian 1991). The first VLBI station comprising of a 25 m telescope was completed in 1986 in Sheshan, Shanghai. The current CVN includes 5 antennas (Seshan 25 m, Urumqi 26 m, Kunming 40 m, Miyun 50 m and Tianma 65 m) and one data processing centre in Shanghai. The longest baseline is 3249 km between Shanghai and Urumqi telescopes. It is one of the few VLBI networks having very short baselines ($\sim$ 6 km between Sheshan 25 m and Tianma 65 m), which is essential for imaging extended emission structures.

The CVN was initially designed for geodetic and astrophysical observations. A notable application of the CVN is the tracking of the Chinese lunar satellites, offering accurate position measurements beyond the reach of other techniques. In the latest *Chang′E-3* mission, the time delay between data acquisition at the telescopes and orbit measurement at the data analysis centre is less than one minute. A relative position accuracy as good as 1 m between the *Chang′E-3* rover and the lander was achieved in post-correlation data analysis (Tong, Zheng & Shu 2014). The CVN is also expanding its applications in astrophysics and astrometry (An et al. 2012; Shu et al. 2017).

The Seshan 25 m and Urumqi 26 m joined the EVN since 1993 and 1994, respectively. The two Chinese telescopes importantly contributed to the increase of the EVN baseline from $\sim$ 3000 km to $\sim$ 9000 km in the east-west direction, improving the angular resolution of the EVN by a factor of three. The Kunming 40 m joins the EVN observations when requested. The Tianma 65 m has participated in EVN observations since 2014. It significantly increases the longest-baseline sensitivity, creates the opportunity of detecting weak sources, and also allows for super-resolution imaging (An, Sohn & Imai 2018).

A.1.4 EAVN

The EAVN plays an important role in promoting regional VLBI cooperation, including the major facilities of the CVN, the Korean VLBI Network (KVN), the Japanese VLBI Network (JVN) and VLBI Exploration of Radio Astrometry (VERA). The EAVN consists of 21 radio telescopes distributed over a maximum baseline of $\sim$6000 km, offering a highest resolution of 0.5 mas at 22 GHz. The first EAVN observing session started in the second half of 2018. The operational frequency bands are 22 and 43 GHz, and will be expanded to cover lower frequencies in the near future.



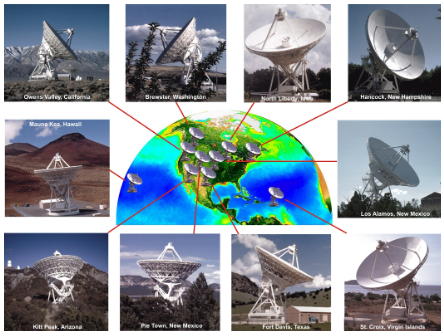
The East Asia VLBI Network (EAVN). Image from An, Sohn & Imai (2018).

The EAVN includes 21 geographically distributed telescopes with sizes ranging between 11 m and 500 m, with baselines ranging between 6 to 5000 km, typically operational in the 2.3 to 43 GHz radio frequency range. More telescopes (e.g., under-construction 110 m telescope in Xinjiang, China, and the planned Thailand VLBI network) in the near future will further broaden the science capability of EAVN (An, Sohn & Imai 2018).

New facilities and development for the EAVN are currently ongoing. The Five-hundred-meter Aperture Spherical radio Telescope (FAST 500 m; Nan & Zhang 2017) in southwest China witnessed the discovery of a dozen new pulsars since its inauguration in 2016 September. A 110 m radio telescope (QTT) has been funded for construction in Xinjiang, China. It will be the largest fully steerable single-dish radio telescope operational in the 0.15-115 GHz bands. The FAST and QTT can enormously increase the sensitivity of the global VLBI. The planned Thailand VLBI Network will join the EAVN on completion. The connection of the EAVN and the Long Baseline Array in Australia forms a transcontinental Asia-Oceania VLBI network at centimetre and long millimetre wavelengths (Li et al. 2018). The Korean and Japanese telescopes have been upgrading their millimetre-wavelength equipment to enhance the observational capability of the global mm-wavelength VLBI network, and especially the EHT, that has recently imaged the event horizon of the central supermassive black hole in our Galaxy.

A.1.5 VLBA

The Very Long Baseline Array (VLBA; Napier et al. 1994) was inaugurated on Aug 20, 1993 as a stand-alone dedicated VLBI array. In the 25 years since, many aspects of the VLBA have been upgraded, including installation of a $\lambda 3$ mm receiver, widebanding of the $\lambda 6$ cm receiver to span the entire 4 to 8 GHz octave, and bandwidth increase from 16 MHz to 256 MHz per polarisation, with a further doubling to be complete by early 2019. The VLBA's dedicated hardware correlator was upgraded to a software correlator based on the DiFX software correlator (Deller et al. 2007), and shortly thereafter DiFX2 (Deller et al. 2011). DiFX2 supports geodetic processing, pulsar binning, massive-multi-phase-centre correlation (enabling survey observations), and frequency matching capability (allowing flexible correlation of antennas observing with mismatched frequency bands).



The VLBA consists of 10 identical 25 m dishes spread across the continental US, Hawaii, and US Virgin Islands and is operated by NRAO from Socorro, NM. Image: AUI/NRAO

The VLBA routinely observes as part of a larger network. Four such networks are, the IVS), the EVN, the GMVA, which includes ALMA, and the HSA. The HSA is coordinated by VLBA staff and includes the VLBA, Effelsberg, Greenbank, JVLA, and Arecibo.

To illustrate some of the key capabilities of the VLBA, three recent results are highlighted here. Excellent astrometric precision over 12 years demonstrated relative motion between two black holes (Bansal et al. 2017). The results confirm the existence of supermassive binary black holes with a separation small enough to imply coalescence; objects such as this are likely targets for low frequency gravitational wave detectors such as *LISA*. VLBA relative astrometry of a water maser has reached a precision suitable for direct parallax measurements directly across the Milky Way (Sanna et al. 2017). This particular result was preceded by numerous other VLBA measurements of methanol maser positions and velocities, allowing the creation of a map of the galaxy, demonstrating a barred-spiral plan and refining the Oort constants in the process (Reid et al. 2014). The scheduling and frequency agility of the HSA, combined with imaging and astrometric performance, demonstrated that the radio emission from neutron star merger event GW 170817 arose from a relativistic jet (Mooley et al. 2018). Jet parameters made from these measurements provide substantial evidence that short gamma-ray bursts are indeed neutron star mergers.

New VLBA capabilities will continue to be developed in the 2020s. A VLBA techical roadmap is under development which outlines a series of upgrades that will transform the instrument. The roadmap includes:

- Wider bandwidths: The goal is to increase bandwidth by another factor of 16, bringing it to 4 GHz per polarisation, or a factor of four in raw sensitivity.
- New and upgraded receivers: A top priority is a Ka-band receiver, operating in the 27 GHz to 40 GHz range. If deployed, this receiver would include a dual-frequency capability, allowing simultaneous observation at X-band (8 GHz to 9 GHz) and Ka-band.
- Real-time correlation: Options for deployment of high-speed fiber-optic networks to each VLBA station are being explored. In addition to offering new user capability, such an option would simplify VLBA operations and would increase its interoperability with other VLBI arrays around the world.

A.1.6 LBA

The Long Baseline Array is the only astronomical VLBI network in the Southern Hemisphere and is operated as a National Facility by CSIRO Astronomy and Space Science in collaboration with the University of Tasmania, Auckland University of Technology and Hartebeesthoek Observatory. The LBA observes about 30 days per year with time being awarded by the Australia Telescope National Facility Time Allocation Committee (ATNF TAC) based purely on scientific merit and applications are open to all.

Comprising a core of 7 stations (ATCA, Parkes, Mopra, Hobart, Ceduna, Warkworth and Hartebeesthoek) supplemented by up to 3 more at certain frequencies and with some restrictions on availability (Katherine, Yarragadee, Tidbinbilla), the LBA also frequently operates in conjunction with telescopes of the EAVN and EVN (in particular the co-longitudinal Kunming and Tianma telescopes in China). A joint application procedure with the EVN already exists, with plans to unify this further so that only a single time request and TAC review will be required in order to secure resources on both arrays, in a manner analogous to the system currently employed for the Global VLBI Network.

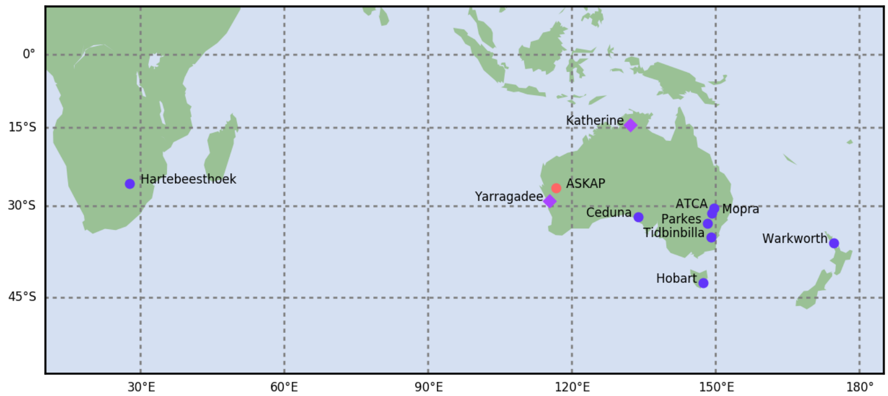
The LBA is heterogeneous in nature with telescopes ranging from 12 m to 64 m and including one phased array. The inclusion of the Parkes 64 m and ATCA phased array (5×22 m), means that the array has good sensitivity, especially at frequencies below 10 GHz. Data rates up to 1 Gbps are currently supported with plans to increase this to 4 Gbps in the near future. Standard observing bands are 1.4, 1.8, 2.3, 5.4, 6.6, 8.4 and 22 GHz, but observations up to 34 GHz are possible with a subset of the array. The ATCA is operational up to a maximum of 115 GHz and is occasionally used in conjunction with the KVN or other high-frequency telescopes at frequencies above 35 GHz.

The Southern Hemisphere location of the LBA provides it with a special niche for observing southern sources in general, with particular advantages for high precision astrometry of objects in the region of the Galactic centre and Magellanic clouds (e.g. Krishnan et al. 2017; Miller-Jones et al. 2018). LBA telescope positions are known to sub-centimetre accuracy (many participate in the IVS Geodetic network) and the high quality timing systems available allow for very accurate astrometry. Although only a part-time array, observing sessions are planned with consideration for the requirements of ongoing parallax campaigns. Target of opportunity and rapid response observations are also supported on a best-efforts basis.

LBA data are correlated on the Magnus supercomputer at the Pawsey Centre for SKA Supercomputing using DiFX2 (providing essentially all the capabilities described in the VLBA section above). The 1500 nodes available on this shared resource provide an essentially unlimited correlator resource allowing extremely computationally demanding correlation modes to be supported.

Efforts are currently under way to enhance the sensitivity of the array. The newly deployed

Ultra Wideband Low (UWB-L) receiver at Parkes will have a native VLBI mode enabled in its GPU post-processing backend, capable of providing up to 2 GHz of bandwidth in VDIF format at frequencies between 700 MHz and 4 GHz. A planned Ultra Wideband High (UWB-H) receiver will make up to 4 GHz of bandwidth availabale between 4 and 25 GHz (expected on a timescale of a few years). The ATCA is also planned to receive an upgraded GPU correlator which will include a tied array capable of delivering up to 2 GHz of bandwidth in any of the ATCA's available receiver bands (this is almost continuous from 1 to 115 GHz). Telescopes operated by University of Tasmania and Auckland University of Technology are increasing their potential recording bandwidth with the deployment of DBBC3 and Flexbuff recorders, with 4+ Gbps likely to be available in the near future. A currently unfunded, but eagerly anticipated, enhancement is the development of a tied-array system at ASKAP which will create a 36×12 m VLBI element in Western Australia (some 5000 km from Parkes) at frequencies between 700 MHz and 1.6 GHz.



The locations of the LBA stations, distributed across the Southen Hemisphere from South Africa, through Australia to New Zealand. Image: `https://www.atnf.csiro.au/`.

A.1.7 The Global mm-VLBI Array and the Event Horizon Telescope

The Global Millimeter VLBI Array (GMVA) combines the European telescopes capable of 3mm-VLBI, the VLBA, the GBT, the KVN, the GLT, and beam formed ALMA; additionally 7-mm observations are performed for the equipped telescopes, with the addition of the Noto telescope. The GMVA operates under a Memorandum of Understanding between the partner institutions (see https://www3.mpifr-bonn.mpg.de/div/VLBI/globalmm/mou.html), and has also developed an ALMA concept (completed in 2016) to observe jointly after the ALMA Phasing Project provided green light for joint observations, which are now possible since 2017. Data are post-processed at the DiFX correlator cluster at the Max-Planck-Institut für Radioastronomie. The GMVA offers 3-4 times more sensitivity and a factor of 2 higher angular resolution than the stand-alone VLBA or the HSA. For logistical reasons GMVA observations cannot be "dynamically" scheduled and are scheduled in time blocks, which combine the individual proposals and optimise the use of the available observing time and recording media. The GMVA block observations are scheduled in special observing sessions, performed twice per year, typically in spring (April, May) and autumn (September, October). The actual duration of each session depends on proposal pressure and ranges between 2 and 5 days. Proposal submission for the GMVA is synchronised with the VLBA. Proposals are reviewed by the NRAO and the programme/time allocation committees of the participating observatories. Recent scientific highlights of the GMVA are the studies of the jet in M 87 paving the way for the Event

Horizon Telescope (EHT) (Kim et al. 2018) and the best imaging results to date of the Galactic Centre (Issaoun et al. 2019).

The EHT is an experimental VLBI array that comprises millimetre- and submillimetre-wavelength telescopes spread across the globe. The nominal EHT angular resolution is 25 μas at 1.3 mm observing wavelength. This is sufficient to resolve the two most nearby supermassive black hole candidates on spatial and temporal scales that correspond to their event horizons. The EHT scientific goals therefore are to probe general relativistic effects in the strong-field regime, and to study accretion and relativistic jet formation on event horizon scales. The key developments that have facilitated the robust extension of the VLBI technique to EHT observing wavelengths were high-bandwidth digital systems that process data at rates of 64 gigabit/s, exceeding those of currently operating cm-wavelength VLBI arrays by more than an order of magnitude, development of phasing systems at array facilities, new receiver installation at several sites, and the deployment of hydrogen maser frequency standards to ensure coherent data capture across the array. The recent publication of the first image of the shadow of a black hole in the heart of Messier 87 is one of the scientific highlights of VLBI science in the recent years (EHT Collaboration et al., 2019a, 2019b, 2019c, 2019d, 2019e, and 2019f).

A.1.8 JVLA and ngVLA

The Jansky Very Large Array (JVLA) is a connected-element radio interferometer array of twenty seven 25 m antennas operating at frequencies between 74 MHz and 50 GHz. While first available for science in the early 1980s, it continues to deliver spectacular scientific results, with users showing increased interest in triggered observations and astronomical transients, such as the localisation of the repeating FRB 121102 (Chatterjee et al. 2017; Marcote et al. 2017) and the detection of the radio afterglow of the neutron star merger, GW 170817 (Alexander et al. 2017). A phased-array sum can be formed and recorded as a VLBI element with an equivalent diameter of 130 m.

Two VLA antennas on the Plains of San Agustin, New Mexico. Image: AUI/NRAO.

Three major initiatives are underway at the VLA. The first is the VLA Sky Survey (VLASS), which is the highest resolution survey ever undertaken of the radio sky. The survey is being conducted at a frequency of 3 GHz in the B-configuration, giving an angular resolution of 2.5 arcseconds. The survey began in September 2017 and will be carried out in three epochs over seven years. It will use $\sim$ 5500 hours of VLA observing time. The survey will identify numerous sources worthy of follow-up with VLBI observations. Additional details on VLASS can be found at https://science.nrao.edu/science/surveys/vlass (Lacy et al. 2019). The second initiative is a programme to improve the 40+ year old infrastructure at the VLA site. The programme entails replacing heavy vehicles, track maintenance equipment, rail track, machine shop mills and lathes, building roofs, and the overhead crane in the Antenna Assembly Building. The programme's main objective in 2018 is to replace the VLA's electrical switchgear and backup generator. The third initiative is the development of a scientific and technical concept for a next generation VLA (ngVLA) for the US Astro2020 Decadal Survey. The ngVLA (ngvla.nrao.edu) is envisioned to have 10 times the sensitivity and 10 times the angular resolution of the VLA. It will be located in the southwest US centred on the present location of the VLA, and operate over a frequency range of 1.2-116 GHz. The ngVLA concept includes a long baseline component ($\sim$ 1000 km), and incorporates transformative technology relevant to VLBI, such as LO and time distribution, wideband feeds, and economic cryogenic systems. If the concept is endorsed at the U.S. Decadal Survey, we envision a detailed design and development phase in 2020-2024 followed by a construction phase in 2025-2034.

Community enhancements of the VLA also continue to be made. In collaboration with NRAO, the US Naval Research Laboratory (NRL) expanded its 360 MHz VLITE commensal observing system (Clark et al. 2016) from 10 to 16 VLA antennas. The University of California Berkeley is leading the installation of realfast (Law et al. 2018), a commensal, real time, transient detection system on the VLA. The University of New Mexico is leading the eLWA project, which connects its 74 MHz Long Wavelength Array (LWA; Taylor et al. 2012) with the VLA.

A.1.9 LOFAR

The LOw Frequency ARray (LOFAR; van Haarlem et al. 2013) is an interferometric array of dipole antenna stations centred in the Netherlands and scattered throughout Europe. LOFAR operates from the ionospheric cutoff of the "radio window" near 10 MHz up to 240 MHz. In total, 51 stations are currently operational. 38 of them are located in the Netherlands and spread out from a core near the village of Exloo, in the northeast of the country. Additionally, the system includes 13 international stations, which are located in the United Kingdom (1), France (1), Sweden (1), Germany (6), Poland (3), and Ireland (1). To date, funding has been secured to build additional stations in Latvia (1) and Italy (1) in the next few years.

The layout of LOFAR, comprising 51 operational stations and the soon-to-be-built stations in Latvia (near Irbene) and Italy (near Medicina).

To cover the very broad frequency window, the system adopts different and relatively low-cost antenna designs. Specifically, the Low Band Antennas (or LBAs) cover the range between 10 to 90 MHz, while the High Band Antennas (or HBAs) span 110 to 240 MHz. HBAs and LBAs are grouped together to form a LOFAR station.

Left: a LOFAR LBA dipole. The inset images show the molded cap containing the Low Noise Amplifier electronics as well as the wire attachment points. *Middle*: a LOFAR HBA tile, clustering 16 antenna elements together. *Right*: layout of a LOFAR station (credit: G. B. Gratton/STFC).

LOFAR stations have no moving parts and, due to the effectively all-sky coverage of the component dipoles, the system has a large field of view. At station level, the signals from individual dipoles are combined digitally into a phased array. Electronic beamforming techniques make the system agile and allow for rapid repointing of the telescope as well as the simultaneous observation of multiple, independent areas of the sky using the available 96 MHz instantaneous bandwidth.

Before the construction of LOFAR, subarcsecond imaging was possible only down to 325 MHz. With LOFAR, this has been enabled for the first time at frequencies below 300 MHz. With a maximum baseline of approximately 1980 km, angular resolutions of ~ 250 mas are possible at frequencies around 150 MHz, enabling a variety of astronomical applications. These include measuring the angular broadening of galactic objects due to interstellar scattering, spatial localisation of low-frequency emission identified in low-resolution observations, or studying the evolution of black holes throughout the Universe through high-resolution low-frequency surveys.

LOFAR is running production observing since 2012 and is using transformational technologies and novel software approaches to deliver unique data to the community with increasing observing efficiency approaching 70%. Efforts are already ongoing to upgrade the current system to a new version: LOFAR 2.0. This will enhance the imaging capabilities of the system at LBA frequencies and provide a crucial data set for astronomy, which will remain the state-of-the-art for at least the next 20 years. Many of the scientific deliverables of LOFAR 2.0 will come from a 10 to 90 MHz all-northern-sky survey, which will be over 100 times more sensitive (reaching 1σ sensitivities of 1 mJy beam^{-1} at 60 MHz and 5 mJy beam^{-1} at 30 MHz) and will have a more than $5\times$ higher resolution (15 arcsecond at 60 MHz) compared to any previous or planned survey at these exceptionally low frequencies. The new system will address a broad range of scientific topics, such as (i) the formation and evolution of the earliest massive galaxies, black holes, and protoclusters, (ii) the nature of galaxy clusters and the steep-spectrum sources therein, including the influence of magnetic fields, shocks and turbulence, (iii) the Milky Way galaxy, including the topology of its magnetic field, (iv) exoplanets and their magnetospheric properties, (v) the composition of high-energy cosmic rays, and (vi) the structure and properties of the ionosphere. With an angular resolution over $10\times$ higher than the proposed low-frequency array for the SKA, SKA1-LOW, and also accessing the largely unexplored spectral window below 50 MHz, LOFAR 2.0 will continue to be a unique instrument through the next two decades.

A.1.10 uGMRT

The GMRT (Swarup et al. 1991) is one of the largest and most sensitive fully operational low frequency radio telescopes in the world today that employs a full open skies policy. The array was commissioned in 2001. It consists of 30 antennas (each of 45 m diameter) spanning over 25 km, provides a total collecting area of $\sim$30,000 m^2 at metre wavelengths with arcsecs-scale angular resolution. It nicely bridges the VLA and LOFAR in frequency at comparable angular resolution. In addition to the regular Earth rotation aperture synthesis mode, the GMRT provides incoherent and phased-array beamformer options, which allow for high quality observations of compact objects like pulsars. This phased-array mode can be formed and recorded as a global-VLBI station with an equivalent diameter of $\sim$250 m.

Shortly after comissioning of GMRT, new facilities such as LOFAR (e.g. van Haarlem et al. 2013), MWA (e.g. Tingay et al. 2013), LWA (e.g. Ellingson et al 2013) were conceived and started becoming operational. Keeping in mind the growth of low frequency radio astronomy in the world, and learning from our own efforts and experiences of building and using the GMRT, a plan to upgrade the GMRT was proposed during the period 2007–2012 and the first serious work in this direction was initiated around 2010. The main goal was to add extra capability to the existing GMRT array in terms of frequency coverage and sensitivity, which would allow to open new windows of research in astrophysics and the study of the Universe.

Therefore, following are the key aspects of the upgraded GMRT (uGMRT):

1. Nearly seamless frequency coverage from 50 MHz to 1,500 MHz;
2. maximum instantaneous bandwidth of 400 MHz;
3. improved receiver systems with higher G/T_{sys} and better dynamic range;
4. versatile digital backend correlator and pulsar receiver catering to the 400 MHz bandwidth;
5. revamped, modern servo system;
6. sophisticated next generation monitor and control system; and
7. matching improvements in mechanical systems, electrical and civil infrastructure and computing resources.

In addition to several new and interesting results in a wide range of topics in astrophysics, one area where the GMRT has made a difference is that of low frequency all sky surveys. The 150 MHz survey, the TGSS carried out with the GMRT (Intema et al. 2016), providing a sensitivity complementary to that of the NVSS at 1,400 MHz. To illustrate some of the new science capabilities of the uGMRT, a few science cases, including new recent results are highlighted below.
Spectral line science: The increased frequency coverage of the uGMRT allows searches for redshifted HI 21 cm absorption from damped Lyman-α absorbers and neutral hydrogen associated with active galactic nuclei out to the highest redshifts at which these systems have been discovered (see also Kanekar 2014, for new detections of redshifted HI 21 cm absorption in two high-z galaxies).
Continuum imaging science: The improved sensitivity for continuum imaging with large bandwidths has great potential for new science with the uGMRT. A good sampling of the *uv*-plane over a large range of angular scales is necessary to image diffuse, extended, low-surface brightness emission. The large fractional bandwidths of the uGMRT bands provide excellent *uv*-coverage to map such diffuse structures. This together with the improved sensitivity and arcsecond-scale resolution will open up several areas of study, going from galaxy clusters to high-z steep spectrum sources, from Galactic Plane studies to the Transient Universe and pulsar studies.

One of the major threat faced at low frequency is of RFI. At the observatory, this has required a multi-pronged approach, in particular,

- to reduce the RFI – coordinating with mobile phone operators, power utilities agencies, etc.,
- to block the strongest RFI – accomplished via feed designs having appropriate cut-offs in frequency with notch filters in the receiver,
- to filter RFI in the digital domain – schemes are implemented after the digitisation stage in the digital back-end for the signal from each antenna at very high time resolution (Buch et al. 2016), and
- to avoid the RFI in space and time – locations and trajectories of satellites having transmissions in the observing band of uGMRT are determined along with the angular separation of the satellite from the beam of the uGMRT antenna, a.k.a. 'zone of avoidance' thereby avoid non-linear effects due to RFI in the data.

In summary, the upgraded GMRT, which promises to open exciting new windows on the low frequency radio Universe, is now a reality available to the global astronomy community as a competitive facility.

A.1.11 ALMA

The Atacama Large Millimeter/submillimeter Array (ALMA) is a connected element interferometer consisting of the 12-m Array, made up of fifty 12 m diameter antennas, plus the Atacama Compact Array (ACA) made up of twelve 7-m antennas packed closely together (the 7-m Array) and four 12-m antennas (the Total Power or TP Array). ALMA is a complete imaging and spectroscopic instrument operating at wavelengths of 3 to 0.3 millimeter, capable of doing polarimetry, mosaics, and combining the data from the various arrays (12-m Array, 7-m Array, TP Array) to examine the observed source structure on various spatial scales. The 12m-array antennas are movable and can be arranged into a number of configuration permitting baselines lengths from 0.16 km to 16 km.

The night sky over ALMA, located on the Chajnantor Plateau in the Chilean Andes. Image: ESO/C. Malin

Unlike most radio telescopes, the ALMA antennas are located at a roughly 5000 km altitude on the Llano de Chajnantor in northern Chile, one of the driest locations on Earth. The atmospheric transparency and stability at sub-mm wavelengths are essential for ALMA, and combined with the large number of antennas and wide bandwidth, make the ALMA interferometer the most sensitive mm observatory on Earth.

To enable the integration of phased ALMA in VLBI networks, the ALMA beamformer was developed within the ALMA Phasing project (Matthews et al. 2018) and new calibration strategies designed (Goddi et al. 2019). The aggregated collection area of phased ALMA, when all 50 12-m antennas are considered, is equivalent to a single dish with $\sim$84 m diameter, boosting the signal-to-noise ratio of VLBI baselines to ALMA. Starting from Cycle 4, ALMA VLBI observing mode has been offered in conjunction with the GMVA (86 GHz) and EHT (230 GHz, and possibly 345 GHz in the future; see A.1.7).

The plan for future developments of ALMA has been published in 2018, in the ALMA Development Roadmap [1].

ALMA Array operations are the responsibility of the Joint ALMA Observatory (JAO), while the telescope itself is located at the Array Operations Site operated from the Operations Support Facility. The JAO has a central office in Santiago (Chile). The interface between the observatory and the global astronomical community is through the ALMA Regional Centers (ARCs) spread across East Asia, Europe and North-America. The proposal submission deadline is once a year, in April.

Aside from phased-ALMA, the ALMA data are an excellent complement to VLBI data. ALMA can reach tens of mas angular resolution, comparable to the short baselines in the EVN. Contrasting with VLBI, ALMA can observed thermal spectral lines and thermal continuum emission. For example, 6.7 GHz methanol and water masers have been combined with ALMA CH_3CN and CH_3OH maps to study the disk and jet system around a 10 $M_\odot$ protostar (Moscadelli et al. 2019).

[1] `http://www.eso.org/sci/facilities/alma/announcements/20180712-alma-development-roadmap.pdf`

A.1.12 Space VLBI missions

The radio astronomy technique of VLBI involves simultaneous observations of the same radio source by multiple widely separated telescopes. Data collected from each of these telescopes is correlated to produce a resultant radio image. In 'traditional' VLBI, radio telescopes are distributed across the globe. The longer the distance between the observing telescopes – the baseline – the higher the resolution of the eventual image. Consequently, one of the limiting factors of traditional VLBI is the baseline that can be achieved between telescopes on Earth.

Left: (*HALCA*) of the *VSOP* programme (JAXA). Right: *Spektr-R* spacecraft (Lavochkin Scientific and Production Association).

In 1997, the Institute of Space and Astronautical Science (ISAS) in Japan led an international collaboration, which placed the space-borne radio telescope HALCA in orbit. This was part of the VLBI Space Observatory Programme (*VSOP*) - the first dedicated Space VLBI (SVLBI) mission - which operated until 2003. In 2011, the next dedicated space VLBI mission *RadioAstron*, led by the Astro Space Center of Lebedev Physical Institute and Lavochkin Science and Production Association in Russia, advanced space VLBI by offering baselines comparable with the distance to the Moon. In 2019, *RadioAstron* completed its in-orbit operations. The *VSOP* and *RadioAstron* missions constituted the first generation of dedicated space-based VLBI instruments.

While the comprehensive lessons learned from the first demonstration experiment and two dedicated space VLBI missions are still awaiting thorough attention, several preliminary conclusions are summarised in Gurvits (2020b). A broad picture of the current state of affairs and prospects of high-resolution space-borne radio astronomy are presented in twenty papers (and references therein) in the Special Issue of Advances in Space Research (Gurvits, 2020a). Of special interest to the overall development in high-resolution radio astronomy is a highly synergistic to the EVN and global VLBI the concept of TeraHertz Exploration and Zooming-in for Astrophysics (THEZA, Gurvits et al. 2019).

A.2 The current technological framework for the EVN and prospects for its development

The last EVN Vision Document titled "The future of the European VLBI Network" (EVN2015) was released in 2007 and contained a number of recommendations related to technological improvements of the array and the correlator, based on requirements that were derived from the science goals. These recommendations mainly focused on wider bandwidths (and thus higher bitrates), more observing frequencies, more participating telescopes, RFI mitigation, the inclusion of the *e*-MERLIN baselines, higher speed real-time observations, and active preparation for operations in the SKA era. A number of these have been realised through the past decade. In this section we will focus on the technological developments achieved since 2007 and on the prospects for the forthcoming decade.

A.2.1 Current status

To define our future goals we will first describe the current status of the technological areas, referred to in the previous EVN science document.

- New **telescopes** have become members of the EVN since 2007. The previous document listed 7 potential candidates for the EVN of which Latvia (32 m), Yebes (40m), SRT (64 m) and Kunming (40 m) are already fully operational at the observing frequencies for which they have receivers. Moreover, the three Russian 30 m Quasar VLBI Network telescopes, Svetloe, Zelenchukskaya and Badary, joined the EVN, as did the Korean VLBI Network (KVN), composed of three 21m radio telescopes (Yonsei, Ulsan and Tamna). On the other hand, the phased-up WSRT was lost to the EVN with the installation of the APERTIF front ends in most of its dishes, leaving just a single 25m dish for VLBI observations.
- Very high-bandwidth (more than 13 GHz) **receiver systems** for ∼GHz frequencies are currently under development. This development is being funded by RadioNet, as part of the Work Package BRAND. Related developments have taken place within VGOS (VLBI Global Observing System). However, no wide bandwidth receiver below 15 GHz has been built yet.
- Several **back-ends** have been developed within the EVN in the past years. Although most of the stations operate DBBC2s there have been back-end developments by IAA (Russia) and ShAO (China). The Korean VLBI Network (KVN) and Jet Propulsion Laboratory (JPL) are also using new back-ends, while Haystack Observatory has continued its development in line with three different versions of RDBEs. On the other hand the DBBC3, the European back-end, is already a reality and some early versions have been delivered to some institutes and observatories. This world-wide activity has enlarged the knowledge of creating FPGA-based systems, has provided higher bandwidths and data rates in the EVN, and increased its operational reliability. Compatibility, however, may well become an issue.
- **Multi-frequency receivers** at 22, 43, 86 and 129 GHz are deployed in the KVN (South Korea). This multi-frequency receiver which allows observing four different frequencies simultaneously has proven extremely efficient for VLBI studies at frequencies above 20 GHz. Currently the 40 m Yebes radio telescope is the only telescope within the EVN equipped with such a receiver and, together with the KVN telescopes, capable of 22/43 GHz simultaneous observations. A compact prototype has already been developed to fit in telescopes with tight space constraints (Han et al. 2017).
- Internet connections at **multiples of 10 and 100 Gbps** have become standard in current research networks (see the GÉANT map topology of January 2018). There are still differences amongst countries within Europe and the highest speeds are not generally available outside of

Europe. Some of the observatories within the EVN are still connected at multiples of **1 Gbps**.

- **Disk shipping** has become obsolete in a large part of the EVN, greatly simplifying observing and scheduling logistics. The current scheme consists of using local storage at the stations able to contain at least one complete EVN session, and deploying a similar amount of storage at the JIVE correlator, allowing the processing of one more EVN session. The observations are automatically transferred to the correlator via e-shipping.
- ***e*-MERLIN** telescopes have been successfully included in regular EVN operations. This inclusion provides short baselines that increase the fidelity of the images obtained with the EVN.
- The design of the **SKA** comes with high performance challenges which will lead to new technological approaches which might be applicable to VLBI data processing.
- The **VDIF data format** has been adopted widely making global observations far easier than previously. Scheduling and correlation have benefited from this adoption.
- **Software correlation** has delivered a number of important advantages like flexiblity and scalability, as well as many new features like multiple phase centres and mixed bandwidth observing. It has also enabled individual stations to make tests and check the quality of their data in near real time. Distributed correlation is possible in principle but not used in practice. Currently, the two major correlator software packages are DifX and SFXC. These have been compared extensively, both to the previous Mark4 hardware correlator and to each other, and found to produce identical results. These correlators mostly run on modestly sized CPU clusters, which can be easily extended for added computing power. GPU correlation has been investigated, but while GPU correlators are well suited for large-N networks, it is not entirely clear yet whether this holds for VLBI as well.

In summary, over the past years correlation capabilities and data transport have developed well, aided by several international projects that have provided funds. Further improving the sensitivity of the EVN array with the current telescopes is still possible, by increasing the observing bandwidth which is currently limited to 256 MHz.

A.2.2 New telescopes: sensitivity and fidelity

Sensitivity is improved by increasing the number of radio telescopes, preferably with large collecting areas, and/or by increasing the observing bandwidth. Fidelity is achieved by increasing the number and variety of baselines to improve the coverage of the *uv*-plane.

Extending the EVN

A number of telescopes might join the EVN in the coming years. Three types of telescopes are considered.

- Newly built or to-be-built radio telescopes: FAST 500 m (China), QTT 110 m (China), NARIT 40m (Thailand), MeerKAT (South Africa) and the proposed 30-40 m radio telescope in the United Arab Emirates. The latter project is still in a conceptual phase.
- Refurbished telecommunication antennas: Goonhilly 26 m (UK), Usuda 64 m (Japan), Sao Miguel 32 m (Portugal), the Hellenic telescope 30 m (Greece), Ghana 32m (Ghana), Xi'An 40 m (China) and ROT 54 m (Armenia).
- Geodetic 13.2 m telescopes: two at Ny Ålesund, two at Wettzell, one at RAEGE Santa María and one at RAEGE Gran Canaria. The inclusion of these telescopes however will not be straightforward due to limited time availability.

Including and validating new telescopes, in particular the refurbished telecommunication dishes,

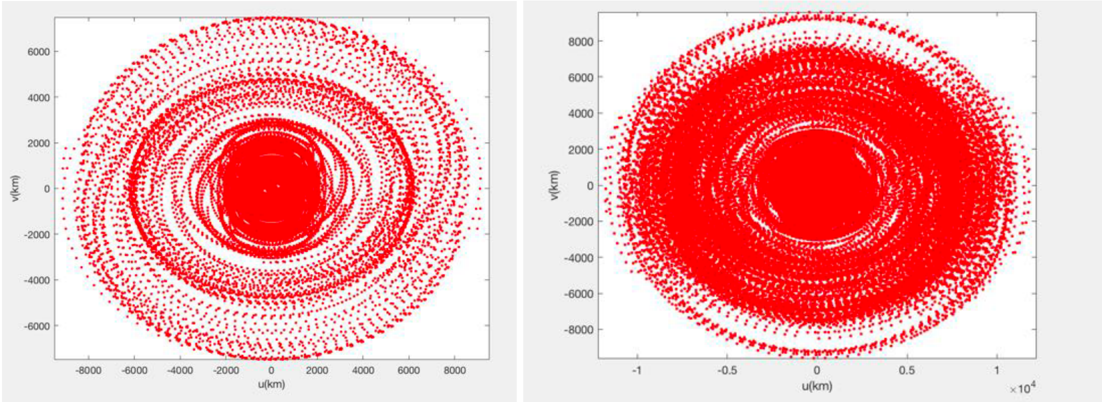


Figure A.1: Left: *uv*-coverage of EVN and *e*-MERLIN with 18 stations total. Right: global VLBI *uv*-coverage with 30 stations world-wide. In both cases for wide bandwidth continuum observations via using Multi-Frequency Synthesis remaining gaps in *uv*-coverage can be robustly filled.

may require the temporary deployment of VLBI back-ends at those sites. The EVN might consider providing such equipment for this purpose.

Extending the e-EVN

The real-time capacity of the EVN can be extended, by adding more telescopes observing at higher aggregate bit rates, going from the current 2 Gbps to 4 and 8 Gbps. Real-time VLBI has important advantages above recorded VLBI, enabling rapid response to transient events, as well as faster turn-over of scientific results. To increase its scientific relevance it will be crucial to add the *e*-MERLIN short baselines, the intermediate Quasar VLBI Network baselines filling the gap between the European and Chinese parts of the EVN, and the great sensitivity of the Sardinia and FAST telescopes. Although the transport of recorded data has been greatly simplified through the advent of FlexBuff recorders, the independence of recording media when doing e-VLBI still offers a tremendous advantage, especially at higher data rates.

Real-time data rates of 8 Gbps and above will obviously necessitate higher connectivity to JIVE, and a further upgrade of correlator capacity at JIVE. This could be in the form of upgrading the SFXC hardware, possibly including GPUs. Special observing modes require recording data during real-time sessions at JIVE, and recorrelation at a later time. This is done occasionally, but could be routinely available. Having sufficient recording capacity in the EVN would of course reduce this problem to doing regular e-VLBI in parallel to regular recorded VLBI.

A.2.3 EVN-light and fast response

The concept of EVN-light, a sub-array of EVN stations, has been considered for many years, but has never been pursued. Such an array could be deployed in the gaps between the regular EVN sessions and would be very useful, for example, for monitoring campaigns (e.g. astrometry, transients) and other long-term projects.

The capability to quickly respond to transient events is becoming more and more important as new instruments come online. Although, depending on the type of trigger, as a rule as many telescopes as possible will be requested, the presence of an operational EVN-light would make follow-up observations at short notice far easier.