EVN biennial report 2019-2020

April, 2021

Image by Paul Boven (boven@jive.eu). Satellite image: Blue Marble Next Generation, courtesy of Nasa Visible Earth (visibleearth.nasa.gov).

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Front page: Image credit: A. Bartkiewicz, see section Expansion of the methanol ring for details.

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1 Foreword from the EVN Consortium Board of Directors chairperson

It is a pleasure to introduce this European VLBI Network Biennial Report, covering the years 2019 and 2020. And it is a particular pleasure to stress that, during this period, the EVN has been able to accomplish its mission offering access to a unique radio astronomy infrastructure that, providing extremely high resolution and high sensitivity observations between 1.4 GHz and 43 GHz, is delivering high impact cutting edge science.

This was particularly remarkable for 2020, the year when the COVID-19 pandemic hit the planet causing profound disruption in our society. Indeed astronomy was not an exception, and COVID-19 impacted on the operations, technological developments, scientific research, and meetings of all astronomical observatories around the world. In this context, it is noteworthy that the EVN performed extraordinarily well: many telescopes of the network and the correlator continued being operated remotely, so the EVN has continued to work non-stop during the pandemic, producing amazing scientific results of the highest quality. This was only possible thanks to the dedication and proffesionalism of the EVN stations staff and of EVN officers, and we should be deeply grateful to them.

EVN's management also adapted very quickly to the new situation. During 2020, EVN CBD, Programme Committee, and TOG meetings were held remotely, and the EVN Symposium originally scheduled for July 2020 was postponed, but other scientific initiatives are making it possible for the EVN scientists to keep fluid and frequent exchanges.

This report is composed of 9 chapters with information on the EVN science, operations, observatory reports, activities at the Joint Institute for VLBI ERIC (JIVE), meetings and publications.

Chapter 2 summarizes the most interesting scientific outcomes published between 2019 and 2020. These results have been divided in five fundamental areas following the same scheme as in the EVN VLBI 2020-30 scientific roadmap: galactic science, transient phenomena and stellar compact objects, AGN, galaxies and (non-stellar) black-hole systems, gravitational lensing, and development of new techniques and software. We have selected three papers per topic based on their impact, but this is a quite random selection and we could have selected other different, or many more. In any event, these results demonstrate that the EVN is an excellent and very top instrument for providing high angular resolution and high sensivity at frequencies between 1.4 and 22 GHz.

Within the operations, one the most relevant facts of this period is the full inclusion in 2019 of e-Merlin in the EVN array and of the Russian Quasar antennas and Chinese Kunming telescope at 1 Gbps in e-VLBI observations. The demand of e-Merlin within the EVN has increased steadily since then. Another relevant fact is the consolidation of 2 Gb/s as the standard recording rate, which allows observations of 256 MHz bandwidth with 2 polarizations. This has been achieved thanks to the investments in new storing capabilities by the EVN institutes and to new firmware which allows up to 8 Gbps with the current DBBC2s, the most widespread backend within the EVN. The next step is to adopt regularly 4 Gbps, already tested and technically possible at the stations and at the correlator, both for recorded and e-VLBI observations. Most of the stations have also implemented continuous calibration which should improve the amplitude calibration of the observations.

Transient science has grown strongly in popularity thanks to new phenomena such as the Fast Radio Bursts, but also due to a significant number of proposals devoted to supernovae, stellar tidal disruption events, X-ray binaries and other transient sources. The preferred observing frequencies at the EVN continue being 18/21 cm and 6 cm, although in 2020 a larger number of proposals requested 22 GHz.

H2020 Radionet project finished in 2020 and one of its main research activities (JRAs) has a great importance for the EVN: BRAND, a 1.5-15 GHz wide band receiver. The prototype is being integrated by MPIfR from parts built and delivered by several EVN institutes. The coverage of this wide frequency band is one of the mid-term goals described in the EVN scientific roadmap. H2020 JUMPING JIVE has also been a great benefit to the EVN. It has funded and facilitated the ellaboration of the EVN 2020-2030 scientific vision document, provided prospects for incorporating new telescopes to the EVN, a new scheduling software (pySCHED), new geodetic capabilities to the JIVE correlator and developed interfaces for including the SKA in global VLBI among other goals.

This two year period has seen the surge of remote meetings using specialized tools for such events that connnect people virtually from their home or institutes without being physically present. The EVN organized a series of on line seminars seminars given by some of the best specialists in the world on their research topics. In addition, a virtual mini-symposium was organized to be held in 2021, while the large EVN Symposium is being organized to take place in Cork by summer 2022.

The virtual format of the meetings has been provoked by the COVID-19 pandemics and will probably stay in the future. Many future meetings will probably be held with a hybrid format: on-line and present. These new formats offer more opportunities to participants from very distant institutes, or with any difficulties to travel, and they will help decrease the carbon footprint caused by air flights. However, some meetings with physical participation will still be needed since they facilitate fruitfull discussions and help connecting people.

Finally, I take this opportunity to thank Pablo de Vicente, who served during this period as Secretary of the CBD in an exemplary way, making everything easy. He also has collected and summarized the many EVN activities and results in this fantastic report that, I'm sure, you will very much enjoy reading.

Rafael Bachiller

Chair, EVN Consortium Board of Directors (July 2019 – December 2020)

2 The European Consortium for VLBI

2.1 EVN Consortium Board of Directors membership

The EVN is governed by a Consortium, founded in 1984 following 4 years of EVN observing made under less formal arrangements. The Directors of EVN Member Institutes form the Consortium Board of Directors (CBD). A list of Board membership during 2019-2020 is given in Tables 2.1 and 2.2.

Table 2.1: Full EVN CBD members, 2019-2020

Name		Institute
Indra Dezde	Until January 2020	Ventspils International Radio Astronomy Centre, Ventspils, Latvia
Aleksejs Klokovs	Since January 2020	Ventspils International Radio Astronomy Centre, Ventspils, Latvia
Rafael Bachiller	Chair from July 2019	National Astronomical Observatory, Instituto Geográfico Nacional, Madrid, Spain
Fernando Camilo		South African Radio Astronomy Observatory, Hartebeesthoek, South Africa
John Conway	Chair until July 2019	Onsala Space Observatory, Chalmers, Onsala, Sweden
Simon Garrington		Jodrell Bank Observatory, University of Manchester, Jodrell Bank, UK,
Zhiqiang Shen		Shanghai Astronomical Observatory, Shanghai, China
Dmitrii Ivanov		Institute of Applied Astronomy, St. Petersburg, Russia
Andrzej Marecki	Until March 2020	Toruń Centre for Astronomy, Toruń, Poland
Agnieszka Slowikowska	Since March 2020	Institute of Astronomy of Nicolaus Copernicus University, Toruń, Poland
Wang Na		Xinjiang Astronomical Observatory, Xinjiang, China
Tiziana Venturi		Institute of Radio Astronomy, Bologna, Italy
Francisco Colomer		JIVE ERIC, Dwingeloo, Netherlands
René Vermeulen		ASTRON, Dwingeloo, Netherlands
Anton Zensus		Max-Planck Institut für Radioastronomie, Bonn, Germany

Table 2.2: EVN associate CBD members, 2019-2020

Name	Institute
Taehyun Jung	Korea Astronomy Space Science Institute, Daejeon, South Korea
Francisco Cordova	Arecibo Observatory, Puerto Rico, USA
Torben Schueler	Geodetic Observatory Wettzell, Wettzell, Germany
Joni Tammi	Metsähovi Radio Observatory, Aalto University, Finland

The CBD meets twice per year to discuss EVN activities, to make EVN policy decisions and to appoint EVN Officers (Chairs of the Program Committee and Technical & Operations Group, and the Scheduler), and members of the Program Committee. Meetings are attended by the EVN Officers and also by representatives of EVN observing partner organizations (e.g. NRAO and RadioAstron), and other individuals who may be invited to address topical meeting agenda points. The locations and dates of the CBD meetings during 2019-2020 are given in Table 2.3. Due to the COVID-19 pandemic both meetings in 2020 took place via videoconference.

Table 2.3: CBD Meetings during 2019-2020

Place	Date
Bologna, Italy	16 May, 2019
Dwingeloo, the Netherlands	13 November, 2019
Remote meeting	13 May, 2020
Remote meeting	12 November, 2020

3 Selected EVN Scientific Results

This chapter holds a number of relevant scientific results obtained with the EVN and published in refereed journals. They have been classified in five different topics: galactic science, transient phenomena and stellar compact objects, AGN, galaxies and (non-stellar) black-hole systems, gravitational lensing, and development of new techniques and software.

3.1 Galactic science

3.1.1 Astrometry: a look into black hole birth

P. Atri et al.

The birth of stellar mass black holes can be unraveled by studying black hole X-ray binaries (BHXBs), a binary system of a star and a stellar mass black hole wherein the black hole is accreting matter from the star. Theoretical models suggest that BHs are born when a massive star dies, either with or without a supernova (SN) explosion. When a compact object (e.g.,black hole and neutron star) is born with a supernova explosion, we expect asymmetries in the explosion to give the remnant object a large recoil velocity. On the contrary, if the star collapses onto itself, without a SN, then the remnant BHXB does not incur large kick velocities. Studying and measuring the kick velocities of BHXBs gives us an insight into the final living moments of the massive star that gave birth to the black hole. Combining the proper motion with systemic radial velocity and distance to the source enables us to measure the full three-dimensional motion of the system. Integrating the orbit of the BHXB back in time to the moment of birth can thus help us estimate the velocity of BHXB right after the BH was born.

BHXBs are usually faint, but sometimes go through a period of high activity (lasting months or years) and become bright at X-rays and radio wavelengths. We use this momentary brightness of BHXBs in radio to pinpoint the system's location in our Galaxy and measure their proper motion. Typical BHXBs are a few kpc away and move a few milliarcseconds in a year, and so Very Long Baseline Interferometry (VLBI) is essential for high precision astrometry of this order. The EVN has been highly instrumental in conducting high precision astrometry of BHXBs and has aided the successful proper motion measurement of two BHXBs and the parallax of one.

We used the EVN along with the VLBA to measure a highly precise proper motion of Swift J1753.5-0127 and MAXI J1820+070. We observed Swift J1753.5-0127 for 5 epochs separated by a few months to get a long time baseline to get strong constraints on the proper motion. Combining this proper motion, with systemic radial velocity and the distance to the source we measured a kick velocity distribution with a median of 177^{+135}_{-103}

km/s, where the error bars are the 5^{th} and 95^{th} percentile. We suggest that this high velocity is because the BH was born with a SN explosion. We used these constraints along with measurements of 15 other systems to report the first observationally constrained BHXB kick distribution.

MAXI J1820+070 stayed bright for almost a year, thus enabling not only a proper motion measurement but also a highly precise 10σ parallax measurement of the source, improving by leaps and bounds on the 3σ measurement done by Gaia. This gave a highly constrained distance to the source of 2.96±0.33 kpc. We used this newly constrained distance to obtain updated mass estimate of the BH in the system (9.5±1.4 solar masses) and also to obtain a kick velocity distribution (120^{+30}_{-25} km/s) that suggests the BH was born with a SN explosion in MAXI J1820+070.

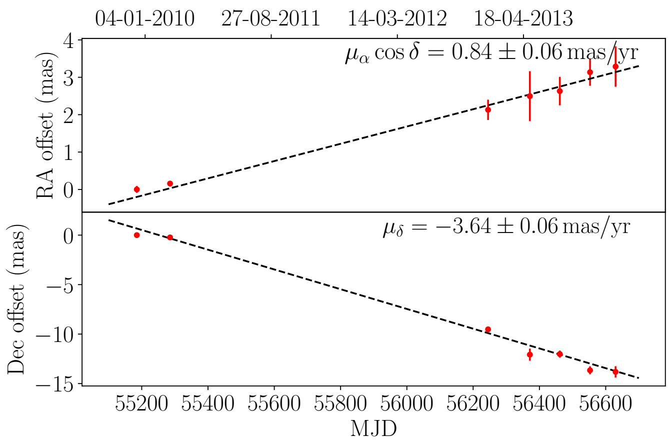

Figure 3.1: *Parallax measurement of MAXI J1820+070. The top and bottom panel show the offset of the object from the reference position after removing the proper motion.*

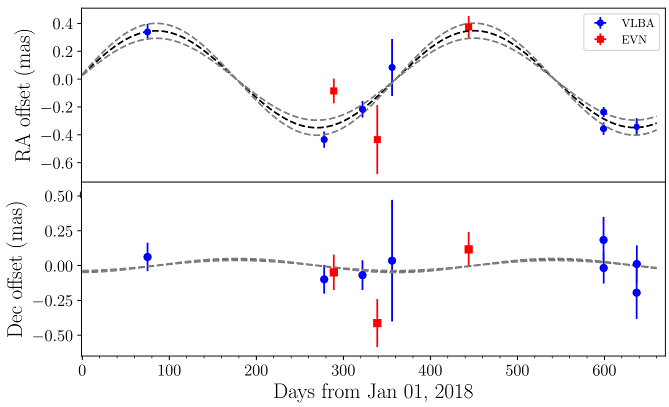

Figure 3.2: *Proper motion of Swift J1753.5-0127. The first two epochs were measured with the VLBA and the last 5 with the EVN.*

Published in: Atri, P et al. (2019)

3.1.2 Expansion of the methanol maser ring

A. Bartkiewicz et al.

Methanol masers are widely used to study high-mass star formations, in particular to discover the kinematics of the close environment of newly born high-mass stars. The EVN plays a role in cosmic maser studies due to its sensitivity and hight angular resolution. In 2004, using eight antennas, we discovered the ring-like methanol maser structure at the 6.7 GHz transition towards G23.657-00.127 (named after the Galactic coordinates) (Bartkiewicz et al. 2005). The question then became what the origin could be of this special morphology. Searches for a H II region and water masers did not bring any detections. Non-thermal tracers at high angular resolution have not been available to put constraints on the high-mass protostar.

After almost 9 and 11 years, we followed the same source using nine EVN antennas. Good quality data allowed us to identify proper motions of single maser cloudlets; they expand mainly in the radial direction (see Fig. 3.3) with a mean velocity of 0.21 milliarcseconds per year. That corresponds to 3.2 km/s for a distance of 3.19 kpc. Detailed studies led us to consider two possible scenarios where the methanol masers trace either a spherical outflow arising from an (almost) edge-on disc, or a wide angle wind at the base of a protostellar jet (see Fig. 3.4).

One can notice that the almost circular structure (radius is 405 au) shows two gaps (emission free region) along the direction at position angle about 80 deg. This region might mark the mid-plane of a circumstellar disc, and the masers would expand above and below this plane. Considering the fact that elongated near-IR emission was reported by De Buizer et al. (2012) and it is consistent with the orientation of this emission-free region, we can also think about a possibility of an underlying jet, inclined with respect to the line of sight. The central star would still lie at the centre of the methanol maser ring, but the masers would now be expanding at each side of the jet axis, and would trace a wide angle wind at the base of the protostellar jet. Masers would be tracing a combination of rotation around and expansion along the jet axis, similarly to what was observed in the maser source G23.01-0.41 (Sanna et al. 2010). From monitoring the G23.657-00.127 using the 32 m Torun antenna over 20 year, we know that the target remains constant (Szymczak et al. 2018). However, the EVN observations revealed significant changes in the intensity of individual cloudlets over the whole emission range. That allowed us to estimate an average lifetime of a cloudlet of about 40 years. We did the most direct investigations of the methanol maser ring using EVN. Forthcoming studies need to include sensitivity studies of thermal tracers at compatible angular resolution.

The research leading to these results received funding from the European Commission Seventh Framework Programme (FP/2007-2013) under grant agreement No. 283393 (RadioNet3).

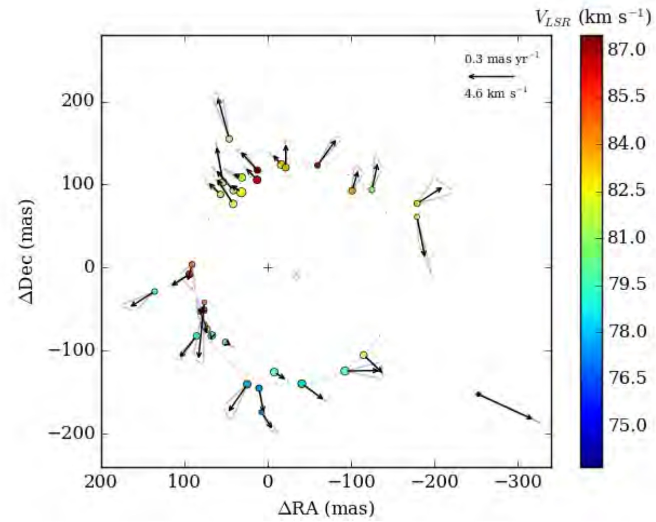

Figure 3.3: *Widespread, almost circular symmetric 6.7 GHz methanol masers in the G23.657-00.127 high-mass star forming region. They are marked by filled circles with colours corresponding to the local standard velocity scale presented in the vertical wedge. The black arrows indicate the best fits of the relative proper motion for the three epoch data as measured relative to the centre of motion marked by the plus sign. The dotted ellipse traces the best flux-weighted fit to all cloudlets (except the SW blue-shifted one). The centre of the ellipse is marked by the cross.*

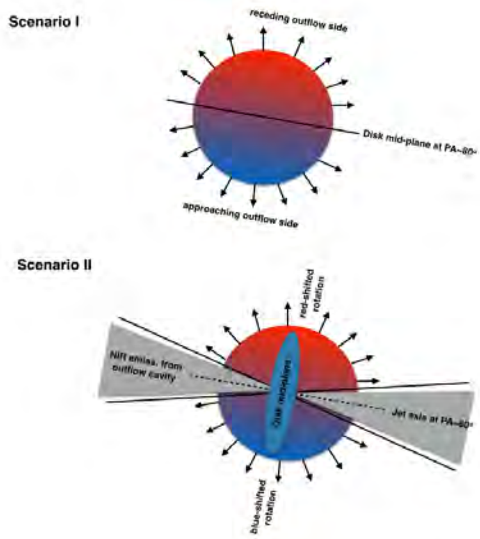

Figure 3.4: *Schematic models of maser expansion related to a sphere-like outflow or tracing a wide angle wind at the base of the protostellar jet.*

Published in: Bartkiewicz et al. (2020).

3.1.3 Imaging a water maser superburst

R. Burns et al.

In September 2017, during the IAU Symposium 336 “Astrophysical masers: Unlocking the mysteries of the Universe”, reports surfaced of two water maser sources going ”superburst”. The Maser Monitoring Organisation (M2O), a team of astronomers led by Ross Burns (a JIVE support scientist at the time), conducted a rapid follow-up study to image the superburst in detail. Their findings clarify that the observed superburst was the result of a rare spatial alignment of two maser cloudlets.

Masers are invaluable tools for the study of star formation. Their bright, compact emission outlines disks and bowshocks associated with the accretion and ejection structures of protostars, and can be used to derive accurate source distances via annual parallax measurements. However, while maser amplification has a well established theoretical background some aspects of astrophysical maser behaviors still defy firm explanation, referring in particular to their notoriously extreme variations in brightness. The superbursts detected with single-dish telescopes and reported during the IAU symposium 336 ”Astrophysical masers: Unlocking the mysteries of the Universe”, identified a sudden raising in brightness by several orders of magnitude in two maser sources, reaching flux densities of tens of thousands of Janskys (Jy). In an attempt to tease out the process by which such extreme variability can occur, a team of astronomers requested target-of-opportunity observations with the European VLBI Network (EVN) to image the superburst masers with milliarcsecond resolution.

A few days later electronic Very Long Baseline Interferometry (e-VLBI) spectral line observations were successfully conducted, with the observing session split across the two targets. The array contained both short and long baselines, comprised of Effelsberg, Jodrell Bank (MkII), Onsala (20 m), Torun, Yebes and Hartebeesthoek. By the scheduled date of the observations one of the superburst sources had already abated and rapidly returned to its pre-burst state, however, the other superburst source, a massive star forming region called G25.65+1.05, was still fully active at a flux density of almost 12,000 Jy.

The data revealed a complex distribution of maser emission, tracing two arcs presumably associated with shocks in a protostellar jet or outflow. The superburst maser was found to reside in one of the arc structures that comprised around seven other maser cloudlets which had not changed in their flux density. A comparison of the superburst flux density on the long and short EVN baselines revealed sub-milliarcsecond structure which aligned on the sky with two spatially separated regions of maser emission which flanked the position of the superburst.

The team concluded that the superburst maser had occurred as a result of a rare spatial alignment of two maser cloudlets along the observer’s line of sight in which the background maser was subsequently amplified by the foreground maser. The two stage amplification lead to a spectacular surge in the measured flux density, most of which originating from a sub-milliarcsecond scale region. Several weeks after the EVN observations the G25.65+1.05 water maser had returned to its quiescent phase, only to go superburst yet again, reaching a flux density of 130,000 Jy and making it one of the most powerful sources of maser emission in our Galaxy. The EVN investigation gleaned essential insights into the mechanism of action of the superburst class of maser sources, of which only two other maser sources are known.

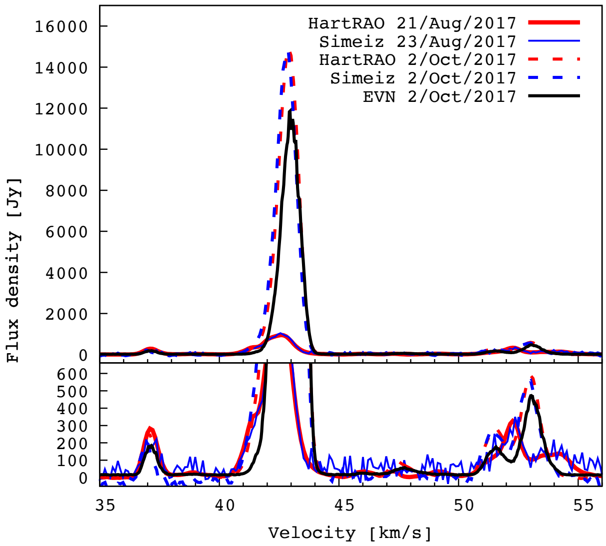

Figure 3.5: *The scalar averaged, cross-power water maser spectrum measured with the EVN (solid, black line) is shown in comparison to single-dish spectra provided by the M2O on the same date (dashed red and blue lines), and (solid red and blue lines) pre-flare. The panel below highlights the low-flux density maser features.*

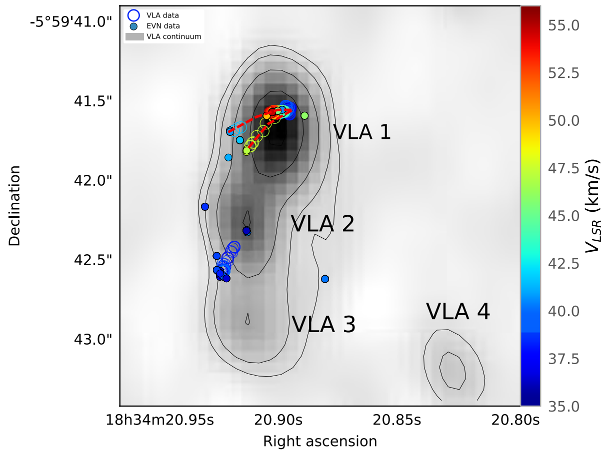

Figure 3.6: *Visual summary of the water maser and 22 GHz continuum emission in G25, comparing results from this work with VLA data from Bayandina et al. (2019), taken on the 9th of December 2017, from which the continuum sources VLA 1, 2, 3, and 4 are labelled. Open circles indicate maser emission.*

Published in: Burns, R. et al. (2019).

3.2 Transient phenomena and stellar compact objects

3.2.1 VLBI exposes the aftermath of a violent merger of neutron stars

G. Ghirlanda and O. S. Salafia

The binary neutron star merger event GW170817 was detected through both gravitational waves and electromagnetic radiation. Early optical observations discovered a bright transient identified as the kilonova emission powered by the radioactive decay of heavy nuclei produced in the neutron rich material ejected in the merger. A non thermal bright emission component was discovered starting 9 days post the gravitational event discovery and observed for more than 200 days. This emission, interpreted as the afterglow of the short gamma ray burst associated to the gravitational wave event, posed the challenging question whether it originated from narrow relativistic jet or a mildly relativistic nearly isotropic outflow.

A group of international astronomers, led by G. Ghirlanda, has recently presented the imaging results of a global very-long-baseline interferometry observation with 32 radio telescopes. The apparent source size, 207 days after the merger, is constrained to be smaller than 2.5 milliarc seconds at the 90% confidence level. The compact structure indicates that GW170817 produced a structured relativistic jet that was able to pierce through the dense merger material moving ahead of it.

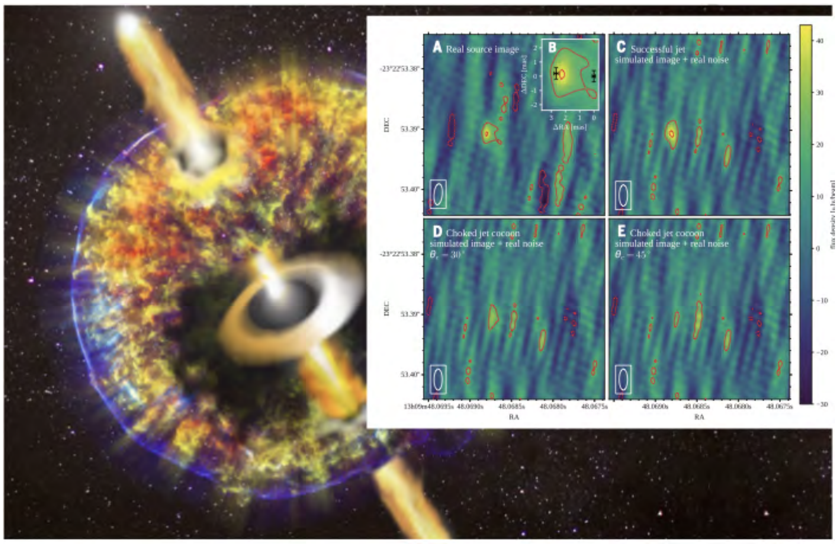

Figure 3.7: *Cartoon representing the jet breaking out from the dense neutron rich material ejected as a consequence of the merger. The insert shows the real VLBI image (A) and three synthetic images (C, D, E) obtained simulating a collimated relativistic jet (C) and possible configurations of a mildly relativistic nearly isotropic outflow (D, E). The successful jet case (C) is very similar to the real image (A).*

Published in: Ghirlanda G. et al. (2019).

3.2.2 A repeating Fast Radio Burst from a spiral galaxy deepens the mystery of where these signals originate

B. Marcote et al.

Telescopes in the European VLBI Network (EVN) have observed a repeating Fast Radio Burst (FRB) in a spiral galaxy similar to our own. This FRB is the closest to Earth ever localised and was found in a radically different environment to previous studies. The discovery, once again, changes researchers' assumptions on the origins of these mysterious extragalactic events.

At this point in time, one of the greatest mysteries in astronomy is where short, dramatic bursts of radio light seen across the universe, known as Fast Radio Bursts (FRBs), are originating from. Although FRBs last for only a thousandth of a second, there are now hundreds of records of these enigmatic sources. However, from these records, the precise location is known for just four FRBs - they are said to be "localised".

In 2017, one of these four sources was observed to repeat, with bursts originating from the same region in the sky, in a non-predictable way. This resulted in researchers drawing distinctions between FRBs where only a single burst of light was observed ("non-repeating") and those where multiple bursts of light were observed ("repeating"). The discovery of this FRB and its very particular and extreme environment inside a dwarf galaxy raised several questions, such as whether there was a fundamental difference between repeating and non-repeating FRBs.

On 19th June 2019, eight telescopes from the European VLBI Network (EVN) simultaneously observed a radio source known as FRB 180916.J0158+65. This source was originally discovered in 2018 by the CHIME telescope in Canada, which enabled the team, led by Marcote, to conduct a very high resolution observation with the EVN in the direction of FRB 180916.J0158+65. During five and a half hours of observations the researchers detected four bursts, each lasting for less than two thousandths of a second. The resolution reached through the combination of the telescopes across the globe, using a technique known as Very Long Baseline Interferometry (VLBI), meant that the bursts could be precisely localised to a region of approximately only seven light years across.

With this location the team were able to conduct observations with one of the world's largest optical telescopes, the 8-m Gemini North on Mauna Kea in Hawaii. Examining the environment around the source revealed that the bursts originated from a spiral galaxy at redshift of $\sim$0.0337, specifically, from the apex of a prominent v-shaped star-forming region. The found location is radically different from the previously located repeating FRB, but also different from all previously studied FRBs. The differences between repeating and non-repeating fast radio bursts are thus less clear, suggesting that these events may not be linked to a particular type of galaxy or environment. It may be that FRBs are produced in a large zoo of locations across the Universe and just require some specific conditions to be visible.

While the current study casts doubt on previous assumptions, this FRB is the closest to Earth ever localised, allowing astronomers to study these events in unparalleled detail. Continued studies will unveil the conditions that result in the production of these mysterious flashes. More precise localizations of FRBs would, ultimately, allow astronomers to understand their origin.

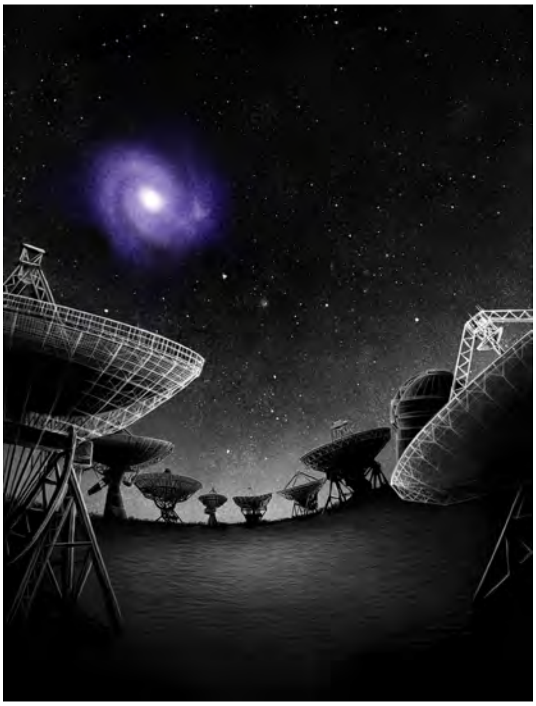

Figure 3.8: *Artist impression of all EVN antennas that participated in the observation plus the Gemini North used to obtain the optical data. The real image of the host galaxy of FRB 180916.J0158+65 appears in the sky. Credit: Danielle Futselaar (www.artsource.nl).*

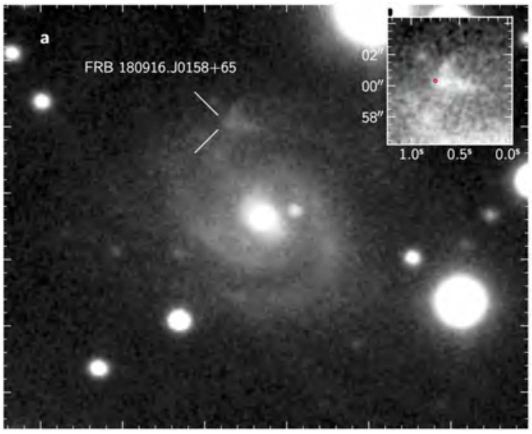

Figure 3.9: *Optical image from Gemini North (r' band) of the host galaxy of FRB 180916.J0158+65 and a zoom-in of the star-forming region from where the bursts arise. The location of FRB 180916.J0158+65 is highlighted by the white cross and the red circle. The uncertainty in the position of FRB 180916.J0158+65 derived from the EVN data is smaller than the resolution of the optical image.*

Published in: Marcote et al. (2020).

3.2.3 The cosmic cow explained - radio signals point to an explosion and a newborn magnetar

Mohan, Ann & Yang

Among short-lived sky phenomena, AT2018cow (The Cow) is an astronomical event like no other. First detected in 2018, it received its memorable name based on alphabetical protocol to classify such events. However, it was not just its name that makes it memorable. AT2018cow was identified in a relatively nearby galaxy (about 200 million lightyears away) and the brightest fast-rising blue optical transient (FBOT). The proximity of AT2018cow, exceptionally brief brightness and unusually high temperature led to widespread attention upon discovery. Accretion onto the central compact object (neutron star or black hole) can produce a relativistic jet which if pointed towards us can appear extremely bright, possibly responsible for the observed brightness in the Cow.

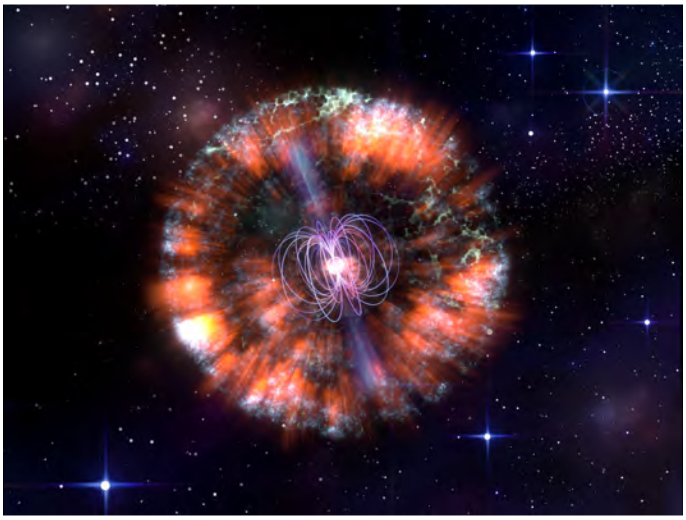

Figure 3.10: *Artist's impression of the cosmic cow.*

Observations using 21 telescopes of the European VLBI Network (EVN) reveal the compact radio afterglow emission from AT2018cow. The study spans five observation sessions spanning about 1 year after the discovery, capturing the afterglow evolution during the transition and later phases ($\sim$90 days and later). The source remains unresolved at all epochs, and shows no detectable variation of the emission peak position within the timespan of $\sim$1 year. A tidal-disruption-event or a regular core-collapse Supernova seem less possible due to the steep late-stage decline. A collimated relativistic jet is absent (proper motion < 0.14 c) thus suggesting an intrinsically luminous ejecta. This, an expansion into a dense magnetized environment and late-time flux density evolution of the afterglow, is indicative of a newly formed magnetar driven central engine produced in the successful explosion of a relatively low-mass star (few - ten solar masses).

This interestingly entails a possible future inference of fast radio bursts (FRBs) from the magnetar interaction with the strongly magnetized environment.

The EVN is the most sensitive standalone VLBI network in the world that has delivered cutting-edge results in the field of transient science. It has by now provided the most accurate localisations of two FRBs. There is an intriguing possibility that there may be a link between FRBs and other types of transient sources (like the event that produced AT2018cow, an FBOT).

Published in: Mohan, An & Yang, (2020).

3.2.4 Very long baseline interferometry imaging of the advancing ejecta in the first gamma-ray nova V407 Cygni

M. Giroletti et al.

It was March 2010 when a transient gamma-ray source was revealed by the Large Area Telescope on board the Fermi gamma-ray satellite. To everybody's surprise, the transient source matched the position of the symbiotic nova V407 Cygni. Initially considered a sort of "stellar exception", V407 Cygni, instead, gave birth to a new class of gamma objects. Symbiotic novae are rare and exceptional objects, couples of stars composed of two very different companions: a small, dense, white dwarf and a pulsating red giant. The red giant emits a wind of material that is accumulated on the surface of the white dwarf and, when it reaches a critical density, gives rise to a very bright explosion.

Soon after the discovery, we observed the source with the EVN in e-VLBI mode. Thanks to its sensitivity and prompt feedback, the EVN revealed a faint, compact 5 GHz feature, which convinced us to follow the evolution of the source for a few more epochs. The following observations, ranging between 31 and 203 days after the optical event, revealed a much richer and rapidly evolving structure.

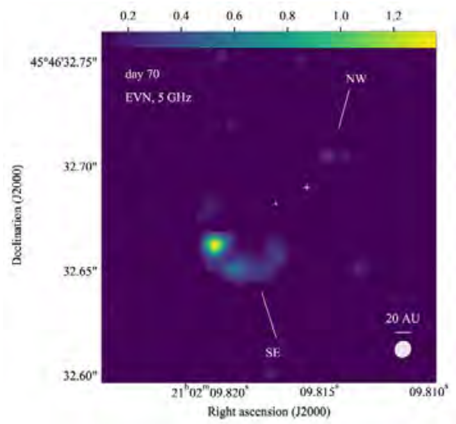

Figure 3.11: *A radio image of the emission from V407 Cyg, 70 days after the explosion. The colour scale indicate the intensity of the emission (yellow is brighter), which is developing on two opposite fronts with respect to the location of the central white dwarf.*

Not only the observations demonstrated for the first time in a direct way the presence of a shock in this type of events, we could also determine the geometry of the source: the red giant is in the foreground in front of the white dwarf, and from the latter two opposite jets depart, in the plane of the sky, perpendicular to the line of sight. Moreover, the observations also allowed us to reveal traces of previous events in the life of this binary star, one around 2003, one even dating back to the 1930s. A step forward in understanding the evolution of these rare objects.

These results are the outcome of an intense and ambitious observational campaign. The sensitivity of the EVN, in particular in the short baseline range, and its real time capabilitiy, were key elements for the characterisation of the system.

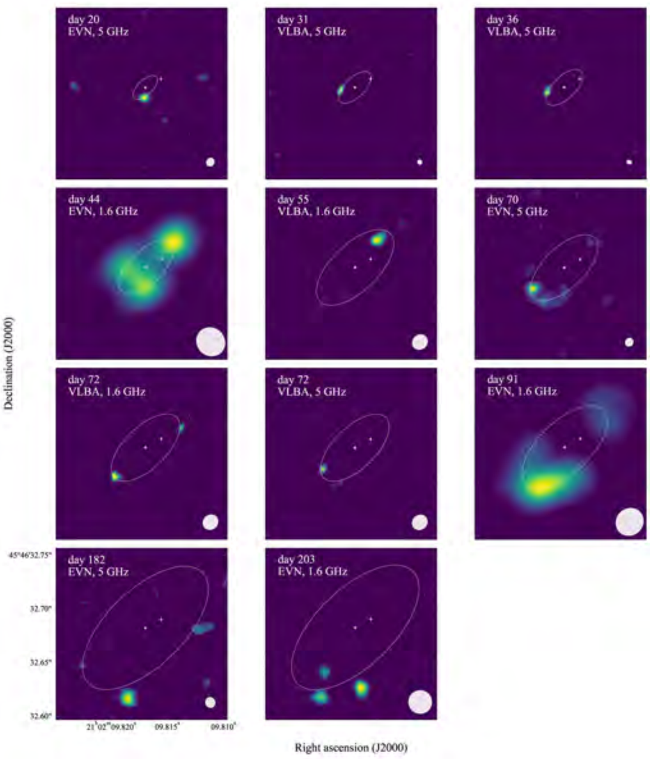

Figure 3.12: *The set of EVN and VLBA images obtained from the observations, starting 20 days after the discovery of the nova event and tracing the advance of the shock front for over six months. The panels have different restoring beam (shown in the bottom right corner) and heterogeneous sensitivity/frequency. However, the overall expansion of the structure can be appreciated, as illustrated by growth of the dotted white ellipse fitting the spatial distribution of the radio emitting features.*

Published in: Giroletti et al. (2020).

3.3 AGN, galaxies, and (non-stellar) black-hole systems

3.3.1 20 years of VLBI monitoring of the starburst galaxy Arp 220 E

E. Varenius et al.

The nearby ultra-luminous infrared galaxy (ULIRG) Arp 220 at 77 Mpc is an excellent laboratory for studies of extreme astrophysical environments. It is a merger, with two radio-emitting disk nuclei about 1 arcsecond apart (Norris 1988). For decades, global cm-VLBI has been used to monitor a population of compact sources in the disks, thought to be supernovae (SNe), supernova remnants (SNRs), and possibly active galactic nuclei (AGNs) (Smith et al. 1998; Rovilos et al. 2005; Lonsdale et al. 2006; Parra et al. 2007; Batejat et al. 2011, 2012). SNe and SNRs are thought to be the sites of relativistic particle acceleration which power star formation induced radio emission in galaxies, and are hence important for studies of for example the origin of the FIR-radio correlation.

In this work we analyse new and archival VLBI data, spanning 20 years, and present 23 high-resolution radio images of Arp 220 at wavelengths from 18 cm to 2 cm. Stacking the images, we obtain the deepest (4uJy/beam) images to date of the Arp 220 nuclei, see Figure 3.13.

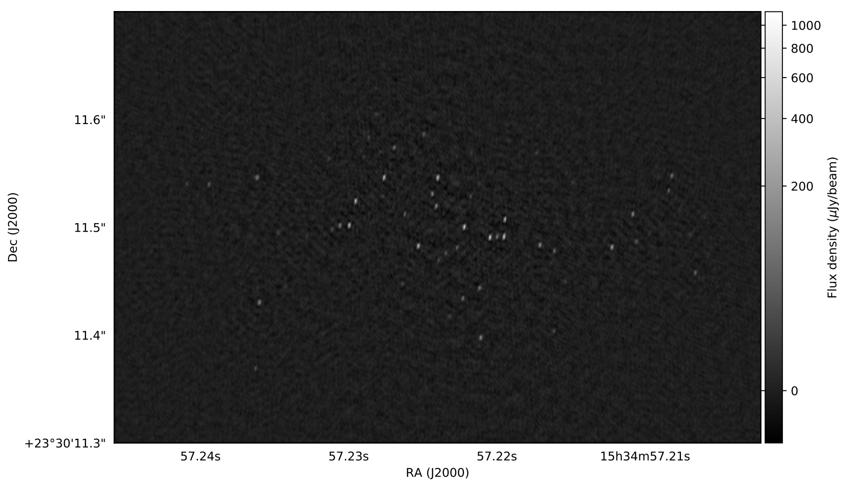

Figure 3.13: *Stacked 6 cm VLBI image of the western nuclei of Arp 220, with off-source rms noise $\sigma = 4\mu Jy/beam$. The two panels are displayed using the same arcsinh grey-scale from -20 $\mu Jy/beam$ (-5σ) to 1140 $\mu Jy/beam$.*

In this work we detect radio continuum emission from 97 compact sources and present flux densities and sizes for the analysed observation epochs. We find evidence for a LD-relation within Arp 220 (see Fig. 3.14), with larger sources being less luminous, where the Arp 220 population appears to be a brighter and more compact version of the sources found in the nearby starburst galaxy M82.

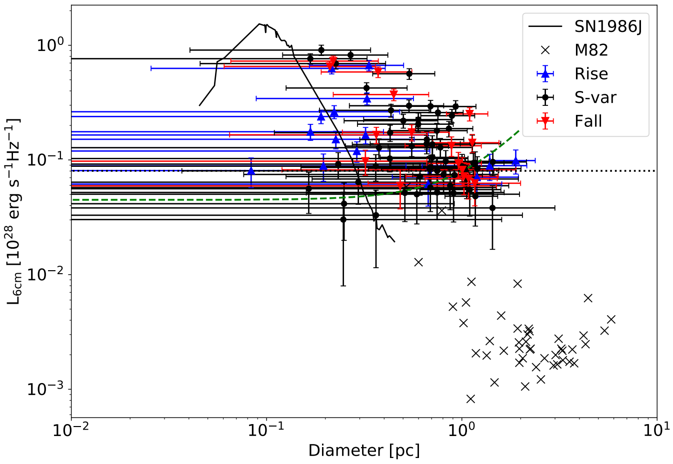

Figure 3.14: *Fitted spectral luminosity vs diameter of the compact sources in Arp 220, labelled according to their light-curve behaviour as rising, falling or slowly-varying (S-var). The black crosses show 45 SNRs in M82 (Huang et al. 1994, their Table 2, scaled to 6 cm assuming* $\alpha = -0.5$*). The evolution of SN1986J during its first 30 years is plotted as a solid curve.*

The most luminous objects in Arp 220 are likely very bright radio SNe or SNRs, observed near their peak luminosity, which in the following years will expand and fade similar to other bright radio SNe such as SN1986J. The brightest (at 6 cm) object 0.2195+0.492 is modelled as a radio SN with an unusually long 6 cm rise time of 17 years, see Fig. 3.15.

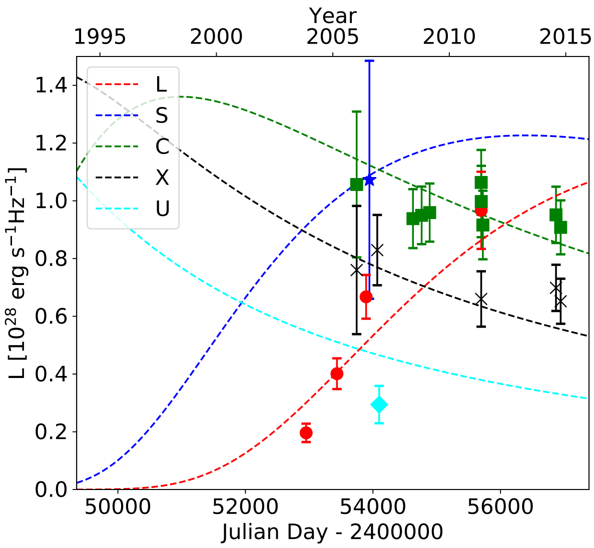

Figure 3.15: *Best-fit lightcurve (spectral luminosity vs time) model overplotted on the observed detections of the brightest object 0.2195+0.492.*

We find a compact source luminosity function (LF) with slope -2.19 ± 0.15, similar to

SNRs in normal galaxies (Chomiuk & Wilcots 2009), and we argue that there are many more relatively large and weak sources below our detection threshold. Extrapolating the LF below our detection threshold we find that the population make up at most 20% of the total radio emission from Arp 220 at GHz frequencies. However, secondary cosmic rays (CRs) produced when protons accelerated in the SNRs interact with the dense ISM, and/or re-acceleration of cooled CRs by overlapping SNR shocks, may increase radio emission compared to the extrapolated value.

Future high-sensitivity observations, ideally using global VLBI including eMERLIN baselines, could possibly constrain the origin of the missing smooth radio component by sampling the full range (arcsecond to milliarcsecond) of spatial scales. Such observations may also allow further studies of the evolution of source lightcurves and sizes for the existing sample, as well as detections of new rising sources as well as old sources currently below the detection threshold.

Published in: Varenius et al. (2019).

3.3.2 Finding a "giant" jet launched by an Intermediate-Mass Black hole in a dwarf galaxy

J. Yang et al.

Intermediate-mass black holes (IMBHs) have masses from one hundred to one million times of solar masses ($M_\odot$). With the EVN observations, a rarely-seen powerful jet associated with the central IMBH of the dwarf galaxy SDSS J090613.77+561015.2 (hereafter short name J0906+5610) has been discovered.

It is very hard to find light IMBHs in the local Universe because of the rapid growth of galaxies and BHs. Finding these nearby "leftover" objects would play an important "ground truth" role in exploring the formation and growth of seed BHs and jet activity in the very early Universe.

To date, radio jets or steady radio-emitting polar outflows compact on sub-pc scales have been revealed in only one dwarf galaxy, NGC 4395 at a distance of 4.4 Mpc. The dwarf elliptical galaxy J0906+5610 hosts an IMBH with a mass of about 400 000 $M_\odot$ at 193 Mpc. To strengthen the identification of its accreting IMBH and search for jet activity, a group of astronomers, led by Dr. Jun Yang, has performed the EVN observations of J0956+5610. The observations reveal two 1-mJy extended features. In Fig. 3.16, the yellow cross and circle mark the central position and the error circle of the optical counterpart. The northern feature in the top region is located in the yellow circle and most likely represents the inner jet base or emerging jet component powered by the accreting IMBH. The southern bottom feature is the more elongated and might be a dying jet component ejected in the early time. The radio structure can be only explained as a consequence of the IMBH jet activity because there is no evidence for the significant stellar activity in the host galaxy.

Compared to the first IMBH jet in NGC 4395, the second IMBH jet in J0906+5610 has ~160 times larger structure and ~100 000 times higher radio luminosity. This finding indicates that more IMBH jets would be detectable in particular in the nearby dwarf galaxies with the existing and future radio facilities.

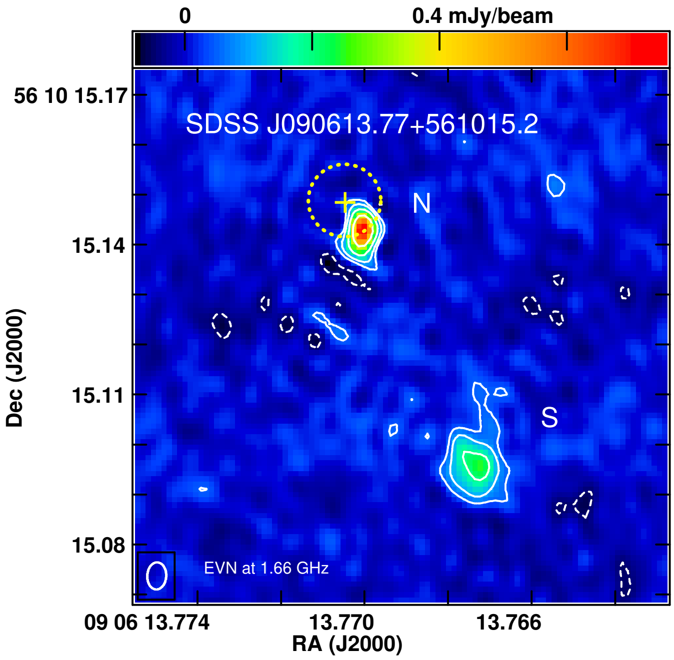

Figure 3.16: *A two-component brightness distribution found by the EVN at 1.66 GHz in the dwarf galaxy SDSS J0906+5610 hosting an accreting IMBH. The yellow cross and circle mark the optical (Gaia DR2) centroid and the error circle. The contours increase by a factor of two.*

Published in: Yang et al. (2020)

3.3.3 The "home address" of the H_2O gigamaser in TXS 2226- 184

G. Surcis et al.

TXS 2226-184 is an elliptical/S0 galaxy located at a distance of about 110 Mpc that is spectroscopically classified as a LINER, evidence for the presence of AGN and/or enhanced nuclear starburst activity. The weak radio emission from the core (see 3.17, from Taylor et al. 2004) is produced by a jet that extends over 100 pc (see Fig. 3.17). This galaxy gained importance in the extragalactic maser community because it is the site of one of the most luminous extragalactic H2O maser ever observed (about 6000 solar luminosities; Koekemoer et al., 1995, Nature, 378, 697). Because of its unprecedented extreme luminosity, this maser source was labeled as "gigamaser". Since its discovery in 1995, no interferometric observations aimed to determine its absolute position have been conducted till 2017, when we started a series of VLBI observations with the VLBA (epoch 2017.45) and the EVN (epochs 2017.83 and 2018.44). In the last EVN epoch, we also carried out polarimetric observations to try the detection, for the very first time, of the polarized emission of an extragalactic H2O maser.

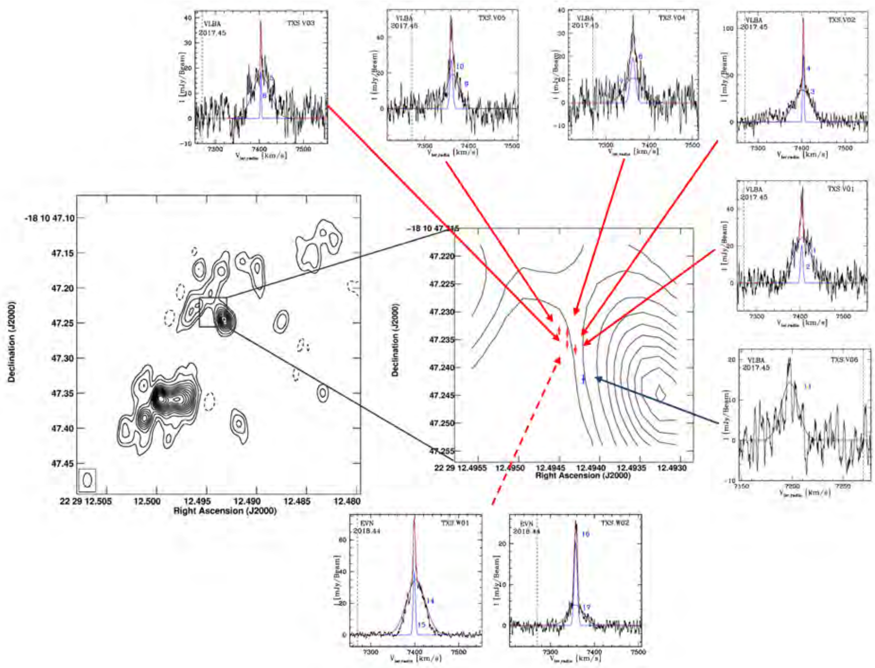

Figure 3.17: *Location of the red- and blue-shifted H_2O masers with respect to the systemic velocity of the galaxy detected with the VLBA in epoch 2017.45 (crosses). The six spectra (small panels) from top to the right are the H_2O masers detected with the VLBA in epoch 2017.45 (solid-line arrows), the two spectra at the bottom are the H_2O masers detected with the EVN in epoch 2018.44 (dashed-line arrow). The continuum (left panel and zoom-in inset) is the 1.4 GHz emission of the nuclear region of TXS 2226-184 as observed with the VLBA in 2002 (Taylor et al. 2004). For more details see Surcis, Tarchi, & Castangia 2020.*

We succeeded in measuring the absolute position of the H_2O maser both with the VLBA and with the EVN; the measured positions agree within the uncertainties, confirming the potential contribution of the EVN also in this kind of studies. The EVN, in fact, is rarely used for determining the absolute position of extragalactic masers due to the limited frequency coverage of the K-band receivers installed at some of the European antennas that, in some case, cannot cover the extragalactic H_2O maser line (note that the frequency of the line in extragalactic object is offset from the rest frequency because of the Doppler effect, sometimes by up to one or more gigahertz). Unfortunately, no polarized emission was detected (Pl< 15%). However, this provides a relevant lower limit for similar future measurements.

We found that the H_2O maser emission originates close to the most luminous north clump of emission detected by Taylor et al. 2004; in particular, the blue- and red-shifted maser features follow the arc-like morphology of the radio continuum emission of the brightest knot in the clump (see Fig. 3.17). However, what the maser features trace is still uncertain because the position of the nucleus of the galaxy is unknown yet. We can identify three possible scenarios considering the continuum emission as produced by a jet-outflow. Case I: the black hole of the AGN is located in the gap between the two largest continuum emissions. In this case the maser features trace a shock due to the jet oriented SE-NW (jet-like maser). Case II: the black hole is located in the most luminous north clump. Two options are viable: the black hole is at the center of the continuum emission (case IIa) or the black hole is where the H_2O maser features arise (case IIb). In case IIa the H_2O maser features trace a jet oriented SW-NE (jet-type maser) while in case IIb they trace an edge-on accretion disk oriented SW-NE (disk-type maser). It is possible to wonder if the profile of the H_2O maser features can help to disentangle the nature of the maser. Actually, this adds more uncertainty. Indeed, the single-dish profile of the H_2O maser (e.g., Surcis, Tarchi & Castangia, 2020) shows only one group of maser features around the systemic velocity of the galaxy and it does not show the other two satellite groups, which are typically present in disk-type masers. On the other hand, the single-dish profile shows a notable stability over a time span of years, which is rarely found in jet/ outflow associated masers.

Further ongoing multi-frequency EVN observations of the radio continuum in the nucleus will allow us to determine the nature of the different radio knots and will help to disentangle between the aforementioned scenarios, providing a definite answer on the puzzling nature of the "gigamaser" in TXS2226-184.

Published in: Surcis, Tarchi, & Castangia (2020)

3.3.4 The most detailed imaging of the blazar's 0716+714 jet from space-Very-Long-Baseline-Interferometry observations

E. Kravchenko et al.

Blazars are a class of active galactic nuclei (AGN) that show extreme variability on various timescales. It is commonly accepted that they are powered by accretion onto super massive black holes, which is accompanied by formation of two-sided relativistic jets. Due to preferential orientation close to the line of sight ($\sim 5^\circ$), they exhibit apparent superluminal speeds of a few tens of the speed of light (Hovatta et al. 2009), which yields significant enhancement of their emission. These mechanisms make AGNs to be one of the most powerful objects in the Universe.

0716+714, known as one of the most active blazars on the sky, was the first AGN imaged with the *RadioAstron* space VLBI mission that featured a 10 m antenna on board of the Spektr-R satellite (Kardashev et al. 2013). Few years later, in 2015, new high-resolution polarimetric observations of the blazar have been conducted within the *RadioAstron* Polarization Key Science Program that focuses on the polarimetry of the most active and highly polarized AGNs in the sky (Lobanov et al. 2015, Gómez et al. 2016). The experiment was performed with the space antenna and eleven radio telescopes of the European VLBI Network (EVN) at 22 GHz (wavelength $\lambda = 1.3$ cm). As a result, the most detailed to-date radio image of 0716+714 jet has been constructed (Kravchenko et al. 2020), at an unprecedented resolution of 24 μas, shown in Fig. 3.18.

On this image we revealed that the visible base of the jet (or the radio core) remains unresolved, meanwhile we captured significantly bent structure of the central 100 μas, such that the jet initially extends toward the southeast and then bends toward the more-larger-scale structure. We suggest that due to the small viewing angle of the 0716+714 jet, of about 5° (Jortsad et al. (2017), and the intrinsic opening angle of the outflow of $\sim 2°$ (Pushkarev et al. 2017), we observe the jet directly from inside. Therefore, the inner jet may appear bent as individual emerging features are ejected at different position angles that are amplified by projection effects. Additionally to this, we detect compact linearly polarized component located about 58 μas downstream from the core. Presence of such compact structures in the 0716+714 jet can explain strong intrinsic variability of the blazar in total and polarized intensities on the timescales of about two days to a week. Though, the nature of much faster, intra-day variability of 0716+714 (Koay et al., 2018) still remains an open question.

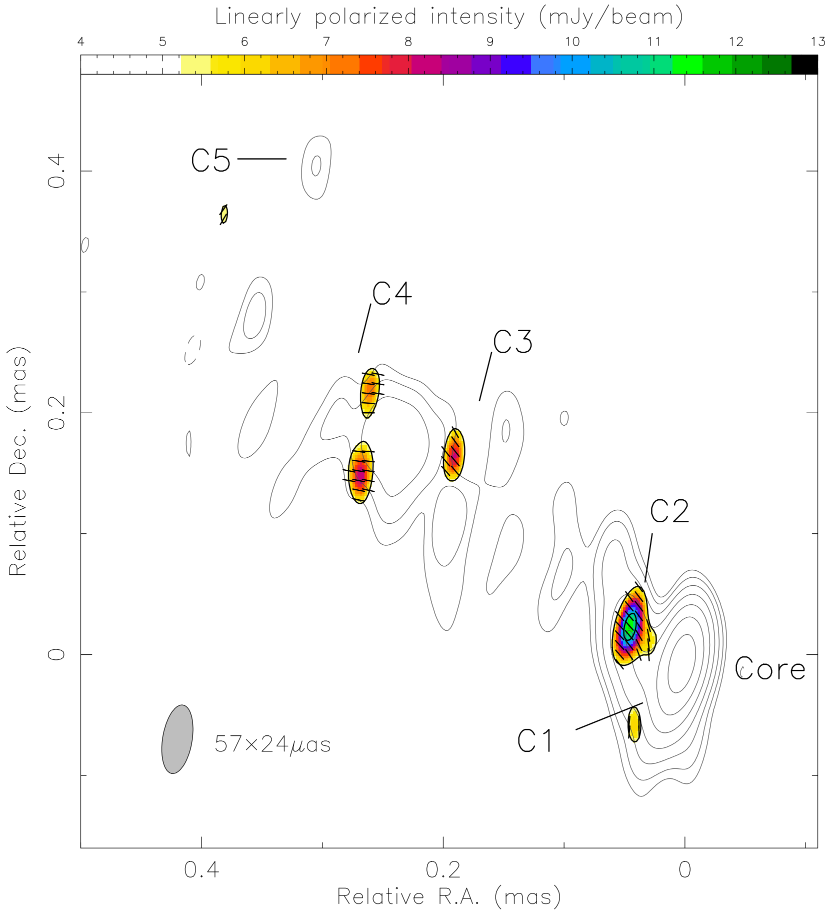

Figure 3.18: *The most detailed image of 0716+714 jet from 22 GHz RadioAstron observations (Kravchenko et al. 2020). "Super" uniform weighting of the visibility function was applied. Black contours depict the total intensity, and linearly polarized intensity is given in color. Black short sticks indicate observed polarization position angles (i.e. uncorrected for the Faraday rotation). The modelled radio core and emission jet features are indicated. Shaded ellipse displays the synthesized beam.*

Published in: Kravchenko et al. (2020)

3.4 Gravitational lensing

3.4.1 Strong lensing reveals jets in a sub-microJy radio-quiet quasar

P. Hartley et al.

Despite their discovery in the radio, most quasars produce relatively little radio emission. Consequently, the emission mechanism within so-called radio quiet quasars (RQQs) has been difficult to observe directly, and continues to be hotly debated. This means that the phenomenological description of the one of the largest radio source populations remains incomplete. For galaxy evolution models, feedback processes during the most common state of existence of an AGN are not understood. The radio behaviour of RQQs has largely been investigated using statistical studies, which variously cite either starburst, coronal or AGN jet activity as the dominant emission mechanism. By using strong gravitational lenses as cosmic telescopes in combination with the very high resolution and sensitivity of the EVN, we can instead constrain the emission mechanism by directly imaging it. To this end, a team led by Neal Jackson (Jodrell Bank Centre for Astrophysics, Manchester) undertook 1.65 GHz VLBI observations of HS 0810+2554, a RQQ located at z=1.51 which is magnified and quadruply-imaged by a lensing galaxy located at approximately z=0.8.

The resulting maps (Hartley et al. 2019) find a clear detection of two highly compact source components (Figure 3.19) with brightness temperatures exceeding the limit from starburst activity, pointing instead to the presence of small-scale AGN jets. Additional observations made using e-MERLIN find a relatively steep spectral index in both components, ruling out possible coronal emission from the AGN core. A final piece of evidence results from modelling of the lensed pattern in combination with HST data, revealing a linear alignment of twin radio components on opposing sides of the optical quasar core, with the typical morphology of a compact symmetric object (CSO) (Fig. 3.20). Magnification values obtained from the model determine an intrinsic source brightness of just 880 nJy per beam: the faintest radio source ever imaged. Thanks to lensing, the components are not only visible, but with the EVN are imaged to an intrinsic scale of just 0.27 pc: the highest ever resolution image of a RQQ. The model points to a non-smooth mass distribution in the lensing mass itself, hinting at the presence of dark matter substructure which has manifested as astrometric perturbations of the VLBI lensed images.

Given that this lensed RQQ has been found by Stacey et al. (2018) to fall on the radio–FIR correlation, the latest observations lead the team very tentatively to suggest that radio–FIR correlation cannot always be used to rule out AGN activity in favour of star-formation activity. The correlation - or at least its scatter - may conceal the coexistence of kinetic and radiative feedback modes within AGN. With new EVN data from two other RQQ soon to be analysed, the team will be able to test this hypothesis. Detection of more jetted sources in this region would demand an urgent review of the use of the correlation to classify star-forming and AGN activity within low-power radio sources.

Published in: Hartley et al. (2019)

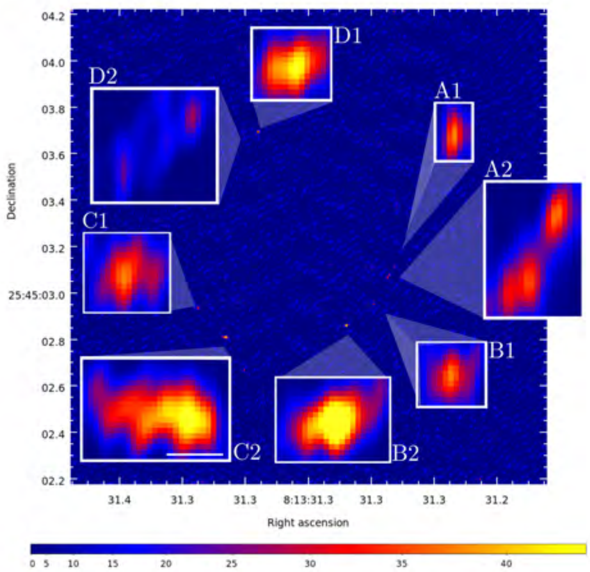

Figure 3.19: *EVN image of HS 0810+2554 at 1.65 GHz produced using a natural weighting scheme. The peak surface brightness is 52 μJy per beam, at component B2. The beam is at full width of half maximum (FWHM) at 12.0 $\times$ 8.5 mas at a position angle of $-3°$. The nomenclature of Reimers et al. (2002) is assigned to respective pairs of components associated with background sources 1 and 2.*

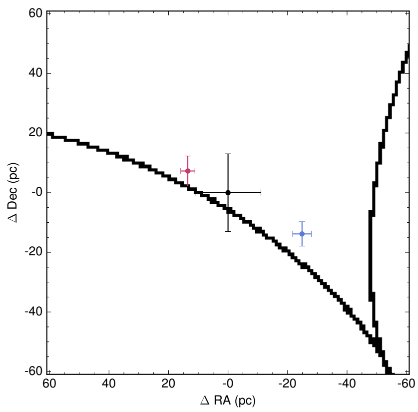

Figure 3.20: *Reconstruction of the lensed sources using both HST (black) positions and VLBI (blue and red) positions from the best-fit EVN+HST model. The black curve represents the lensing tangential caustic, which is traced back to the source plane from points in the lens plane where magnification reaches theoretical infinity. Positional uncertainties were obtained from the Multinest Bayesian sampling tool and are represented at 1 sigma by the error bars. The components are plotted in the source plane at z = 1.51, assuming a standard flat cosmology with Ω_m = 0.27 and H_0 = 68 km/s/Mpc.*

3.5 Development of new techniques and software

3.5.1 A CASA-based fully automated Very Long Baseline Interferometry calibration and imaging pipeline

M. Janssen et al.

The Common Astronomy Software Applications (CASA) package has become the primary software tool for the reduction of radio interferometric data sets, most prominently for connected element interferometers like ALMA and the VLA. For VLBI data, CASA was missing a few crucial calibration capabilities and its precursor, the Astronomical Image Processing System (AIPS), has been the standard calibration tool so far. Recently, a joint effort from JIVE and Radboud University supported by the BlackHoleCam and RadioNet projects in collaboration with NRAO has led to the augmentation of the CASA package with all required VLBI functionalities (e.g., a fringe-fitting task), making it possible to reduce both connected element interferometer and VLBI observations with the same software package. CASA has the advantages of an intuitive IPython user interface resulting in a low learning curve for new generations of radio astronomers, an active software development and support, a built-in MPI standard satisfying the need for hardware scalability of future observations, and batch processing for science reproducibility is easily facilitated.

Based on the recent VLBI upgrades, a CASA-based VLBI data reduction pipeline called the Radboud PIpeline for the Calibration of high Angular Resolution Data (rPICARD) has been developed. The code is publicly available and is published by Janssen et al. (2019). The primary purpose of the pipeline is the calibration of VLBI data, but it can also be used to reconstruct images with the CASA multi-scale multi-frequency synthesis tclean task (Fig. 3.21, right panel). Using self-tuning parameters (an example is shown in the left panel of Fig. 3.21), rPICARD is able to deliver high quality calibrated data without human interaction. On the other hand, many parameters can be manually adjusted. Every step of the pipeline can be re-run effortlessly and verbose diagnostics are created so users can quickly review how well the calibration worked. The idea is that users blindly calibrate their data in a first step, check if the science goals can be reached, and re-run specific steps with adjusted parameters as needed for severe data issues. The pipeline is able to reduce data from any standard VLBI array, including the EVN, VLBA, HSA, GMVA, and EHT. It was used by a team at Radboud University Nijmegen and IRA-INAF Bologna as one of three independent calibration pipelines that lead to the EHT results published in 2019, revealing the first image of a black hole.

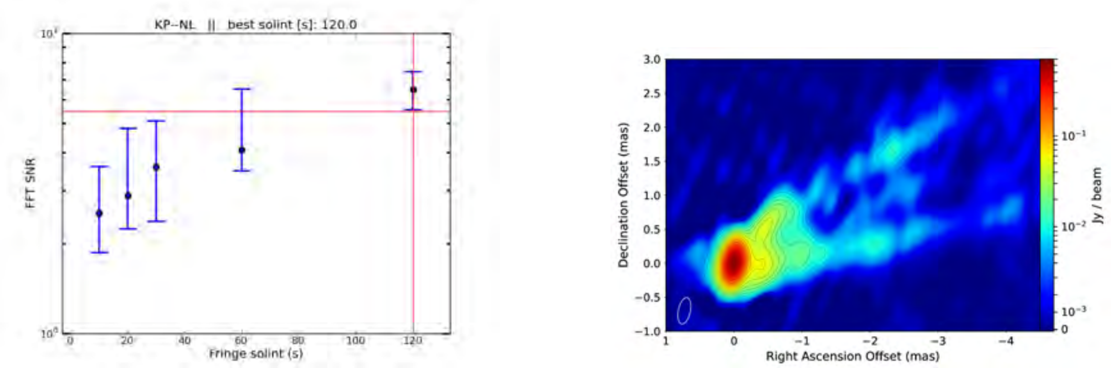

Figure 3.21: *Results from the rPICARD pipeline. The left panel shows how rPICARD optimizes the fringe-fit solution interval for a baseline between the KP and NL antennas for 86 GHz data. The data is segmented with different intervals, which results in the ranges of SNR shown in blue. Increasingly longer intervals are tried until the median SNR is above the threshold of 5.5 for a 120s solution interval, which yields robust fringe detections within narrow delay and rate search windows. The right panel shows an image reconstruction of the 7mm jet of M87 based on VLBA data calibrated and imaged with rPICARD.*

Published in: Janssen et al. (2019)

3.5.2 Precise radio astrometry and new developments for the next-generation of instruments

M. Rioja & R. Dodson

The field of astrometry, through the measurement of the precise positions of astronomical objects, is a fundamental tool for astrophysics. Radio astrometry with VLBI provides the highest accuracy and precision in astronomy. The next-generation of radio instruments coming online will open up a new era for VLBI studies, resulting from widely applicable ultra-high precision radio astrometry, to perform large unbiased surveys of many objects, at a much wider range of frequencies (hundreds of MHz to hundreds of GHz) than those available today. The next-generation data analysis methods are fundamental in allowing us to reach the potential of the new instruments, by reducing the magnitude of systematic errors.

We have combined traditional and new analysis techniques into a common framework, which paves the way to improve the astrometric accuracy by an order of magnitude. The predictions from this framework allow the easy identification of the dominant astrometric error contributions, arising from: propagation media effects, source pair angular separation (*hereafter systematic errors*) and instrumental sensitivity (*hereafter thermal errors*). Fig. 3.22 shows the thermal error limit for the typical DR of 100:1 achievable with current instruments (shown with grey dotted line). Similar simple estimates based on sensitivity indicate that up to 1 μas astrometry should be routinely achievable with the next-generation instruments, i.e. SKA-VLBI and ngVLA. However it is clear that the analysis with conventional, or even advanced, methods will be dominated by systematic errors (shown with solid lines), preventing one from reaching the potential of the new instruments.

Basic methods (Conv. PR in Fig. 3.22), relying on alternating observations between the target and a reference source, are suitable for measuring positions accurate to about a mas at $\sim$1 GHz, and 20-30 μas at 22 GHz, for 1° pair angular separation (the black line in Fig 3.22 shows the predicted performance). For high frequencies (>8 GHz) advanced tropospheric calibration (ATC, green line), such as GeoBlocks, can achieve position errors of 10 μas, at 22GHz. For low frequencies (<8 GHz), position errors of 0.1 mas are reachable using advanced ionospheric calibration (AIC, blue line), but at L-band the main advances came from the regular detection of a very close calibrator source (In-beam $PR_{10'}$; brown line), made possible with improved sensitivities.

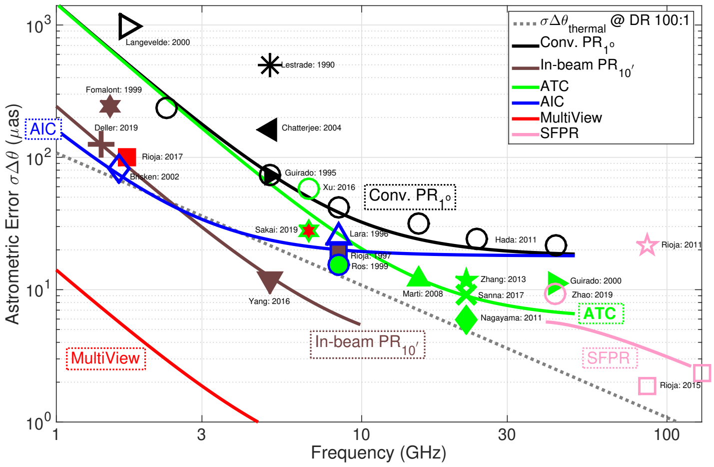

Figure 3.22: *Present: High-precision astrometric performance over a range of frequencies, achieved with different methods (solid lines) and the potential of current instruments (grey dotted line). Overplotted are examples from the literature. See text and paper for details.*

Next-generation methods of Source/Frequency Phase Referencing (SFPR, pink line) and MultiView (MV, red line) open up the domain for ultra-precise astrometry up to hundreds of GHz and improve on In-beam $PR_{10'}$ systematics by an order of magnitude, respectively. SFPR relies on dual frequency observations and uses the solutions at the lower frequency to provide an optimum compensation of tropospheric residuals at the higher frequency. MV uses observations of multiple calibrators around the target to construct a 2D phase surface and deduce precise atmospheric corrections for the target. Overplotted with symbols are a host of "real-life" astrometric precision achieved over the last 3 decades, using the same colour scheme described above. The measurements and predictions show a good agreement.

In order to achieve ultra-precise astrometry with next-generation instruments, these must be equipped with multi-beam systems such as multi-feeds and PAFs, and simultaneous multi-frequency receivers such as the wide single feed systems (e.g. BRAND system and similar developments) and multi-path multi-band systems (e.g. the KVN system and similar developments).

Fig 3.23 brings together measurements of residuals and shows that SFPR and MV offer matching systematic limits (pink and red solid lines, respectively) to the predictions of the thermal astrometric errors (grey dotted line) of the next generation telescopes. This results in 0.1 mas astrometric errors at 300 MHz and 1 μas errors at 6.7 GHz and up to 130 GHz, per epoch. This leads to innovative high-impact science possibilities across the full radio frequency spectrum, examples of which are included in the figure. Finally we note that there is no implicit upper-limit for the application of SFPR and related dual-frequency techniques, which would also be suitable for applications on the ngEHT.

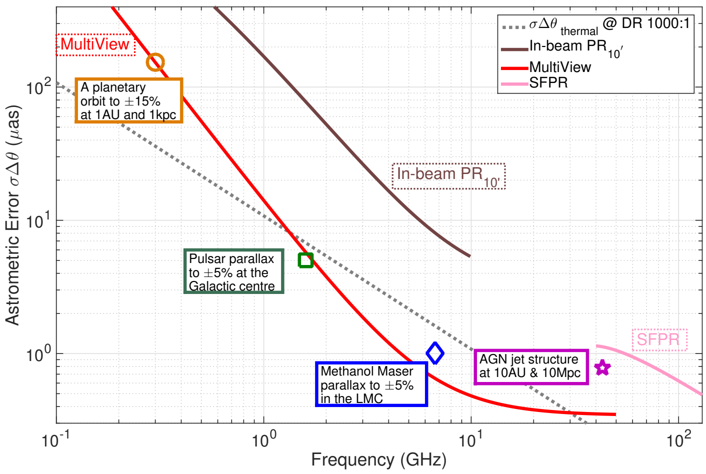

Figure 3.23: *Future: Ultra-precise astrometric performance with the next-generation of instruments (thermal, grey dotted line) and methods (systematics, solid lines). See text and paper for details.*

Published in: Rioja & Dodson (2020)

3.5.3 A novel approach to visibility-space modelling of interferometric gravitational lens observations at high angular resolution

D. Powell

Modern VLBI arrays now provide us with milli-arcsecond angular resolution images of strong gravitational lens systems at high signal-to-noise ratios. This is a powerful tool for studying astrophysical phenomena, including the evolution of high-redshift galaxies and the particle nature of dark matter. However, properly modelling these data sets poses a computational challenge due to both the large number of radio visibilities (as high as 10^{10}) and the high image resolution needed to pixellate the sky.

In Powell et al. (2020), we develop a Bayesian forward-modelling technique for simultaneously reconstructing the source brightness and the lens mass in a self-consistent way from VLBI observations. Our method requires no pre-averaging or other data reduction steps prior to modelling, which sets it apart from previous approaches to this problem.

We achieve this by expressing the sky-plane covariance (which is formally a dense matrix with $>\sim 10^{12}$ elements) as a convolution with the dirty beam of the instrument, which is rapidly computed using an FFT. The dirty beam and dirty image are computed using a non-uniform FFT (NUFFT), which consists of a visibility gridding operation, an FFT, an apodization correction, and a zero-padding operation applied sequentially; this gives an accuracy better than 10^{-8} relative to the expensive direct Fourier transform. We perform the gridding operation and FFT on a GPU, which drastically accelerates the computation. Inversion of the source is done using a preconditioned conjugate gradient solver (which requires a convolution with the dirty beam at each iteration), and the lens model parameters are optimized using gradient descent. We apply a custom preconditioner for the conjugate gradient solver, which speeds convergence.

We verify the performance and accuracy of the method on a mock dataset created from the global VLBI observation of the lensed quasar MG J0751+2716 (Spingola et al. 2018). This observation was taken over 18.5 hours using 24 stations from the EVN and VLBA at a data rate of 512 Mbit/s. After correlation, the observation consists of 2-second integrations in 256 spectral channels and 2 polarizations for a total of 7×10^8 visibilities. We insert our own known sky and lens models and combine the polarizations for testing purposes. Using this mock observation, we verify that this technique recovers the source surface brightness with 1 percent accuracy, and the lens model parameters within a fraction of a percent. We also measure the speed of the modelling process; for this mock observation and a source containing 5.4×10^5 pixels, we are able to fully optimize the source brightness and lens model in 15 hours using one GPU. This includes ~ 250 gradient descent steps, which each require a source inversion taking ~ 4 minutes. Note that these performance figures include some algorithmic improvements implemented after the acceptance of the paper.

We are encouraged by the performance of this method, and excited to apply it to observational data. Already, Rizzo et al. (2020) have published a paper in Nature examining the kinematics of a z=4 galaxy in unprecedented detail. We are currently using VLBI observations of strong lenses to constrain the dark matter particle mass. In the future we would also like to include self-calibration as a part of the forward model itself. We note that our method is not limited to gravitational lens modelling, but can also be used as a stand-alone radio imager, which could prove invaluable for future dense arrays like SKA with ~ 200 antennas. With VLBI as an established observational tool, we hope that others will find this modelling technique to be useful in achieving their own science goals as well. We encourage the reader to refer to our publication (Powell et al. 2020) for further details.

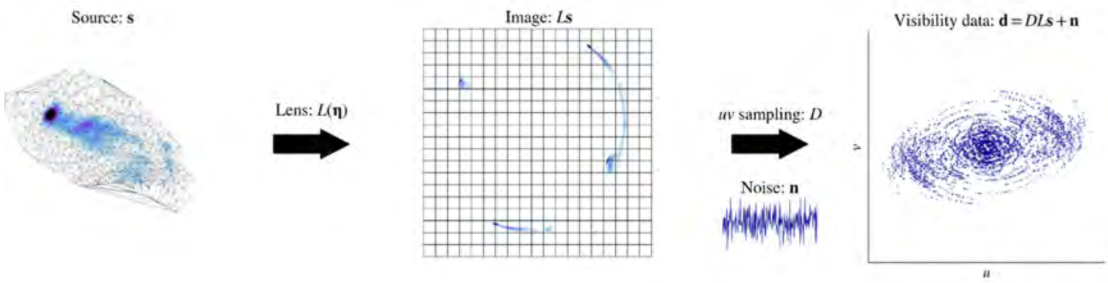

Figure 3.24: *A schematic of the forward-modelling process for VLBI data. The source brightness is represented on a Delaunay tessellation, which naturally adapts to the magnification provided by the lens (Vegetti and Koopmans 2009). The lens operator maps the source brightness into the sky plane. The simulated instrument response is then applied using an FFT to arrive at model radio visibilities.*

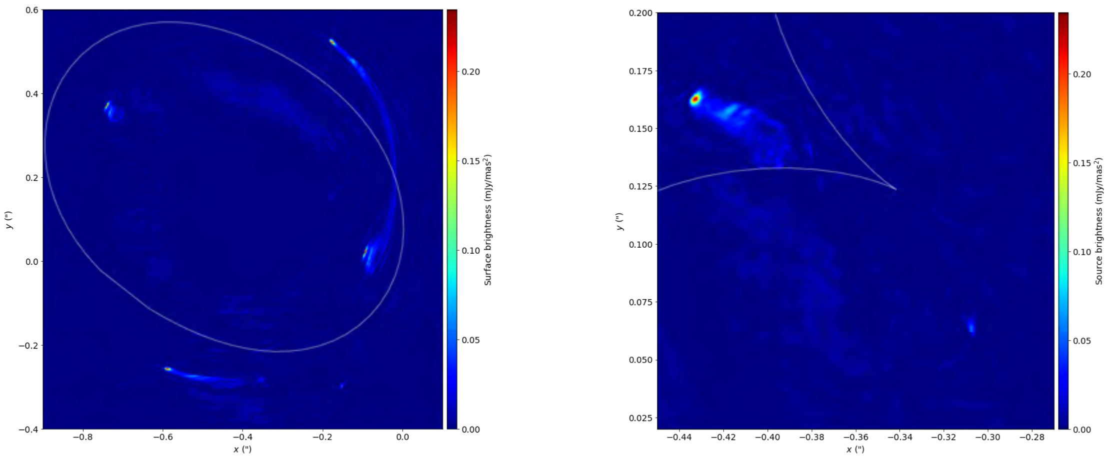

Figure 3.25: *Pixellated sky (left) and source (right) models of the lensed quasar MG J0751+2716 obtained using our method. Critical curves of the lens are plotted in white.*

Published in: Powell et al. (2020)

4 EVN Network Operations

4.1 The EVN programme committee report

The EVN Program Committee (PC) is an independent body appointed by the EVN CBD, which carries out the scientific and technical assessment of all standard EVN, e-VLBI and global VLBI requests for observing time. The EVN PC consists of 13 voting members, 8 drawn from the EVN institutes and 5 *at-large* representatives from other European institutes. In addition, the EVN Scheduler and the EVN Correlator Representative attend PC meetings as non-voting members. Members typically serve on the committee for a period of around 3 years, and are then replaced by other representatives invited by the EVN CBD. The PC membership through 2019-2020 is listed in Table 4.1, including the NRAO and GBO representatives, and the e-MERLIN TAG chair who contribute to the EVN PC.

4.1.1 EVN PC meetings

The EVN PC meets three times a year, typically around a month after each proposal deadline, to discuss recent proposals received, to allocate a grade to each successful proposal, and to provide detailed feedback to each PI. Meeting locations and dates for the period 2019-2020 are given in Table 4.2. The meetings in 2020 have been held partially to completely via Zoom due to the Covid-19 pandemic.

All standard EVN, EVN+e-MERLIN, global VLBI and e-VLBI proposals are evaluated at the PC meetings, for observations in upcoming standard and e-VLBI scheduled sessions. Each EVN PC member provides a review and a pre-grade of the proposals before the meeting, then a thorough discussion on each proposal and the final evaluation are carried out during the meeting itself. For proposals requesting the inclusion of the e-MERLIN array, the e-MERLIN Time Allocation Group is consulted for their approval (based on the justification given for e-MERLIN inclusion). For the consideration of global VLBI proposals, independent grades are provided by NRAO and GBO. In addition, voting members from NRAO join the PC meetings for extended discussions (see Table 4.1). Summary comments as well as the detailed comments of each PC member are sent to the PI afterwards. Target of Opportunity proposals received outside formal deadlines are circulated to PC members by the PC Chair, grades and feedback being returned to the PI typically within a few days.

Table 4.1: List of members of the EVN PC during 2019-2020 and their roles.

Name	Institute	Role
Ivan Agudo	IAA-CSIC Granada, ES	*At-large* member until July, 2019
Tao An	Shanghai Observatory, CN	Member
Danielle Fenech	Univ. of Cambridge, UK	*At-large* member until Jan., 2020
Jan Forbrich	Univ. of Hertfordshire, UK	*At-large* member from Feb., 2020
Krisztina Gabányi	Eötvös Loránd Univ., Budapest, HU	*At-large* member from Oct., 2019
Talvikki Hovatta	Univ. of Turku, FI	*At-large* member from Dec., 2017
Michael Lindqvist	OSO, Göteborg, SE	Member
Andrei Lobanov	MPIfR, Bonn, DE	Member
Iván Martí-Vidal	Univ. Valencia, ES	*At-large* member from Aug., 2019
John McKean	ASTRON, NL	Member
Alexey Melnikov	IAA RAS, St. Petersburg, RU	Member
Tom Muxlow	JBCA, UK	Member
Francesca Panessa	INAF-IAPS, IT	*At-large* member until Dec., 2020
Zsolt Paragi	JIVE, NL	Member (vice-chair)
Kazi Rygl	INAF-IRA, IT	Member (chair)
Valeriu Tudose	ISS Bucharest, RO	*At-large* member until Sep., 2019
Bob Campbell	JIVE, NL	EVN correlator representative
Alastair Gunn	JBCA, UK	EVN scheduler
Mark Claussen	NRAO, US	NRAO VLBA/VLA Scheduler
Toney Minter	GBO, US	GBO Scheduler
Mark Sargent	Univ. of Sussex, UK	e-MERLIN TAG chair

Table 4.2: PC Meetings during 2019-2020.

Place	Date	Period
ISS, Bucharest, RO	March 21,2019	Trimester 19A
Brindisi, IT	July 2, 2019	Trimester 19B
INAF-IRA, Bologna, IT	November 19, 2019	Trimester 19C
Partially Zoom @ JBO, UK	March 12, 2020	Trimester 20A
Fully Zoom @ MPIfR, DE	June 25, 2020	Trimester 20B
Fully Zoom @ JIVE, NL	November 11, 2020	Trimester 20C

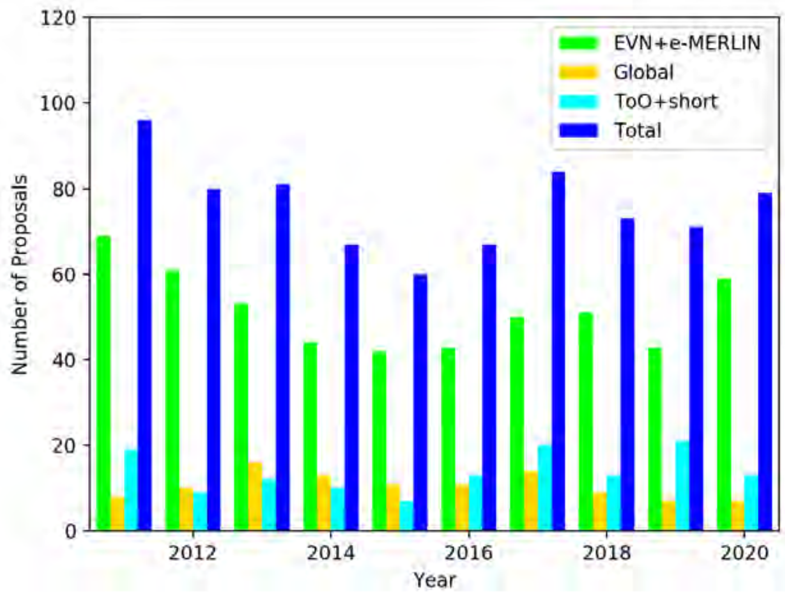

Figure 4.1: *Total number of proposals received between 2011 and 2020 (dark blue), subdivided into EVN+e-MERLIN proposals at the regular deadlines (lime), global proposals at the regular deadlines (yellow), and Target of opportunity and short observing proposals (cyan).*

4.1.2 Proposal statistics

The EVN operates an open-sky observing policy with proposals scheduled into 3 main observing sessions per year, plus regular (monthly) additional e-VLBI days. A Call for Proposals is distributed three times a year, with proposal deadlines on 1st February, 1st June and 1st October. It is also possible to submit Target-of-Opportunity (ToO) proposals. Proposal statistics from 2011 to 2020 are shown in Fig. 4.1. The total numbers of hours proposed and the EVN network hours are shown in Fig. 4.2. Since the peak in proposal numbers in 2011, the numbers have subsided somewhat. In 2019 relatively few proposals were received at the regular deadlines, though there was an increase in ToO and short observation proposals. In hours proposed, 2019 and 2020 show a slowly increasing trend from the minimum seen in 2018, but the numbers are still low with respect to 2011-2015 period. The total network time has remained roughly the same. The over-subscription rate for 2019-2020, (hours requested)/(EVN network hours), stands at 1.7.

From 2019, the inclusion of the full e-MERLIN array became available. A steady rise in demand can be seen over 2019-2020: from 25% of the proposals in the 2019A trimester up to 71% of the proposals in the 2020C trimester. The number of global proposals stayed relatively stable at an average 12% of the total proposals (ranging between 8 to 16% over 2019-2020).

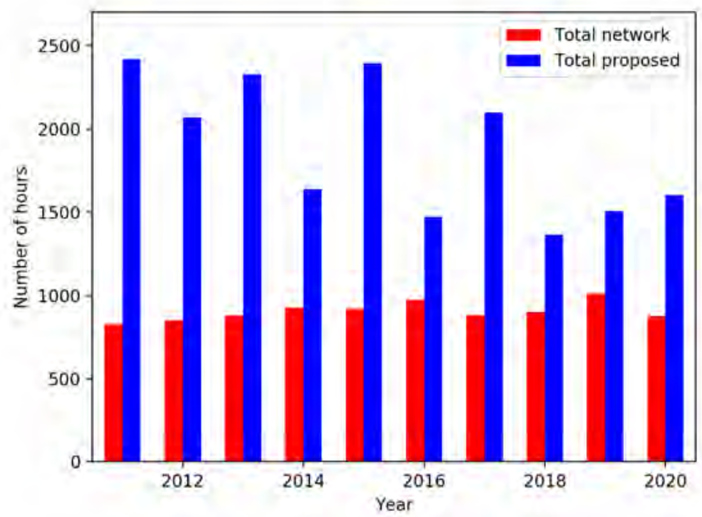

Figure 4.2: *Proposed number of EVN Network hours and total proposed hours between 2011 and 2020.*

4.1.3 Requested science research areas and observing bands

The dominant research areas are those of AGN/Jets, Stars/YSOs, and Transients which account for about 70% or more of proposals received (Fig. 4.3). With respect to the previous biennial reports, Transient science has grown strongly in popularity thanks to new phenomena such as the Fast Radio Bursts, but also due to a significant number of proposals targeting supernovae, stellar tidal disruption events, X-ray binaries and other transient sources.

The requested frequency bands are dominated by these research areas resulting in large numbers of proposals requesting the 18/21 cm and 6 cm bands. However, the remaining bands are still rather populated with proposal requests (see Fig. 4.4).

There is a large international pool of users of the EVN and Global VLBI array which stretches beyond the EVN member institutes and countries. Although the majority of PIs are based within Europe, a significant amount of EVN users are found worldwide.

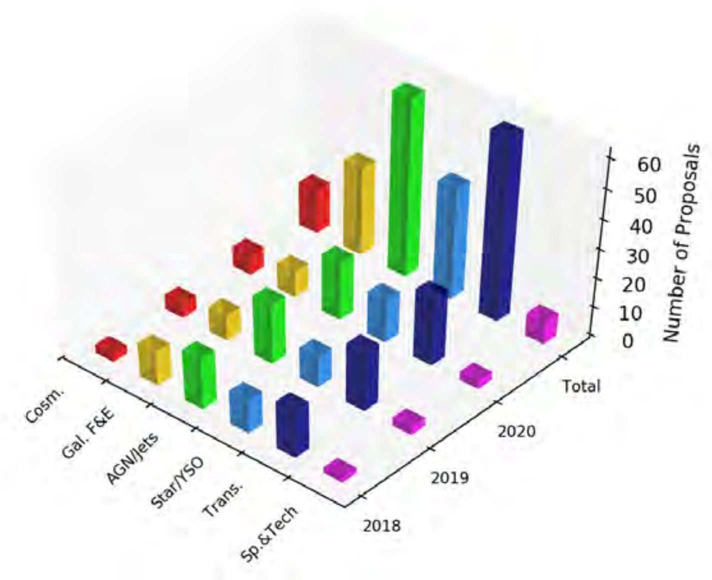

Figure 4.3: *The distribution of scientific categories (Cosmology, Galaxy Formation & Evolution, AGN/Jets, Stars/YSOs, Transients, Space and Technology) for proposals submitted from 2018 to 2020.*

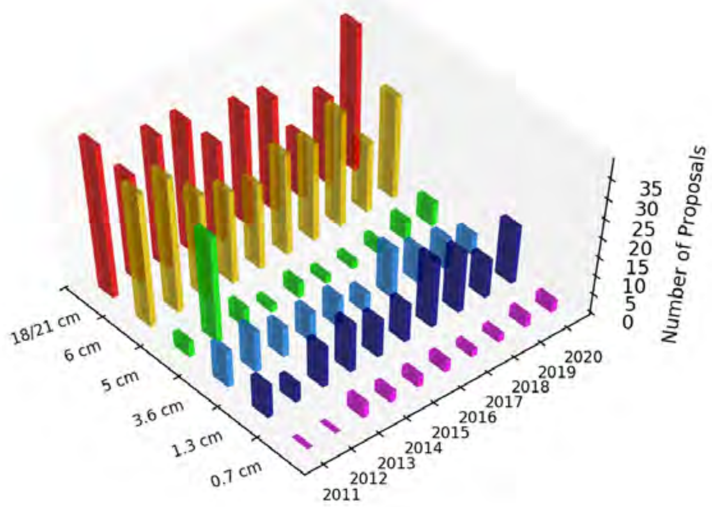

Figure 4.4: *Distribution of requested wavelength bands for regular proposals submitted from 2011 to 2020. In addition, some proposals request 90 and 13 cm.*

4.2 Scheduling and Operations

As in previous years, in each of 2019 and 2020 there were three major (disk-based) EVN observing sessions, each of three weeks duration, and ten e-VLBI runs of up to 24 hour duration (plus 4 hours fringe-finding time). The basic parameters of the regular disk-based sessions are summarized in Table 4.3. Table 4.4 and Table 4.5 give further details of the regular disk-based EVN sessions for 2019 and 2020 respectively.

Observations in each disk-based session utilised between five and six different observing bands. The efficiency (defined as the percentage of available time actually scheduled) in the disk-based sessions ranged from 27.6% to 61.1%. This efficiency is primarily dictated by the time needed to change observing band and the demand on GST range (which is far from uniform). The lower than usual efficiency in EVN Session II 2020, and the corresponding drop in observing hours, was due to COVID-19 restrictions which prevented some experiments being performed, particularly global and joint EVN+e-MERLIN observations.

Figure 4.5 shows the distribution of EVN hours against observing band for 2019 and 2020. These figures include hours observed during regular disk-based EVN sessions, eVLBI runs and out-of-session observations. C-band and L-band observations were the most common in 2019, whilst K-band was more popular than C-band in 2020.

Table 4.3: Summary of regular EVN Sessions 2019-2020.

Session	**Dates**		**Length**	**Efficiency**	**Wavelength (cm)**						
					0.7	1.3	3.6	5	6	18/21	92
2019-I	21 Feb	14 Mar	21.0	44.3		✓	✓	✓	✓	✓	
2019-II	23 May	13 Jun	21.0	61.1		✓	✓	✓	✓	✓	
2019-III	17 Oct	7 Nov	21.0	60.3		✓	✓	✓	✓	✓	
2020-I	20 Feb	12 Mar	21.0	53.0	✓	✓	✓	✓	✓	✓	
2020-II	28 May	18 Jun	21.0	27.6		✓	✓	✓	✓	✓	
2020-III	15 Oct	5 Nov	21.0	60.9		✓	✓	✓	✓	✓	

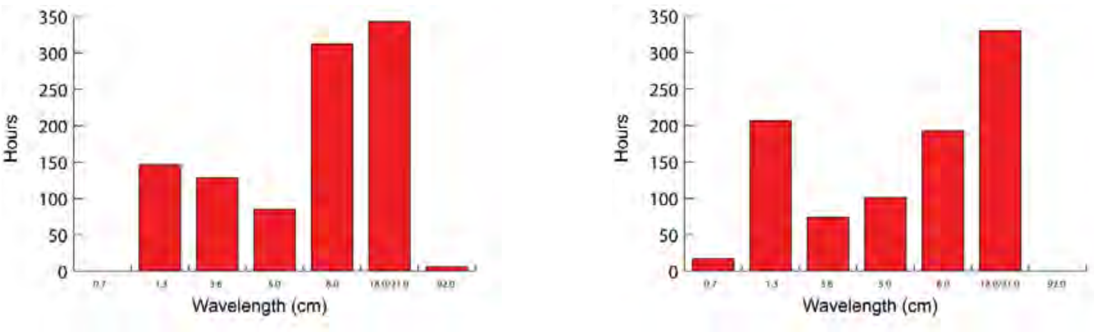

Figure 4.5: *Distribution of EVN hours against observing waveband for 2019 (left) and 2020 (right).*

Table 4.4: Details of EVN Sessions in 2019, showing the number of observations, hours and TBytes scheduled, correlators used and number of observations for associated antennas.

	Session 2019-I			**Session 2019-II**			**Session 2019-III**		
	No	Hours	TBytes	No	Hours	TBytes	No	Hours	TBytes
Total	34	224.0	1496.1	37	308.0	1560.6	37	304.0	2809.4
EVN-only	22	152.0	835.3	30	272.0	1425.4	28	272.0	2554.0
Global	4	51.0	570.9	2	21.0	75.1	2	14.0	174.2
Short	1	4.0	27.6	0	0.0	0.0	2	3.0	26.3
Tests	7	17.0	62.3	5	15.0	60.1	5	15.0	54.9
Correlators									
EVN	34	224.0	1496.1	37	308.0	1560.6	37	304.0	2809.4
Bonn	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
VLBA	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
eEVN	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
Other	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
CAL	5	20.0	0.0	5	20.0	0.0	5	20.0	0.0
Associated antennas									
e-MERLIN	3			8			6		
VLBA	4			2			2		
VLA	0			0			0		
GBT	0			0			2		
Arecibo	1			4			6		
Robledo	1			0			0		
KVN	4			3			5		
Wettzell	3			0			0		
Kunming	0			0			0		
LBA	3			0			1		

In 2019 the total number of hours scheduled was 1125.0 and in 2020 it was 924.0. In 2019, 836.0 hours were scheduled within regular sessions, 188.0 hours within eVLBI sessions, and 101.0 hours as out-of-session observations. In 2020, 714.5 hours were scheduled within regular sessions, 191.5 hours within eVLBI sessions, and only 18.0 hours as out-of-session observations.

Over this two-year reporting period, 272 separate observations were performed, of which 185 were standard experiments, 15 were global experiments, 33 were network monitoring or fringe-finding experiments, 16 were EVN 'short' observations and 23 were target-of-opportunity observations. The 239 science experiments performed in 2019-2020 came from 87 regular proposals, 15 'short' proposals and 16 target-of-opportunity proposals. During the same period there were 9 triggered observations during eVLBI sessions.

Figure 4.6 shows the distribution of observing hours against EVN station and affil-

Table 4.5: Details of EVN Sessions in 2020, showing the number of observations, hours and TBytes scheduled, correlators used and number of observations for associated antennas.

	Session 2020-I			Session 2020-II			Session 2020-III		
	No	Hours	TBytes	No	Hours	TBytes	No	Hours	TBytes
Total	39	267.0	2211.4	24	140.5	753.7	35	307.0	2491.8
EVN-only	32	235.0	1926.4	19	125.5	711.6	28	264.0	2257.6
Global	1	14.0	224.9	0	0.0	0.0	1	24.0	139.2
Short	0	0.0	0.0	0	0.0	0.0	1	4.0	36.9
Tests	6	18.0	60.1	5	15.0	42.1	5	15.0	58.1
Correlators									
EVN	39	267.0	2211.4	24	140.5	753.7	35	307.0	2491.8
Bonn	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
VLBA	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
eEVN	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
Other	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
CAL	6	24.0	0.0	5	20.0	0.0	5	20.0	0.0
Associated antennas									
e-MERLIN		6			0			14	
VLBA		2			0			1	
VLA		2			0			0	
GBT		2			0			0	
Arecibo		1			2			0	
Robledo		2			0			2	
KVN		3			4			8	
Wettzell		1			0			3	
Kunming		0			0			5	
LBA		0			0			0	

iate antennas for 2019 and 2020. This shows that joint e-MERLIN observations are becoming more popular as the integration process has become easier. Kunming, Irbene and Sardinia are now regular contributors to the network whilst Shanghai has not been justified by PIs in addition to (or instead of) Tianma for this entire reporting period. Details of EVN eVLBI observations in 2019-2020 are shown in Table 4.6 and details of out-of-session (OoS) EVN observations for 2019-2020 are shown in Table 4.7.

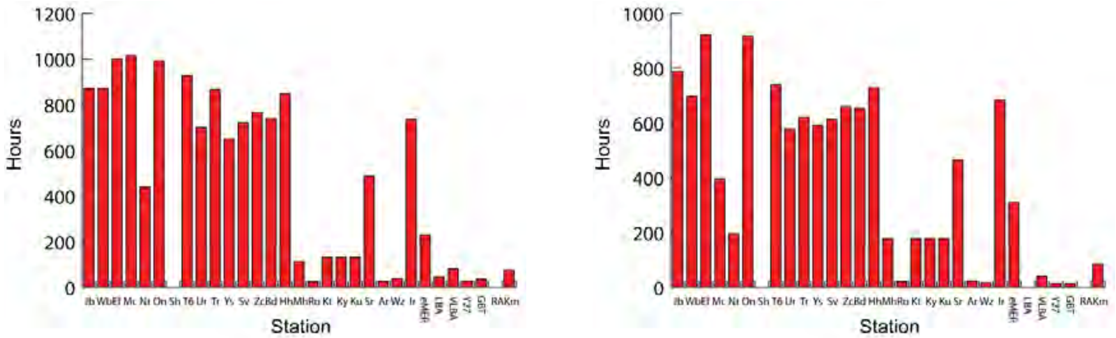

Figure 4.6: *Distribution of observing hours for EVN stations and affiliates for 2019 (left) and 2020 (right).*

Table 4.6: Details of EVN eVLBI runs 2019-2020, showing dates and waveband, number of hours scheduled per run, the type of observation and the number of trigger observations scheduled and actually triggered.

Run	Date	Wavelength	Hours	eVLBI Proposal Type				
				Queued			Trigger	
				Normal	Short	ToO	Scheduled	Triggered
19e01	22 Jan 2019	18cm	18.0	2	2	0	3	0
19e02	14 Feb 2019	6cm	20.5	2	2	1	2	0
19e03	19 Mar 2019	6cm	19.0	2	0	1	4	0
19e04	16 Apr 2019	18cm	11.0	0	0	0	7	1
19e05	14 May 2019	6cm	20.5	1	0	0	4	1
19e06	18 Jun 2019	18cm	24.0	0	1	0	5	2
19e07	17 Sep 2019	6cm	22.0	0	1	1	8	1
19e08	15 Oct 2019	6cm	16.0	0	0	2	6	0
19e09	12 Nov 2019	6cm	13.0	0	2	1	6	0
19e10	03 Dec 2019	18cm	24.0	2	1	0	7	1
20e01	21 Jan 2020	18cm	23.5	2	3	0	7	0
20e02	11 Feb 2020	6cm	6.0	0	0	0	4	1
20e03	17 Mar 2020	18cm	17.5	2	0	0	6	0
20e04	07 Apr 2020	18cm	17.0	2	0	0	6	0
20e05	12 May 2020	18cm	24.0	1	0	1	2	1
20e06	23 Jun 2020	18cm	24.0	4	0	0	2	0
20e07	15 Sep 2020	6cm	24.0	1	0	0	1	0
20e08	06 Oct 2020	6cm	24.0	3	0	0	2	0
20e09	17 Nov 2020	6cm	14.0	2	0	0	6	0
20e10	01 Dec 2020	6cm	17.5	0	0	1	4	1
	Total		379.5	26	12	8	92	9

Table 4.7: Details of EVN out-of-session (OoS) observations 2019-2020 showing number of observations, hours and TBytes scheduled, correlators used and number of observations for associated antennas.

	2019 OoS			2020 OoS		
	Number	Hours	TBytes	Number	Hours	TBytes
Total	10	101.0	259.8	4	18.0	153.4
Correlators						
EVN	3	14.0	8.8	4	18.0	153.4
Bonn	2	44.0	251.0	0	0.0	0.0
ASC	0	0.0	0.0	0	0.0	0.0
eEVN	5	43.0	0.0	0	0.0	0.0
Associated antennas						
e-MERLIN	1			1		
VLBA	2			0		
VLA	4			0		
GBT	4			0		
Arecibo	2			0		
Robledo	2			0		
KVN	2			0		
Wettzell	0			0		
Kunming	0			0		
LBA	0			0		

4.3 The EVN Technical and Operations Group

The Technical and Operations Group (TOG) is made up of the personnel at the EVN stations who provide the technical and operational expertise for operating the EVN as a VLBI array. They are also responsible for advising the EVN Consortium Board of Directors on all aspects of technical and operational issues relevant to the reliability and performance of the network. The TOG is also the body which implements technical and operational upgrades across the network.

The meetings of the TOG take place every 9 months in a different observatory of the EVN to allow a direct exchange of technical expertise and experience between the station personnel. Every 18 months the TOG meeting is held together with a meeting of the GMVA technical group (GTG). The meetings are attended by VLBI friends and technical staff of the stations and the correlators as well as by selected external experts.

Starting from 2019 Uwe Bach from the MPIfR in Bonn chaired the TOG as the successor of Pablo de Vicente from Yebes Observatory, who led the group the previous 4 years. In 2020 Harro Verkouter took over the vice-chair from Arpad Szomoru, who filled this position for almost 8 years. The TOG met three times during the period of this report. The meeting in 2019 was held in June at Jodrell Bank Observatory in the new SKA Headquaters building. The next meeting was planned to be in May 2020 at the MPIfR in Bonn, but due to the world wide pandemic the meeting had to be held virtually. The same was true for the November 2020 meeting that was again held virtually only. Reports from the meetings are available on the RadioNet Wiki[1].

Beside, maintaining the high level of performance achieved in the previous years, the main emphasis of the TOG activities during the period of this report was the reliable operation at an increased recording rate of 2 Gbps for all EVN continuum observations, corresponding to 256 MHz of bandwidth at each polarization, and the preparation for even higher recording rates. Based on the EVN VLBI20-30 scientific roadmap[2] published by the EVN CBD together with many scientists, a technical roadmap was compiled with the most relevant technical developments that should help to achieve the science goals. More bandwidth and wider frequency coverage are the most common requirements for all science fields and the TOG started the discussion of how to achieve this most efficiently.

Significant points to be noted here are (in no particular order):

- 11 stations are using Flexbuffs for data recording and e-transfer to the correlator, which allows flexible scheduling and fast data availability.
- Disk and Flexbuff capacity increased to about 500 TB per station, allowing to record all continuum observations at 2 Gbps.
- Continuous calibration with a noise diode switched at 80 Hz is used at 11 stations as well, which allows more precise measurements of system temperatures and therefore better amplitude calibration of VLBI data.

[1] https://radiowiki.mpifr-bonn.mpg.de/doku.php?id=na:sustainability:tog
[2] https://arxiv.org/abs/2007.02347

- eMERLIN antennas are now available for eVLBI at 512 Mbps and also the KVAZAR stations participate regularly at rates of 1024 Mbps. Therewith, the total number of available eVLBI stations in e-EVN sessions increased to 18.

- Tests for another increase to 4 Gbps data rates using the DBBC2 were successful and first 4 Gbps science observations have been performed. 4 Gbps data rates are available now in the regular call for proposals.

- The implementation of the DBBC3 has been started with tests at the stations and the upgrade of the VLBI Field System to control the DBBC3. Once established the DBBC3 will allow recording rates of 32 Gbps, corresponding to a sampled bandwidth of 4 GHz at each polarization.

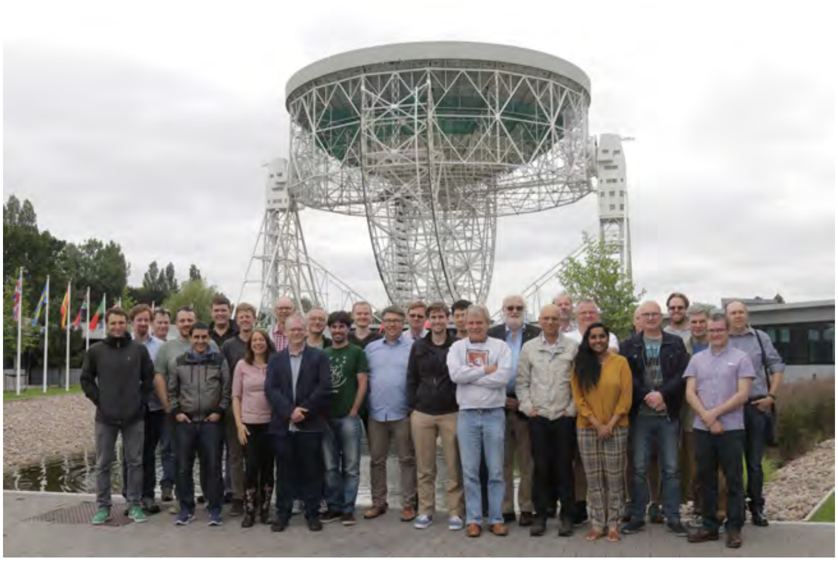

Figure 4.7: *Conference picture taken during TOG meeting at Jorell Bank Observatory (Credit: SKA Organization/ UK).*

5 EVN observatory reports, full members

5.1 ASTRON, The Netherlands Foundation for Research in Astronomy, Dwingeloo, The Netherlands

The Westerbork Synthesis Radio Telescope (WSRT) participated in all EVN sessions of 2019-2020 with a single dish. The total observing hours in the 2019-2020 period, including VLBI and eVLBI observations, are listed in Table 5.1.

Table 5.1: Observed hours per band in EVN Sessions 2019-2020.

Observing band	Hours
L	461.5
C	338.5
M	196
X	208.5
Total	1204.5

In general observations were successful, only a small number of hours were lost due to receiver issues.

For VLBI and RadioAstron the WSRT has two circular Multi Frequency Front Ends (MFFE), which have cooled receivers at 3.6, 6, 13, and 18+21 cm, and uncooled receivers at 49 cm and 92 cm. The MFFEs were placed in the telescopes around 1997, and components are sometimes failing but despite their age they continue to function well.

MASER

In mid 2018 the MASER went out of lock, we managed to repair it but we don't consider the MASER to be reliable anymore also considering its age of almost 21 years. So a new MASER has been ordered and we expect delivery in March 2021.

Before the new MASER arrives we have to change our current LO system. The MFFE needs 180 MHz and 1 MHz for the LO. The current MASER provides 180 MHz. The new MASER provides 5 MHz/10 MHz /100 MHz and 1 PPS. So we have to generate the 180 MHz and 1 MHz. The 180 MHz we generate with a signal generator. We are now in the process of designing a 1 MHz band pass filter.

Flexbuff

Since 2018 there is a Flexbuff installed at JIVE. Only one Flexbuff is needed since there is a direct fiber connection between Westerbork and Dwingeloo. It is equipped with 36 10 TB disks.

Figure 5.1: *Multi Frequency Front End.*

DBBC

The DBBC has four core2boards. The DBBC is running on Windows 7 for security reasons.

5.2 Institute of Radio Astronomy (INAF IRA), Bologna, Italy

5.2.1 Medicina

Antenna

The telescope has been idle from mid-December 2019 to the end of July 2020 due to a couple of mechanical issues. In particular, two steel girders composing the reticular structure that supports the counterweights were broken. Mainly for safety reasons the antenna was stopped and a structural investigation has been done in order to make a survey of the problem on the whole antenna. After the replacement of the broken beams we discovered that one not driving wheel was showing a broken bearing. The time needed to restart the operations has been seriously affected by several delays due to the COVID-19 pandemic.

An active surface system for the Medicina primary mirror has been funded. The upgrade will include new aluminum panels with enhanced surface accuracy, electromechanical actuators to move panels in order to compensate for gravitational deformation and a completely new subreflector with low RMS surface (one will be provided for Noto as well). Once completed, Medicina will be able to observe at high frequencies up to 116 GHz with good overall efficiency. The timeline to complete the project is within 2022.

Receivers and observations

In 2019 INAF succeeded obtaining funding under the programme PON (Programma Operativo Nazionale) issued by the Ministry of Research. This has allowed the purchase of a simultaneous 3-bands receiver (18-26, 34-50, 80-116GHz) to be installed on the radio telescope. The receiver is planned to be available within 2022.

In order to increase the bandwidth of the 18/21cm receivers a wider filter at intermediate IF band replaced the old one.

The IF bandwidth of the 6cm and 5cm receivers has been extended from 400 to 800 MHz.

VLBI back-end

Below we list the firmware and software versions in use:

- Fila10G with V4.1 231118 firmware
- DBBC with v107 firmware
- PFB with v16 Firmware
- Flexbuff still with jive5ab-2.9.0, but the new 3.0 has been installed and tested.

e-VLBI

Medicina is routinely running e-VLBI experiments.

Field System

- The last version we have installed is a new FSL10 Debian machine and we are running the new FS 10.0.0-beta2.
- The continuous cal system is working for the Cassegrain receivers (6, 5 and 1.3 cm) and from session 2/2019 is available also for the primary focus receivers at 3.6 and 18/21 cm.

Feedback report for the EVN sessions

- 2019. No particular problems were found in running the three sessions
- 2020. Due to the stop of the antenna for structural problems Medicina did not participate at the EVN session 1 and 2, but successfully participated at session 3.

5.2.2 Noto

Antenna

The linear actuators moving the subreflector and allowing the primary to secondary focus commutation were refurbished after a mechanical failure (July 2019). The new mechanical system was installed in November 2019. Moreover, during the November 2019 maintenance, some of the actuators of the active surface system were repaired by

Figure 5.2: *The 32 m Medicina radio telescope.*

replacing their control boards and cabling. Presently the whole Active Surface System is up and properly running.

At the end of 2019 we discovered deep "cracks", affecting a large part of the section of two steel girders of the backup structure that supports the counterweights. In order to better check the general status of the mechanical structure of the telescope, IRA assigned a fatigue analysis to an engineering company. The company performed a complete study based on the Finite Element Model (FEM), taking into account only the effects of the gravity (no wind or other factors). A report from the company was delivered in January 2020. It clearly showed that the stress and the strain concentration on the broken steel girders was well beyond the limits of the low cycle fatigue and that type of damage is reasonably traceable to the load cycles during the movements along the elevation. After several months of delay imposed by the pandemy lockdowns, the maintenance (consisting in the replacement of the steel girders) was completed in July 2020.

In November 2020 we replaced an azimuth motor and the bearing coupling the motor to the wheel. This maintenance was forced by a failure that happened during the EVN session at the end of October.

At the end of September 2020 we also had a failure on the mechanical components of the Z Axis (focusing) of the servo system moving the box of the primary focus receiver into position. The problem does not allow to switch between foci so only primary focus frequencies are available (L, S and X band), C, M and K band are not. The repair is planned as soon as the spare parts are procured, probably during spring 2021.

Future plans

A complete refurbishment of the helium pipes to the vertex room and the cooling system of the telescope have been funded by INAF. Presently, the timeline of the task is not defined but our goal is to complete by the end of 2021.

In the framework of the PON (Programma Operativo Nazionale) funding, Noto will be equipped with a simultaneous 3-bands receiver (18-26, 34-50, 80-116 GHz). The receiver will output large bandwidth IFs (K band: 8 GHz, Q Band 16 GHz and W Band 16+16 GHz) that will be down-converted to tuneable, 2 GHz bands. The receiver will be built by KASI and is planned to be available in 2022. Also the PON funding will allow to buy a DBBC version 3. The call for tender has already been issued by INAF.

A new IF distributor to be installed in the control room is under development. The device will automatize and ease the receiver configuration allowing for a better and more reliable setup before the experiments.

The servo system (servo drivers, motors, encoders and power lines) moving the secondary mirror and the primary focus receiver box has been designed and is now being constructed in Medicina. We plan to install it during the second semester 2021.

Receivers

All hardware and software required for the continuous calibration has been installed and is available for L, S, C, M, X and K band receivers. Following a K band lack of fringes during a NME of the first EVN session 2019 we were able to link the issue to the local oscillator, and the synthesizer was promptly replaced with a new one. The L-S-X primary focus receiver was installed in June 2019 and it's now commissioned and fully operative.

Software

A new station computer has been installed in the control room and a new pointing software is now working during VLBI observations. The Field System station programs were updated accordingly.

Time and Frequency

The workstation that monitors and controls the time and frequency lab has been replaced. Some pieces of code were also updated. That led to a sneaky problem with the GPS data that are used to compute clock offsets. The issue was promptly solved with a joint effort with JIVE staff. A new rubidium clock has been purchased and installed as a backup frequency reference.

VLBI back-end

Below we list the firmware and software versions in use:

- FS Version: 9.13.1-rc2
- DBBC fw version: DDC V107, PFB V16
- FiLa10G fw version: 4.1
- Flexbuff sw version: 2.8.1
- Flexbuff disk space: 360 TB

Feedback report for EVN the Sessions

- 2019
  - Session 1: No fringes during K band NME and Fringe test. The C band part of the session showed no evidence of problems.

Figure 5.3: *The 32 m Noto radio telescope.*

  - Session 2: Fringe tests affected by the clock offset issue (see above), anyway the tests showed fringes for Noto.
  - Session 3: Due to the reported failure on the subreflector, only the primary focus receiver was available (L-S-X bands). SX and L band NME did show fringes.

- 2020
  - Session 1: Due to the damage on the reported mechanical structure, Noto did not observe.
  - Session 2: Due to the damage on the reported mechanical structure, Noto did not observe.
  - Session 3: Only L and X band were available. FTP Fringe test showed fringes in X band.

Some tests and user experiments not observed because of the reported failure in the azimuth wheel.

5.2.3 Sardinia Radio Telescope (SRT)

Antenna

The system tests, calibration, and re-commissioning of the antenna after the heavy maintenance of the active surface system ended in May 2019. The Sardinia Radio Telescope has been awarded one of the grants recently announced by the Italian Ministry of Education, Universities and Research (MIUR) aimed to enhance research infrastructures, pursuant to Action II.1 of the National Operative Programme – Research and Innovation 2014-2020.

Thanks to this grant SRT will be equipped with new high-frequency receivers and backends by 2021. The new receivers are a simultaneous microwave compact triple-band receiving system, a multi-beam cryogenic receiver in W Band (75 – 116 GHz), a multi-beam cryogenic receiver in Q Band (33 – 50 GHz), and a millimetre camera (80 – 116 GHz). The DBBC3 backend will be purchased and installed at Sr by 2021. In addition, a metrology system will also be installed to allow high efficiency performances at the highest operating frequencies. The extension of the optical fiber cable up to 10 Gbps was done on the 29th of December 2018. After a successful test in January 2019 the fiber link is used regularly during e-VLBI sessions since January 2019 up to the highest recording rates that have been scheduled.

The flexbuff units (one at JIVE and one at SRT, of 360 Tb each) were successfully installed and fully operational since session 2/2019.

The hardware required to implement continuous calibration (80 Hz) has been installed for observing at M and K band. Since session 01/2020 the continuous calibration is regularly used at M band, more tests are still necessary at K band.

After the observations of the first SRT call of proposals, that started on the 11$^{\text{th}}$ of December 2018 and finished in May 2019, there have been other four (the deadline of the fifth call of proposal was on the 5$^{\text{th}}$ of October 2020). The antenna had a technical problem with the cooling system of the servo drives in mid May 2020 that required an important maintenance activity that ended in August 2020. The reason for this long period of maintenance was due to the COVID-19 crisis that slowed down the shipping and installation of the new machines. Due to the long inactivity we performed antenna tests during September 2020. The antenna was ready to observe at the end of September 2020. Besides the aforementioned maintenance, the SRT regularly operated during the Covid-19 crisis both as single dish antenna and as VLBI antenna.

Receivers

P, L, M and K band receivers are fully operational. The receivers under development/construction are:

- dual pol, single feed, C band. Advanced status.
- dual pol, 5 feeds, S band. Advanced status.
- see also the antenna section above.

VLBI

Below we list the firmware and software in use:

- Field System: 10.0.0-beta3 for 64 bits
- DBBC: DDC (v107_281019), PFB (16)

Figure 5.4: *The 64 m Sardinia radio telescope.*

- Fila10G: v4.1_231118
- Jive5ab: 3.1.0

Feedback report for the EVN Sessions

The Sardinia Radio Telescope participated in the PI experiments of session 01/2019, 02/2019, 03/2019, 01/2020, 03/2020 with all the available and scheduled receivers (L, M, and K band). Fringes were obtained at all bands during the ftp-fringe tests. The antenna missed part of the observations of the EVN session 02/2019 due to an antenna control problem, and all the observations of the EVN session 02/2020 due to the technical problem mentioned above (see Antenna section). Sr participated in one Out-of-Session observation on the 17^{th} November 2019 (L band).

e-VLBI

We successfully took part to the e-VLBI sessions on the 22^{nd}-23^{rd} January 2019 (L band), on the 3^{rd}-4^{th} December 2019 (L band), on the 21^{st}-22^{nd} January 2020 (L band), on the 17^{th}-18^{th} March 2020 (L band), on 7^{th}-8^{th} April 2020 (L band), on the 6th-7th October 2020 (L band) at full data rate. The e-VLBI sessions in February 2019, March 2019, May 2019, September 2019, October 2019, November 2019, February 2020, September 2020, November 2020, and December 2020 were missed because they were made at C band (unavailable at SRT). The SRT also missed the observations of April 2019 (antenna unavailable), June 2019 (antenna control problem), and May 2020 and June 2020 because of the technical problem with the cooling system of the servo drives (see Antenna section).

5.3 Institute of Applied Astronomy (IAA), St. Petersburg,Russia

5.3.1 QUASAR VLBI Network

The Institute of Applied Astronomy of Russian Academy of Sciences is the host institution of the Quasar VLBI Network. The network includes three VLBI observatories: Svetloe near St.Petersburg, Zelenchukskaya in the Northen Caucasus and Badary in the Eastern Siberia. Each observatory is equipped with the 32-m dish fully steerable radio telescope RT-32 (marked as Bd, Sv, and Zc, respectively), and co-located GPS/GLONASS, DORIS, and SLR systems.

Figure 5.5: *The QUASAR 32 m radio telescopes. From left to right: Zc, Sv and Bd.*

IAA observatories are equipped with the 13.2-m dish VGOS radio telescopes marked as Zv, Bv, and Sw, respectively, and are in test operation at present.

Figure 5.6: *Zv 13.2 m radio telescope at Zelenchukskaya.*

Table 5.2: IAA personnel involved in EVN activities.

Position	Name	email)
Director	Dmitry Ivanov	dvi@iaaras.ru
VLBI friend	Mikhail Kharinov	kharinov@iaaras.ru
Technical friend	Andrey Mikhailov	agm@iaaras.ru
Scheduler	Mikhail Kharinov	kharinov@iaaras.ru
PC member	Alexey Melnikov	aem@iaaras.ru
Disk module shipments	Svetlana Akkuzina	sveta24@inbox.ru

Observations

During the period 2019 – 2020 the Quasar VLBI Network performed various astrometric/geodetic and astrophysical VLBI observations of domestic ("Ru-E" weekly 22-h sessions for EOP, "R-I" daily 1-h e-VLBI sessions for UT1, "Ru-A" 24-h astrometric session with the collaboration of Spain and China) and international projects with our partners: IVS, EVN, KaVA (KVN+VERA), and EAVN.

The 32-m radio telescopes Sv, Zc, and Bd participated in 6 regular EVN sessions and in 16 out-of-session blocks (including e-VLBI) with a total duration of: Sv 47 days, Zc 58 days, Bd 48 days. In addition, the radio telescopes of the Quasar VLBI Network were used in IVS experiments with the total duration: Sv 70 days, Zc 60 days, Bd 66 days.

Antennas

In 2019 from April till May 9 the Bd antenna was stopped because of an azimuth wheel break.

During 2020 on all RT-32 Quasar antennas the panels of secondary dish were replaced with new: Zc on August 18-31; Sv on September 7-15; Bd on September 23-30. Furthermore, the antenna control system of the 32-m radio telescope was upgraded on all observatories.

Receivers

All RT-32 radio telescopes are equipped with receivers in the following bands: L, S, C, X, and K.

In April 2020 the L, S/X, and K band receiver systems in Bd were upgraded to the new dual-channels units and the measured parameters are in Table 5.3.

Table 5.3: Calibration temperature and system temperature for the different receivers.

Band	L (RCP/LCP)	S (RCP/LCP)	X (RCP/LCP)	K (RCP/LCP)
T_{cal} (K)	4/3	16/17	3/3	1.8/0.9
T_{sys} (K)	14/13	27/14	15/12	24/25

5.3.2 IAA Correlator Centre

IAA Correlator Center

The IAA Correlator Center is located in St.-Petersburg, Russia and maintained by the Institute of Applied Astronomy. The main goal of the IAA Correlator Center is processing geodetic, astrometric, and astrophysical observations made with the Russian Quasar VLBI network. At present, 3 correlators are involved in this processing: ARC, RASFX, and DiFX.

ARC

The ARC (Astrometric Radiointerferometric Correlator) is the main geodetic data processing instrument in the IAA Correlator Center for the UT and EOP determination. The ARC is a 6-station and 15-baseline correlator. It is able to process up to 16 frequency channels on each baseline for a total of 240 channels. The correlator is able to handle two-bit VLBI signals with 32 MHz maximum clock frequency. The maximum data rate from each station is 1 Gbit per second. The correlator uses VSI-H input signals and it is equipped with Mark5B playback systems. The ARC was designed and built in the IAA RAS in 2007 - 2009. The correlator is the XF type one and based on FPGA technology.

RASFX

In 2014 the Russian Academy of Sciences' FX (RASFX) 6-station near-real time GPU-based VGOS correlator was developed[1]. During the reporting period the RASFX correlator was mainly used for processing of the geodetic VLBI observations of the Quasar VLBI Network. More than 2500 1-hour S/X ("R") and more than 700 S/X/Ka ("R-X") wideband intensive sessions for UT1-UTC determination using RT-13 radio telescopes have been processed. 1-hour "R-I" daily and 22-hour "Ru-E" weekly sessions in the legacy geodetic mode with RT-32 telescopes have been processed by RASFX as well.

RASFX has also been used for a spacecraft signal processing, and for non-routine purposes. In particular, more than 300 laboratory and field sessions were processed for determining instrumental errors of the receiving and recording equipment of the RT-13 in different modes which affect the accuracy of the UT calculation.

DiFX

Almost all IAA VLBI observations are processed using the DiFX software correlator running the latest stable version (currently DiFX–2.6.2), except for the international sessions of IVS, EVN, and projects with KaVA and EAVN. Combined correlation of mixed sessions with the RT-32 and RT-13 radio telescopes are performed using "zoom band" mode of DiFX. Astrophysical and spacecraft VLBI processing utilize DiFX high spectral and time resolution capabilities.

RASFX HPC cluster

[1] Ken V., Surkis I., et al. IAA VGOS GPU-based Software Correlator: current status and broadband processing. Proceedings of the 22nd European VLBI Group for Geodesy and Astrometry Working Meeting processing. p. 40-42

Both software correlators, RASFX and DiFX (since 2015), are installed on RASFX hybrid blade HPC cluster which consist of 40 servers (8 Intel R2216GZ4GCLX servers and 32 blade servers V200F of the T-Platforms Corp.), each with 16 Intel cores and 2 GPUs Nvidia Tesla K20m. The servers are connected to each other by the InfiniBand local-area network based on Mellanox switches that allow simultaneous transmission at the speed of up to 56 Gb/s. Intel servers are designed to receive input data stream up to 16 Gbps. The cluster also includes the Panasas data storage of 190 TB capacity. The parallel LINPACK benchmark ranked the performance of RASFX HPC cluster as 85.34 Tflops.

5.4 Jodrell Bank Observatory, University of Manchester, UK

Jodrell Bank Observatory (JBO) performed a total of 164 regular EVN experiments during 2019-2020. Fifty-four experiments at 18/21cm, 53 at 6cm, 23 at 5cm and 34 at 1.3cm were scheduled to use Jodrell Bank's Lovell and Mk2 antennas. During this period, 34 of the EVN experiments were joint e-MERLIN projects (more than twice the previous reporting period), all of which were observed simultaneously rather than contemporaneously.

A total of 1251.0 hours of telescope time was scheduled for regular EVN observations during 2019-2020. This consisted of 250.5 hours on the Lovell telescope and 1000.5 hours on the Mk2 telescope. In terms of waveband this was 479.5 hours at 18/21 cm, 302.5 hours at 6 cm, 166.0 hours at 5 cm, and 303.0 hours at 1.3 cm. The total reported data loss at the telescope for 2019-2020 was 48.6 hours (3.9%), i.e. a success rate of 96.1%. JBO also contributed 116.0 hours of observing time to out-of-session experiments (targets of opportunity) and a further 308.5 hours of observing time for 20 regular eVLBI observing sessions during 2019-2020.

A new hydrogen maser was installed at JBO and is now feeding timing signals to all equipment. This includes the Field-System VLBI-equipment (DBBC, Fila10G etc.) and also the e-MERLIN WIDAR correlator and synthesizers, which are used for e-MERLIN-VLBI operations. The new maser performs well and appears more stable than the old one in the sense that residual rates in the data due to the maser drifting should now be reduced.

e-MERLIN-VLBI operations continue with some improvements. e-MERLIN stations are now available to routinely join the EVN in both recorded and real-time (eVLBI) VDIF observations at 512 Mbps. The WIDAR correlator optical-fibre corrections are now turned off by default, which produces smoother residual rates and delays in the correlated data. e-MERLIN now participates in all eVLBI operations for which it is approved, adding significant sensitivity and UV-coverage to the EVN. There has been a corresponding noticeable increase in the number of joint e-MERLIN programs during this reporting period.

The JBO-JIVE fibre connection has been upgraded to 5.5 Gbps, allowing real-time eVLBI observations with one DBBC2/Fila telescope at 2 Gbps (Lovell/Mk2) plus up to 6 e-MERLIN WIDAR telescopes at 512 Mbps each. Network hardware was purchased to upgrade the e-MERLIN WIDAR VDIF streams from the current limit of 512 Mbps (64 MHz dual pol) to 1 Gbps (128 MHz dual pol). However, this requires substantial hardware changes to the e-MERLIN correlator, either (a) waiting delivery of 3-bit sampler hardware, or (2) performing irreversible and risky modifications to the correlator station boards. No decision has yet been made as to which route to take but there remains the possibility that JBO will be able to commission 1 Gbps e-MERLIN VLBI observations in the medium-term.

The Jodrell VLBI equipment has been rationalised and put in new RFI-shielded racks. Furthermore, a new UPS has been installed to feed all VLBI equipment, protecting it against power outages. Finally, network, power and RF cables have been significantly simplified, reducing the interdependence of VLBI hardware with other JBO activities.

This has made the JBO VLBI equipment easier to maintain and operate, as well as simplifying possible future upgrades to the systems.

The Fila10G developed an intermittent fault during this reporting period whereby power was lost and could only be returned with one of the optical modules removed. This has been determined to involve the 3.3V power circuit. It was sent to Bonn for investigation in late 2019/early 2020. Two poorly crimped connectors were found in the 3.3V power circuit but their repair did not fix the problem. Further investigation revealed that the connections on the wires going from the 3.3V PSU to a terminal block were also badly crimped. Replacing these wires seemed to cure the problem. However, plans are being made to upgrade to the DBBC3 unit, in line with other stations, thereby bypassing the need for a Fila10G unit.

COVID-19 restrictions imposed by the University of Manchester meant that all JBO telescopes, including all e-MERLIN outstations as well as on-site antennas, were shut down prior to Session II 2020. However, the Mk2 telescope was returned to operations just before the start of EVN Session II. Hence, the session was much reduced compared to usual and involved no joint EVN+e-MERLIN projects. Operations were returned to normal, although with reduced on-site access, by EVN Session III in 2020.

Figure 5.7: *The Lovel radio telescope and Neowise comet above. Credit: Anthony Holloway, Jodrell Bank Centre for Astrophysics.*

5.5 Max-Planck Institut für Radioastronomie, Bonn, Germany

The Max-Planck Institut für Radioastronomie (MPIfR) was a founding member of the EVN and played a full role in all EVN activities in the period 2019–2020. Its 100 m telescope in Effelsberg is a crucial element of many EVN observations due to its very high sensitivity and wide range of observing frequencies (see section 5.5). The MPIfR Correlator Centre, a joint facility of the MPIfR and the German geodetic VLBI community (see section 5.5), continues to play a role for some EVN projects, notable those involving the Russian space–VLBI project RadioAstron. The institute operates, supervises, and correlates the Global Millimetre VLBI Array projects, and is a major partner and stakeholder in the Event Horizon Telescope project, taking 50% of its correlation duties, among other tasks.

MPIfR staff involvement in EVN activities

EVN CBD

Prof. J. Anton Zensus attended meetings. Uwe Bach attended the meetings in his role as TOG chair.

EVN PC Andrei Lobanov attended meetings as the MPIfR representative, and was Secretary of the Committee.

EVN observations in Effelsberg

Uwe Bach was the "VLBI Friend" at Effelsberg, responsible for the execution of EVN observations.

EVN correlation at MPIfR

Helge Rottmann took over the position as head of the MPIfR Division of VLBI Technology from Walter Alef in Nov 2019. The department is responsible for the MPIfR Correlator Center and VLBI technical developments. Mikhail Lisakov was responsible for the correlation of EVN–RadioAstron projects. Jan Wagner was enhancing the DiFX software correlator capabilities e.g. to enable closed-loop correlation after the failure of the RadioAstron on-board H-maser .

Technical developments for the EVN

Michael Wunderlich, Sven Dornbusch and Marcus Offermanns were responsible for the DBBC2 and DBBC3 VLBI backend development and maintenance. Development of the BRAND digital receiver was carried out by Michael Wunderlich, Sven Dornbusch and Armin Felke. Walter Alef was the BRAND project manager and was responsible to coordinate the work carried out by the international partners of the RadioNet JRA.

EVN TOG

Walter Alef, Uwe Bach, Yurii Pidopryhora and Helge Rottmann attended TOG meetings. Uwe Bach became the new TOG Chair in 2019.

MPIfR staff involvement in other VLBI activities

VLBA, HSA and RadioAstron:

Alex Kraus, as Effelsberg Scheduler, coordinates joint observations with these facilities. Olaf Wucknitz was a member of the RadioAstron Program Evaluation Committee (RPEC) in 2017 and 2018.

GMVA

The organization of the Global 3 mm VLBI Array (GMVA) is led by MPIfR staff. Thomas Krichbaum, in conjunction with GMVA PIs, made the integrated, detailed observing schedule for each session, and organized observing support at Effelsberg and IRAM. Eduardo Ros took over the role of European GMVA Scheduler in 2019 from Richard Porcas (the USA scheduler is Mark Claussen). He organized the dates of observing sessions (including the participation of ALMA), administered the GMVA proposal review, and planned the Block Schedule for sessions. Helge Rottmann took over the position as Head of the GMVA Technical Group (GTG) from Walter Alef in 2019 and was responsible for overseeing technical aspects of the GMVA, in particular issues of recording compatibilities between the GMVA and ALMA. Walter Alef and Helge Rottmann participated in the ALMA phasing project (APP). Helge Rottmann supported observations at Pico Veleta and ALMA. Yurii Pidopryhora served as the GMVA support scientist and oversaw the correlation of GMVA data at the Bonn correlator.

EHT

Anton Zensus is member of the Event Horizon Telescope (EHT) Consortium; he was chair since its constitution in 2015 until October 2020, since then he is Founding Chairman. Eduardo Ros was the Executive Secretary of the Board until October 2020. Thomas Krichbaum is a member of the EHT Science Council. Rocco Lico (at MPIfR until July 2020) is secretary of the Project Management Team. Alan Roy lead the “VLBI at APEX” project, and was responsible for equipping the APEX telescope for VLBI observations with the EHT at 1 mm, and for making observations. Jan Wagner oversaw the correlation of EHT observations at the MPIfR correlator. Rottmann supervised the VLBI observations in Pico Veleta, and Krichbaum supported in-site observations at the telescope. Additionally, several individuals at the MPIfR are coordinators of working groups in the collaboration, such as Thomas Krichbaum (AGN science), Eduardo Ros (Outreach and Proposal Coordination), Helge Rottmann (Correlation, since 2019). The EHT performed observing campaigns in 2017 and 2018, the campaign in 2020 was cancelled due to the CoViD-19 pandemic, new observations are scheduled for April 2021.

Effelsberg Station Report

Activities during 2019-2020

The 100 m Effelsberg radio telescope is a versatile and flexible instrument that can be used to observe radio emissions from celestial objects in a wavelength range from about 1 m (corresponding to a frequency of 300 MHz) down to 3.5 mm (90 GHz). The wide variety of observations with the 100-m radio telescope is made possible by the good angular resolution, the high sensitivity, and a large number of receivers which are located either in the primary or in the secondary focus. Together with a number of distinct backends dedicated to different observing modes, this provides excellent observing conditions for spectroscopic observations (atomic and molecular transitions in a wide frequency range), high time-resolution (pulsar observations), mapping of extended areas of the sky, and participation in a number of interferometric networks (IVS, mm-VLBI, EVN, High-Sensitivity Array, RadioAstron project, Global VLBI even including antennas of the Southern Hemisphere Long Baseline Array, etc.).

About 30% of the observing time of the Effelsberg antenna is used for VLBI observations. Most of them are astronomical observations for the European VLBI Network (EVN), High Sensitivity Array (HSA), Global MM VLBI Array (GMVA) or other global networks, but also geodetic VLBI observations within the IVS are performed.

Effelsberg has participated in all the EVN sessions and e-EVN observations during the reported time period, as well as a few out of session observations and technical test. Despite the restrictions caused by the world wide pandemic, that also caused shutdowns in Germany, the operation of the radio antenna could be kept for all the time. A reduced staff at the observatory ensured the operation and observations were conducted remotely.

One of the technical tests was related to the new DBBC3 backend. In preparation of higher recording rate observations (up to 32 Gbps), a wide band C band observations at 4 Gbps was observed with the new DBBC3 backends at Yebes, Onsala, and Effelsberg. Yebes and Onsala used their VGOS antennas and Effelsberg used the linear polarization broad band C-band receiver. The fringe test was successful, but further test got delayed due to required firmware developments and upgrades of the DBBC3 hardware.

In 2019 a new Ku-band receiver covering 12 to 18 GHz was installed in the secondary focus and can provide an IF bandwidth of up to 4 GHz. Although not an EVN band, the receiver is regular used for observations together with the VLBA.

VLBI Equipment

Effelsberg uses the DBBC2, Fila10G and a Mark6 recorder for all EVN, global, GMVA, and geodetic VLBI observations. Most of the recorded data is e-transferred to the correlators in JIVE and Bonn. In addition there are two NRAO RDBEs connected to one of the Mark6 recorders that are used for observations with the VLBA and HSA. Mark6 modules to Socorro are still being shipped. The two Mark6 recorders currently provide about 340 TB of disk space in a raid configuration and are mounted as flexbuff mount points. The modules in one of the recorder are mounted as raids, each module of 8 disks forms a raid of type 5. One disk can fail without data loss. One slot is currently kept for modules that can be shipped. This is required because VLBA+Eb and HSA observations that are being correlated in Socorro are now recorded on Mark6 as well. The Mark5C recorder is no longer used.

Technical Developments

The DBBC3 for Effelsberg is in the lab in Bonn and is being upgraded for the use with the BRAND receiver. It will be equipped with more and new boards and optical

Ethernet inputs for the BRAND signals. The same hardware can be used for other receivers as well. The installation is delayed because the labs were closed for some time because of the pandemic restrictions. The budget plan for 2021 foresees to buy a new raid for JIVE to fulfill the 500 TB commitment.

Plans for a direct digitization of the RF signals from the receivers in Effelsberg are becoming more concrete. The same digitizers that are used for Meerkat digitize up to 3 GHz at the receiver and the full band at 12 or 14 bit is streamed over 40 Gbps Ethernet using the Speed protocol to the software backend. The digital lab is developing a software backend on a GPU cluster. It currently supports single dish continuum, spectroscopy, and pulsar observations. A basic support for VLBI VDIF is implemented and first zero baseline test to the DBBC2 yielded fringes. However the GPU backend only samples the whole RF band and writes out a single channel of 1536 MHz or decimations of that by factors of two, 768 MHz or 384 MHz... Those bands do not match the traditional VLBI bandwith of 2^x and will cause some overhead and require zoom correlation. Not a practical solution.

An alternative solution would be to convert the Speed protocol stream to a full band VDIF 8 bit stream as it is used for the BRAND receiver and feed that into a DBBC3. Discussion about the further strategy continue as well as the development of the digitization. There are currently two receiver that provide the digitized signals, the 21cm (1.29 to 1.51 GHz) and the prime focus wide band receiver 1-3.5 GHz. Once the system is established it is planned to digitize more and more of the Effelsberg receivers over the next years.

Figure 5.8: Aerial view of the Effelsberg 100 m antenna and the radio observatory (photo N. Tacken, MPIfR).

Bonn Correlator Report

The Bonn Correlator is operated jointly by the MPIfR and the German Federal Agency for Cartography and Geodesy (BKG). The correlation time is shared roughly equally between astronomical and geodetic projects. The main astronomical focus lies on the correlation of mm-VLBI observations performed by the GMVA and EHT networks, while geodetic services fall under IVS and (EU-)VGOS. In addition the Bonn correlator also processes a subset of EVN + RadioAstron experiments (see Table 5.4).

Correlation cluster

The correlation is performed on a HPC-cluster which consists of 68 nodes each with 20 cores (=1360 cores). Three head nodes allow execution of several correlation jobs in parallel. The cluster interconnect is realized via 56 Gbps Infiniband.

Data playback and storage

The number of Mark6 recorders has been increased to 10 playback units. 15 Mark5 units are still available for playback of Mark5 modules of all flavours (A,B,C). All Mark5 units are running SDK9.4. The correlation cluster has a total storage capacity of 2.1 PB combined into a BeeGFS parallel file system mostly used for storage of station data e-transferred over the internet.

E-transfer

E-transfers to and from the Bonn correlator are realized over 2 x 1 Gbps internet connections. The default transfer method is jive5ab; for exceptional cases tsunami can used. More recently the JIVE e-transfer client/daemon is used for some geodesy-involved stations.

Media purchases

A total of 10 x 112 TB Mark6 modules were acquired by the MPIfR mostly for EHT usage.

RadioAstron correlation

From 2019-2020 a number of experiments with participation of the RadioAstron spacecraft antenna were correlated in Bonn. For a summary of these experiments and the current state see table 5.4. All experiments observed after July 2017 were carried out in closed-loop mode after the failure of the on-board H-maser. Correlation of these experiments require a modification of the delay model within the DiFX software (see Section 5.5). Experiments GG085F and GG085G were carried out after the final breakdown of the RadioAstron satellite.

DiFX

All VLBI observations are processed using the DiFX software correlator running the latest stable version (currently DiFX-2.6.2). A special branched version exists for correlation of RadioAstron observations (DiFX-RA-1.0.1). MPIfR staff is actively involved in the DiFX consortium and contributes to the development of new correlator capabilities. Most notably the "output bands" feature has been implemented which allows correlation

Table 5.4: EVN and RadioAstron projects (after 2017) to be correlated in Bonn. All experiments after July 2017 were observed in the closed-loop mode.

EVN code	**Project**	λ	**Obs. date**	**status**
		H-maser mode		
GG081C	KSP AGN & Jets	1.3 cm	2017-03-07	released to PI
GG081D	KSP AGN & Jets	1.3 cm	2017-03-08	released to PI
GG081E	KSP AGN & Jets	1.3 cm	2017-03-08	released to PI
GG081F	KSP AGN & Jets	1.3 cm	2017-03-08	released to PI
GG081G	KSP AGN & Jets	1.3 cm	2017-03-09	released to PI
GG081H	KSP AGN & Jets	1.3 cm	2017-03-09	released to PI
GG081I	KSP AGN & Jets	1.3 cm	2017-03-09	released to PI
GG081J	KSP AGN & Jets	1.3 cm	2017-03-09	released to PI
GG081L	KSP AGN & Jets	1.3 cm	2017-03-13	released to PI
GR039	GOT Grav. lens S5 B0615+820	18 cm	2017-03-21	to be correlated
		Closed-loop mode		
GG083A	KSP AGN & Jets	1.3 cm	2017-10-08	to be correlated
GG083B	KSP AGN & Jets	1.3 cm	2018-01-15	to be correlated
GG083C	KSP AGN & Jets	1.3 cm	2018-01-31	to be correlated
GG083D	KSP AGN & Jets	1.3 cm	2018-02-08	to be correlated
GG083E	KSP AGN & Jets	1.3 cm	2018-04-22	to be correlated
GG083F	KSP AGN & Jets	1.3 cm	2018-04-23	to be correlated
GG083G	KSP AGN & Jets	1.3 cm	2018-04-24	to be correlated
GG083I	KSP AGN & Jets	1.3 cm	2018-04-26	to be correlated
GG083J	KSP AGN & Jets	1.3 cm	2018-04-26	to be correlated
GS042	KSP M87	1.3 cm	2018-05-14	released to PI
EB065	GOT Cygnus A	1.3 cm	2018-09-12	to be correlated
GG085F	KSP AGN & Jets	1.3 cm	2019-03-15	to be correlated (no RA)
GG085G	KSP AGN & Jets	1.3 cm	2019-05-08	to be correlated (no RA)

of incompatible frequency setups of VLBI stations, e.g. phased-ALMA, phased-NOEMA, and future wide-band data of the BRAND receiver.

Another important improvement was implementing the closed-loop mode correlation capabilities into the RA-1.0.1 branch of DiFX. The closed-loop regime of observations was mainly used at RadioAstron in the last two years of its operation due to failure of the on-board H-maser in July 2017. In this regime, the frequency standard for the space telescope is located at the ground and a modification to the delay model is required. Corresponding changes were introduced to the DiFX delay-model handling routines; the default spacecraft delay model can be overridden by adjusted data provided by the Astro Space Center of PN Lebedev Physics Institute. Two closed-loop experiments were correlated and fringes on ground-space baselines were found.

MPIfR Technical Developments

BRAND

The BRAND wide-band receiver was developed with support from the European Union's Horizon 2020 research and innovation programme as a part of RadioNet up to the end of 2020. Due to the project delays caused by the COVID-19 pandemic the goal to integrate all components into a working prototype receiver for the Effelsberg 100-m telescope could not be achieved during the project lifetime. However, the work has been continuing since then with funds from MPIfR and INAF. The project brought together innovative designs and cutting-edge technologies in broad-band feeds, low-noise amplifiers, high-speed samplers and digital technology to construct a novel, largely digital receiver that covers a frequency range of 1.5 to 15 GHz in a single receiving system.

Applications span VLBI imaging, spectroscopy, polarimetry, astrometry and geodesy, as well as single-dish spectroscopy and polarimetry. The project is a collaboration of INAF/Noto, MPIfR, OAN, OSO, ASTRON and VUC.

In the reporting period MPIfR staff finished the layout of the second generation prototype digital frontend board (BRAND-C), a highly complex design of dimensions 30×40 cm with twenty-two layers (Fig. 5.9. Two BRAND-C prototypes were manufactured and received in 2020. First tests of the central sampler components were successfully carried out at a sampling rate of 112 Gsps, lead by G. Tuccari, INAF. Work has started on the implementation of the FPGA firmware for the assembly of the 96 parallel sampler outputs into valid VDIF-formatted data streams. Development of the BRAND control software was mostly finished.

DBBC2

The Digital Base-Band Converter VLBI backend, DBBC2, has become the workhorse VLBI backend for the EVN and IVS. The DBBC2 has been developed in a collaboration between the MPIfR and INAF/Noto and is produced and distributed by HAT-Lab, a spin-off company of INAF. More than 40 units have been deployed in the field by the time of this report. Even though the DBBC2 will be superseded by the DBBC3 (see below) significant work has been carried out by MPIfR and INAF to further enhance the technical capabilities and the reliability of the DBBC2. In particular new DDC firmware and software were developed for recording 512 MHz bands at a data rate of 4 Gbps. These have been used successfully for EVN and GMVA observations at this increased data rate.

DBBC3

The DBBC3 is the successor of the DBBC2 VLBI backend and has been developed in a collaboration between the INAF/Noto and MPIfR. It is produced and distributed by HAT-Lab. The DBBC3 is capable of processing up to 8x4 GHz-wide IFs at a maximum data rate of 128 Gbps. Until the end of 2020 a total of 14 systems were assembled at MPIfR and deployed in the field. Some of the existing systems were upgraded and reworked. Extensive work was done in the reporting period to enhance the reliability and usability in the field. At MPIfR a standardized verification and procedure was established which all DBBC3 systems need to pass before delivery. All tests are documented and documentation is shipped together with DBBC3 units.

The issue of occasional loss of sampler synchronisation was extensively investigated. Several hardware and software modifications have been made that now prevent de-synchronisation. Multicast functionality was added for the DDC modes of the DBBC3 to broadcast the most relevant configuration and monitoring parameters (e.g., Tsys) to multiple clients. Firmware and software of a new DDC mode (DDC_U) was developed that unifies the existing DDC_V and DDC_L modes. MPIfR staff has supported the integration of the DBBC3 into the VLBI field system. A python software package was developed that allows to programmatically control, validate and monitor the DBBC3 backend.

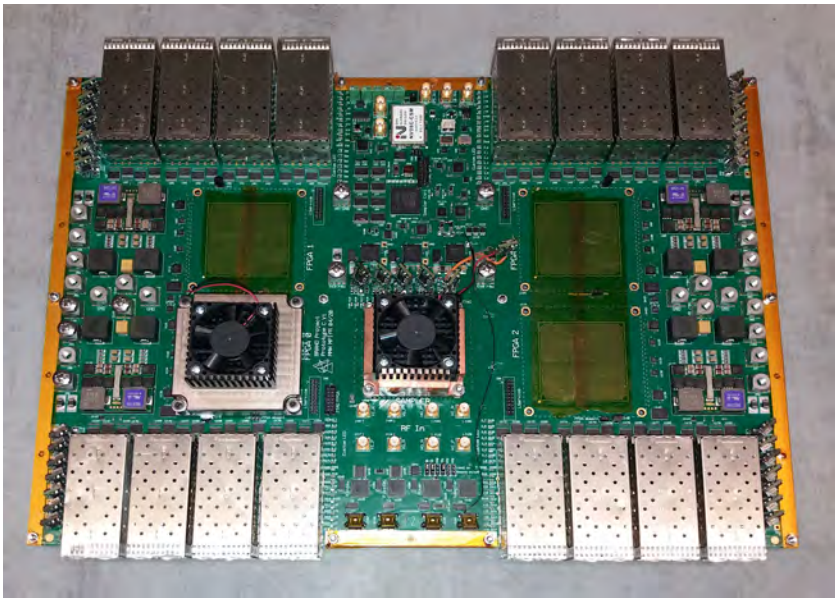

Figure 5.9: *The prototype BRAND-C board consisting of 22-layers. The board dimensions are* 30×40 *cm. The picture shows the board partially populated with only 1 out of the final 4 FPGAs.*

5.6 Instituto Geográfico Nacional, Yebes Observatory, Yebes, Spain

The Observatory of Yebes takes part in the EVN since the 90s but in 2008 its role became more important with the addition of the 40 m radiotelescope to the network. The 40 m radiotelescope is the flagship of the Observatory which also runs the 13.2 m RAEGE radiotelescopes, one of which is located at Yebes. The 40 m RT is a crucial element of the EVN due to its sensitivity and reliability. Below we summarize the status of the telescopes and the technical activities.

Staff involved in EVN activities

- EVN CBD: Rafael Bachiller attended to the board of directors as chair of the EVN CBD on behalf of the IGN (Observatory of Yebes) and Pablo de Vicente as EVN CBD secretary.
- EVN TOG: Javier González is the technical VLBI representative of the Yebes Observatory.
- EVN technical support. The VLBI team is composed by Javier González in charge of all VLBI operations, hardware and software, Ana Chacón who is the suppport scientist, and Francisco Beltrán on general software related to the 40 m radiotelescope and VLBI calibration (ANTAB scripting). There is also a team of engineers and operators who provide support on receivers and mechanics of the antenna.

VLBI observations

The 40 m RT has devoted a total of 1602 h of its time to VLBI observations in 2019 and 1795 h in 2020. This is 31% and 33% of the observed time respectively. The time devoted to VLBI observations is distributed among diffent networks; EVN, GMVA, IVS, as well as third party projects that request observing time in a per observation basis.

- EVN. There are three periods per year three weeks each plus eVLBI sessions, Target of Opportunity observations. The 40m telescope contributes with receivers at 2, 5, 6, 8, 22 and 43 GHz.
- Global Millimeter VLBA Array (GMVA). Two weekly sessions per year. These observations are performed at 86 GHz and use the same backends as the EVN. In 2019 the SIS 86 GHz receiver was replaced with a new HEMT dual polarization receiver, designed and manufactured in-house. A removable lambda quarter plate allows to use the receiver in circular polarization.
- International VLBI Service for Geodesy and Astrometry (IVS) observations. A large fraction of the telescope time is devoted to such observations at 2 and 8 GHz. Typically there are 24 sessions 24 hours each along the year. However every 3 years there is a CONT campaign which requires 14 contiguous days to be added to the standard schedule.
- KAVA: KVN + VERA. Participation of the Yebes' 40m RT in these observations are adhoc and happen during some days per year. They are performed at 22 and 43 GHz simultaneously.
- Others. The Observatory of Yebes receives requests for target of opportunities in which a set of EVN stations take part (usually 5 GHz) or in which the geodetic bands are used (S and X). This is the case for the RUA experiments in which Chinese, Russian and Australian stations usually take part.

The number of hours and observations per network is summarized in the table below. Distribution of time at the 40m RT:

Table 5.5: Distribution of VLBI observations along 2019 and 2020. Number of observations and observed hours per type of observation.

Network	**N. of obs.**	**h**	**N. of obs**	**h**
	2019		**2020**	
EVN	88	730.4	80	605.5
GMVA	11	125.5	10	166.7
IVS	23	530	37	880
Others	20	215.48	11	142
Total	142	1601.3	138	1794.2

VLBI observations with the 13.2 m radiotelescope are done only on geodetic programs, mainly VGOS and EU-VGOS observations. The telescope is part of the VGOS core network since the beginning of operations in 2016. VGOS observations are typically 24 hours long and they are scheduled every 15 days, whereas EU-VGOS sessions are scheduled on the same day of the VGOS ones but their duration ranges between four and six hours. In the 2019-2020 period the Yebes 13.2m telescope observed 48 24-hour sessions and 28 euro VGOS sessions.

Technical activities

The technical activities related to VLBI observations are mainly devoted to receiver developments, software development, maintenance and operation of backends and correlation tests.

Along the period of time from 2019 to 2020 the 40 meters radiotelescope has increased its observing capabilities with the comissioning of two new ultra wide band receivers, at Q and W bands. Both have an instantaneous bandwidth of 19.5 GHz ([32,50] and [72,90] GHz) in linear polarization, making the telescope one of the few that can integrate over such wide bands. The receiver noise temperature ranges between 40 and 60 K at W band and between 20 and 30 K at Q band. Furthermore, together with the already existing K band receiver (2.5 GHz instantaneous bandwidth) they are installed in an optic table that allows simultaneous observing in the three bands. Lambda quarter plates are available to observe in circular polarization. A recently published article in the January 2021 issue of A&A contains a detailed presentation of these receivers.

The old C band receiver in the 40 m RT is to be replaced in the next months. The new receiver will increase the instantaneous bandwidth at such frequency band, covering from 4.5 to 9 GHz. Final integrations works are being done at the present time.

The 40m RT is currently equipped with a DBBC2 and one flexbuff unit which are the nominal backends for observations within the EVN. The storage capacity of the Flexbuff unit is 360 TB. One DBBC3-2L-2H is being repaired at Bonn after a failure when loading the latest firmware version. A second flexbuff unit with 216 TB of storage space is in use

Figure 5.10: *Optical table with 3 receivers, 22, 43 and 86 GHz. By the time of the report 22 and 43 GHz can be used simultaneously.*

for any other VLBI observation outside the EVN. The Internet connection is one 10 Gbps link to the RedIRIS' backbone. Concerning the 13m RT, it is still equipped with four RDBE-Gs together with a Mark6, that allows a maximum processing rate of 16 Gbps, although the recorder is limited to 4 Gbps in single module recording. A spare Mark6 is being used as intermediate buffer to "vmux" or de-thread the VGOS data recorded from four different backend units. Only after the bits from the different bands are merged into a multi channel single thread file, they can be transfered to the correlator. Maximum sustained transfer rates reached to Haystack correlator is 3.5 Gbps.

The Observatory of Yebes has gained experience on correlation using DifX as a powerful tool for debugging and solving problems. Currently we perform correlation tests between two antennas in astronomy and geodesy.

The OY also develops and maintains the ANTAB script used by EVN telescopes and which generates calibrated tables from the the Field System Log files. It support calibration for hot/cold loads, fast swicthed noise diodes and standard noise diodes with the legacy ON/OFF mode.

Within the geodetic activities the OY has delivered VGOS receivers for FGI at Metsahovi and NMA Ny Alesund. The construction of a VGOS receiver for the RAEGE station at Santa María is also finished and is being tested at Yebes, while the workshop is busy with an upgrade for the Yebes' VGOS receiver and the construction of one receiver for HartRAO.

Other technical development activities related to the EVN in which Yebes Observatory has taken part during 2019 and 2020 are the BRAND Radionet project whose aim is a wide band receiver for the EVN with a frecuency coverage between 1.5 and 15 GHz and the leading of WP 5 in the JUMPING JIVE European H2020 project whose goal is the integration of new elements in the EVN.

Within BRAND it was initially planned that Yebes Observatory delivered two standard RF (1.5-15 GHz) cryogenic amplifiers, but for scientific reasons that became apparent during the project, a much more complex development of balanced amplifiers became necessary. This solution was designed, built and tested. In addition, although BRAND initially considered that the generation of the circular polarizations from the linear ones would be done by software, during the project it became apparent that this operation should be performed in the cryostat hardware. This also required another, initially unplanned, development of an ultra-wideband, very low-loss hybrid coupler optimized for operation at cryogenic temperature. Yebes Observatory also carried out numerous tests on all components that form the BRAND receiver chain that is cryogenically cooled, including those delivered by other EVN institutes like filters and superconducting couplers. Yebes Observatory also contributed to BRAND measuring the RFI at three EVN stations with a portable antenna and equipment in the 1 to 18 GHz frequency range.

Figure 5.11: *The 40m (left) and the 13.2 m VGOS radio telescopes at Yebes Observatory.*

5.7 Onsala Space Observatory (OSO), Chalmers University of Technology, Onsala, Sweden

5.7.1 Operations:

The Onsala Space Observatory (OSO) telescopes continued during 2019 and 2020 to play a full role within the global observing program for astronomical VLBI. In total 9 astronomical VLBI-sessions (6 EVN sessions and 3 global mm-VLBI sessions) were conducted. OSO is also regularly involved in e-VLBI sessions (typically ten 24 hour sessions per year) within the EVN. In addition, the Onsala 20 m telescope has been used for 45 and 42 geodetic VLBI experiments in 2019 and 2020, respectively, as part of the observing program of the International VLBI Service for Geodesy and Astrometry (IVS). The VGOS telescopes have been used for 45 and 46 geodetic VLBI experiments in 2019 and 2020, respectively.

5.7.2 Technical R&D:

The 25 m telescope IF-system was moved from the telescope cabin to the 20 m telescope control building. A modern set of equipment, with remote interfacing the two VLBI backends, including IF monitoring covering the existing VLBI IF band, and the newly implemented 4-8 GHz IF band on the 20 m antenna, has been installed. The new IF system allow OSO to well support 8 Gbps observations at C, X, K and Q bands with the DBBC2. OSO was involved in successful 8 Gbps VLBI tests using the DBBC2 on the 20 m telescope. VLBI operation uses the new antenna control software called Bifrost for both the 20 m and the 25 m telescopes.

OSO is involved in the VLBI related H2020 project JUMPING JIVE. During the reporting period, OSO has continued its involvement in work package 7, (WP7, The VLBI future) and work package 8 (WP8, Global VLBI interfaces). The main deliverable of WP 7 was completed in 2020 in the form of a White Paper addressing several relevant points in setting the future priorities of VLBI science capabilities. WP8 addresses 2 main issues, the first is scheduling of observations and the second is the continuous monitoring of the status of stations participating in VLBI sessions.

The BRoad-bAND (BRAND) RadioNet project (the RadioNet project ended 2020-12-31) was developing a revolutionary decade frequency range (1.5-15.5 GHz) receiver for VLBI. OSO was leading the feed design for the first prototype which is optimised for the prime-focus geometry of the Effelsberg 100 m telescope. The feed has been sent in 2019 to Effelsberg in Germany for integration in the receiver cryostat. Due to COVID19 completion of the receiver has been delayed.

OSO was involved in the RadioNet JRA Radio Interferometry Next Generation Software (RINGS). The main objective for RINGS was to deliver advanced calibration algorithms for the next generation of radio astronomy facilities, characterized by a high sensitivity, a high bandwidth and long baselines. During 2019, OSO has completed the work in WP7.2 which involved full polarization and beam modelling for polarization calibration with ALMA and LOFAR, including polarization conversion from linear to

Figure 5.12: *The VLBI Observation room at Nanshan station.*

circular polarization products. Part of the results were published in Creaner & Carozzi (2019). During 2020, OSO completed WP7.5. It dealt with an advanced calibration algorithm for radio interferometry data. In particular, an algorithm for robust self-calibration that applies to full-polarization visibility data and implements direction dependent effects corrections has been implemented. The algorithm has been implemented in a python module called RobVisCal, which utilises casacore functionality, and has been made publicly available on Github.

Since May 2019 the Onsala 25 m telescope has taken part in a VLBI-campaign (PRECISE) that regularly observes Fast Radio Bursts that have been reported to repeat as discovered by the CHIME telescope in Canada. The ad-hoc array is composed of most of the smaller (< 40 m) telescopes that also take part in EVN-observations viz Onsala, Torun, Irbene, Medicina, Noto, Badary, Svetloe, Zelenchukskaya, Urumqi, Shanghai, and Westerbork. Since January 2020, the telescopes in Effelsberg and Sardinia also take part in a subset of the observations. The 25 m telescope has been used for 81 and 34 days in 2019 and 2020, respectively. In addition to that, OSO has been monitoring magnetars and HMXBs as potential galactic sources of FRBs. This is work is done in collaboration with Wb and Tr. In total, the 25 m telescope was used for 56 days in 2020.

5.8 Shanghai Astronomical Observatory, P.R. China

TIANMA 65 Station Report

The Tianma station, also known as "TIANMA65", is located in Sheshan town, Songjiang district, the western suburbs of Shanghai, China. It is built and jointly funded by the Chinese Academy of Sciences (CAS), Shanghai Municipality, and the Chinese Lunar Exploration Program. The Tianma radio telescope with a diameter of 65 m, is a multi-function facility, conducting astrophysics, astrometry, geodesy, as well as space sciences researches with both single dish and VLBI observations. Besides of regular single dish observations on pulsars, spectral line and continuum sources, the telescope is a key member of the VLBI tracking system and spends a large amount of time on the Chinese Lunar Project, including the testing before the launch of the Chang'E satellites, and the tracking campaign after the launching. It is also actively involved in the international VLBI activities of astrometric, geodetic and astrophysical researches.

In 2019, Tianma 65m radio telescope participated in the February, May and October sessions at 18, 6, 5 and 3.6 cm bands with the DBBC2 VLBI backend and Flexbuff. In 2020, Tianma 65 radio telescope participated in the October session and partly of the May session. We missed the February session due to antenna maintenance. We also missed most of session in May due to the Chinese Lunar missions.

Current Status and Activities

Receiver Maintenance in TIANMA65

All the seven sets of receivers (L, S/X, C, Ku, K, X/Ka, and Q band) of Tianma telescope are available for VLBI observation. And the L-band receiver was linear polarization.

Antenna Maintenance with TIANMA65

The maintenance of the TianMa radio telescope focused on eliminating the noise from the pitch axes in 2020. First, we lifted the upper structures which is around 1300 tons including the rational pitch mechanism, back-up structure, quadripod and sub-reflector. Then, we welded the pitch axes, replaced bolts and unloaded the upper load. This work lasted two months, from 15th April to 15th June. Finally, the noise disappeared and pointing accuracy was improved. In addition, the faulty motors and reducers were replaced and the key mechanisms were greased. The telescope shows good running state at present.

e-VLBI

More than 10 e-VLBI experiments among the EVN have been carried out each year in 2019 and 2020 at a data rate of 2048 Mbps for each e-VLBI session.

EAVN

EAVN is the international collaborative VLBI array operated by institutes and stations distributed in China, Korea and Japan. Currently it mainly consists of nine stations including three KVN stations, four VERA stations, Tianma and Urumqi. It started its open-use operations since the late half of 2018. EAVN mainly observes at K (22 GHz) and Q (43GHz) bands at a recording rate of 1Gbps, the 4Gbps recording mode

Figure 5.13: *Self portrait of Tianwen-1 probe released a small camera.*

is under testing. The C (6.7GHz) band observation is under evaluation and will be open in 2021A semester. The observations are carried out two semesters every year, the period of each semester is from the late of January to the middle of June and the early of September to the middle of January next year, respectively. The call for proposals is (https://radio.kasi.re.kr/eavn/proposal_info.php) also released twice per year in April and September. Tianma provide about 200 hours per semester. All the observational data are transferred to the correlator in KASI through the high-speed internet. Besides of routine general scientific observations, EAVN including Tianma focuses on the intensive as well as contemporary observations on the two main target sources (Sgr A* and M87) of the Event Horizon Telescope since 2017.

China Mars probe of Tianwen-1

From the launch of Tianwen-1 on July 23, 2020 to December 30, 85 VLBI observations were made, with the participation of the Tianma telescope. The accuracy of VLBI time delay measurement was 0.1ns, and the time delay rate was 0.3 ps/s, which was far better than the requirements of technical indicators. The VLBI orbit determination mission of Tianwen-1 was successfully carried out, and three orbit corrections and one deep space maneuver were supported. VLBI is an essential means for precise orbit determination of Tianwen-1 in each measurement and control stage, especially in the cruising stage and Mars capture stage, which plays a vital role.

Chang'e-5 Lunar Probe

On Nov 24, China launched the Chang'e-5 spacecraft, comprising an orbiter, a lander, an ascender and a returner. Chang'e-5 was consisted of 11 flight stages, four probes and different assemblies, which were highly challenging for monitoring and controlling events. As an important station of the VLBI orbital sub-system of Chang'e-5, Tianma telescope has participated in the VLBI orbital determination and lunar surface positioning missions of nine flight stages, including Earth-Moon transfer, Braking, Orbiting the Moon, Landing and Descent, Lunar Operation, Power Ascent, Rendezvous and dock-

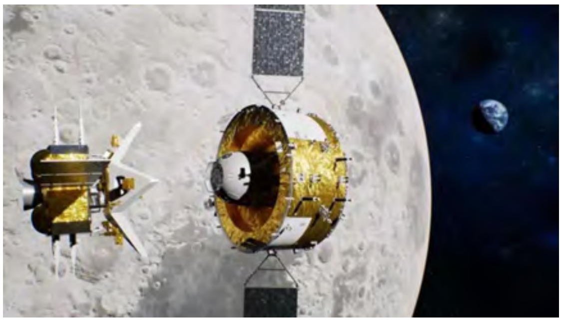

Figure 5.14: *Chang'e-5 orbiter and asciter rendezvous and dock (their relative positions are accurately measured using the same beam).*

ing, Orbiting the Moon, and Moon-Earth Transfer. From its arrival on November 24 to the return of the samples, Chang'e-5 has been tracked and observed for 23 consecutive days, more than 10 hours a day. Successfully completing the orbit determination and positioning tasks of each flight stage, it will continue to carry out the orbiter expansion mission.

Prospects

For the session of 2021, Tianma 65 will participate in L, C, S/X, K and Q bands observations of EVN.

5.9 Hartebeesthoek. South African Radio Astronomy Observatory, South Africa

Since 2017, the Hartebeesthoek Radio Astronomy Observatory (HartRAO) forms part of the larger South African Radio Astronomy Observatory (SARAO), which is a national facilty under the auspices of the National Research Foundation(NRF). The Hartebeesthoek site is located 65 km northwest of Johannesburg, just inside the provincial boundary of Gauteng, South Africa.

Hartebeesthoek continued to operate its two VLBI capable antennas, the original 26-m (built 1961) equipped with multiple receivers ranging from L-band up to K-band and the newer 15-m (built 2007) with a co-axial S/X receiver, including the possibility of simultaneous combined operation. Both antennas are equipped with DBBC2 recording terminals and Mark5B+ recorders, with additional recording capability via integrated FiLa10G interfaces to a Mark5C recorder and a Flexbuf system, with the latter now being used for all disk-based EVN operations.

Due to the ongoing demand for higher bit-rates and its associated disk space requirements, in April 2019 the observatory upgraded the disk capacity of the Flexbuf system to 258 TB by way of a grant intended for ICT infrastructure renewal. However it is not clear where the monies for the 4-Gbps upgrade requirements will come from.

Additionally the 26-m antenna continued to participate as a fully-fledged member of the e-EVN array at up to 2048 Mbps via a dedicated layer-2 light-path over a 10GE fibre connection.

The ongoing COVID-19 pandemic has had little to no impact on VLBI operations thanks to recent advances in remote operation capabilities necessitated by staff shortages. We were also fortunate to be afforded essential service recognition in the light of our geodetic operations which allowed us to deal with failures and preventative maintenance even at the height of local lockdowns.

However no new receivers have been added over this period, and little to no maintenance has been performed on existing receivers (in part due to budget shortfalls but mainly due to the staffing constraints imposed by COVID-19), though many of them are in sore need of refurbishment. In particular there has been little progress on implementation of continuous calibration, with only the L-band receiver being suitably equipped so far.

Construction of the new 13.2-m ring-focus fast-moving VGOS compatible antenna was fully completed by MT Mechatronics in early-2018, with installation of a backup generation capacity being added in 2019. Funding for a fully VGOS-capable receiver chain and associated backend equipment has now been secured and the necessary orders placed with delivery expected in 2022.

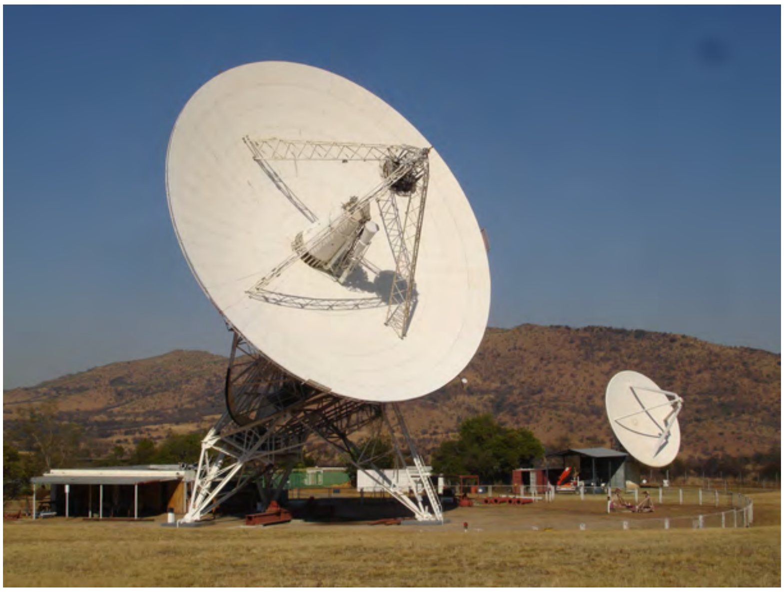

Figure 5.15: *The HartRAO 26m and 15m telescopes are seen during a geodetic VLBI experiment R1551. The 15m was operating in tag along mode with the 26m, as part of commissioning test of the 15m telescope.*

5.10 Institute of Astronomy of Nicolaus Copernicus University, Torun, Poland

After almost 25 years of uninterrupted work, the radio telescope was undergone a major renovation. Numerous corrosion centres have been removed from the antenna structure, and the entire instrument was repainted with particular attention paid to the appropriate protection of the antenna's reflective surfaces. The defects in the concrete foundations of the radio telescope were also supplemented and renewed. Additionally, during renovation works, the signal cables between the antenna and the control room were replaced. The new cables ensure the transfer of intermediate frequencies in the 0 to 2 GHz range, with much lower attenuation above 1 GHz than the previously used connections. Parallel to this work, thorough maintenance of the receiving systems was carried out, where some cryogenic preamplifiers and filters were replaced. The break in the operation of the radio telescope was also used to modernize the computer and internet infrastructure.

Renovation of the radio telescope was financed by the Polish Ministry of Science and Higher Education as a part of a grant for a special research infrastructure. The entire renovation work was carried out by the Toruń company ENERGON SA[2]. Additional modernisation works were carried out by the engineering and technical team of the Institute of Astronomy, NCU. The Department Investments of NCU supervised the implementation of this project.

[2] http://energonsa.pl

Year	Type	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	All
2019	VLBI	8.5	52.0	175.0	30.0	190.5	186.0	9.5	96.5	138.0	291.5	201.5	88.0	1467.0
	e-VLBI	28.5	28.0	25.5	13.0	38.5	0.0	0.0	0.0	29.5	9.5	35.5	28.0	236.0
2020	VLBI	0.0	70.9	162.3	0.0	0.0	0.0	0.0	0.0	0.0	217.8	34.1	0.0	485.2
	e-VLBI	27.7	17.6	24.4	21.5	28.3	0.0	0.0	0.0	0.0	0.0	39.4	21.7	180.6

Figure 5.16: *Summary of the VLBI and e-VLBI observations with the 32-m Toruń antenna in 2019 and 2020. Numbers are given in hours.*

Performed observations

Summary of observations in 2019 and 2020

The summary of the VLBI and e-VLBI observations performed with 32-m Toruń antenna is shown in Fig. 5.16. Total number of hours of the VLBI and e-VLBI observations are 1703 and 665 in 2019 and 2020, respectively. The difference is caused by the anti-corrosion maintenance of the antenna in the time span from May until September of 2020. During this period the antenna was excluded from the observational programs.

OH masers survey

The astronomers from Toruń have completed a survey of the Milky Way plane. They searched for gas clouds with maser emission of the OH molecule. They discovered seven new sources of such emission. It brings them closer to the understanding of the process in which massive stars are born. These significant results were published in Astronomy & Astrophysics journal as *A search for the OH 6035 MHz line in high-mass star-forming regions* written by Prof. dr. hab. Marian Szymczak, dr. Paweł Wolak, dr. hab. Anna Bartkiewicz, NCU Prof. from the Faculty of Physics, Astronomy and Informatics and the PhD students: MSc Michał Durjasz from NCU and MSc Mirosława Aramowicz from the University of Wrocław.

VLBI equipment and software

Current software versions

- Mark5B unit: Debian “Wheezy” version 7.11 (64-bit), StreamStor driver version: 11.50 (SDK 9.4), API version 12.06, firmware version 13.05
- Field System version: 9.13.2
- jive5ab version: 2.9.0

Figure 5.17: *The 32-m Toruń antenna.*

- The DBBC firmware version in “tunable” mode is 1.07.

Changes/Upgrades Made to Hardware

An EVER Powerline Dark 33 100 kVA power supply with an external battery and a bypass was purchased for the 32m radio telescope devices emergency power supply. The three-phase power supply operates in the double conversion mode, i.e. the receivers are connected to the power supply by an inverter. This solution ensures the perfect independence of the receivers from power outage and protects against overvoltage. The inverter is powered by its own battery. The power supply operation can be monitored locally using the built-in touch screen or remotely via RS232, RS485 and USB communication interfaces.

The power supply was installed in the air-conditioned electric cabin of the 32m radio telescope in December 2019. In January 2021, EVER company performed a warranty inspection.

Current Developments

A new receiver covering 8-16 GHz frequency band was built and installed on the antenna. It passed successfully first tests and is used for monitoring of methanol masers at 12.2 GHz.

Personnel Changes

On October 1st 2019 Toruń Centre for Astronomy was converted into Institute of Astronomy of the Nicolaus Copernicus University. Dr hab. Krzysztof Katarzyński, prof of NCU became a new director of this Institute, dr hab. Agnieszka Słowikowska, prof of NCU became a new deputy director for the research infrastructure replacing dr hab. Andrzej Marecki, prof of NCU in his duties.

On February 1st 2020, dr Marcin Gawroński was promoted for the assistant professor position, therefore he is no longer a member of the technical staff of the IA NCU. However, he still is in charge of the general time allocation of the Toruń radio telescope.

Since February 1st 2020, MSc Rafał Sarniak joined our technical team. He is responsible for of allocation of the observing time.

Personel

Technical staff:

- MSc Roman Feiler - station timing control, receivers and antenna calibration, observation scheduling;
- Jacek Jopczyński - receiver maintenance;
- MSc Andrzej Kępa (retired) - digital hardware development, station timing control;
- Adam Król - receiver cryogenics and motors, telescope structure maintenance;
- dr Bartosz Lew - telescope pointing, surface measurements, telescope control system, software development;
- BSc Damian Pawlak - receiver development, digital hardware development, station timing control, CNC workshop;
- Msc Eugeniusz Pazderski (retired) - receiver design and development, digital hardware development, control software development;
- MSc Rafał Sarniak - software development, telescope operators coordination and scheduling;
- MSc Wojciech Szymański - station timing control, RF signal distribution, hardware development and maintenance;
- dr Paweł Wolak - station timing control, receivers and antenna calibration, observation scheduling.

5.11 Ventspils International Radio Astronomy Centre, Ventspils, Latvia

Irbene Ir – RT-32 radio telescope

Since start of 2019 a new L band receiver was developed and installed at RT-32. While still uncooled, in comparison to previous solution, sensitivity is improved at least 5 times (SEFD 650 Jy). Dual circular polarization channels are now available and frequency agility is greatly improved – switching between L band and C/M/X band receivers is matter of running software scripts now. RT-32 has been working quite stably and participated in all EVN disk and e-VLBI sessions. Both cryogenic C/M/X and “warm” L-band (2 circular polarizations) receivers are available for VLBI observations.

Irbene Ib – RT-16 radio telescope

Currently RT-16 serves as backup instrument for VLBI and single dish observations at C/M/X bands, in case if there are issues or maintenance at RT-32. Receiver, H maser and DBBC of RT-16 are working stably.

VLBI infrastructure in VIRAC

A flexbuff (288 TB) is now used as data recorder for all VLBI observations at both antennas. A second Flexbuff unit (288 TB) have been sent to JIVE and currently both Irbene telescopes are fully using Flexbuff as main recorder for EVN since October 2018. While going slowly, first successful tests of 80 Hz calibration functionality were carried out together with DBBC and Field System at L band, but a permanent implementation, including also for C/M/X band, is still pending due to current technical priorities.

VLBI equipment status

- RT-32:
  - Field System: 9.13.2 (Debian Wheezy).
  - DBBC: 4xADB3L, Internal Fila10G, DDC v107;
  - Continuous calibration: implemented on RT-32 C/M/X band receiver.
- RT-16:
  - Field System: 9.13.2 (Debian Wheezy).
  - DBBC: 4xADB2, External Fila10G (only one VSI connection right now), DDC v107
- Flexbuffs:
  - 1. Capacity: 32 TB, jive5ab: 3.1.0 64bit on Ubuntu 20.04.1 LTS
  - 2. Capacity: 288 TB (36x8TB), jive5ab: 3.1.0 64bit on Debian 9.13 Strech.
  - All EVN recordings are done with Flexbuffs and data transfer to Irbene Flexbuff at JIVE works fine.

– Backup units: two Mark5c+ Glapper, jive5ab: 2.8.1 64bit, AMAZON,10GbE;

Continuous calibration

Irbene finally tested continuous calibration injection module with RT-32 C/M/X band receiver together with DBBC and it seems to work fine. Continuous calibration was used it for the first time during C/M band e-VLBI session on 2020.05.28. The Tcal level also was reduced down to 1.2 K.

Miscellaneous

- For the first time the science group led by VIRAC members successfully applied time for regular ENV observation. Selected targets were 3 methanol masers associated with massive star forming regions, observation was successfully carried out in 31.10.2019 as project EA063. In year 2020 in late February the PI, Artis Aberfelds, was visiting JIVE to learn EVN data reduction, kindly supported by RadioNET and support scientists, especially Katherina Immer.
- In September of 2020, the VIRAC team demonstrated first successful continuum flux measurements towards Ultra Compact H II (UCHII) zones associated with massive protostars with active methanol 6.7 GHz masers employing single baseline interferometric observations with RT-32 and RT-16. The obtained sensitivity results are close to theoretical system noise level (6 mJy for 120 s). Calibrator flux measurements were close to values obtained by other observatories. We are going to establish regular and sensitive continuum flux measurements for UCHII zones and probably also for AGN, microquasars and other potential targets. SFXC correlator was used for data correlation. Currently, SFXC correlator is deployed on VIRAC High Performance Computing cluster with following configuration: - 9 nodes; 2 X Intel Gold 24 cores processors, RAM 384 GB, 240 GB SSD per each node; all nodes are connected by 40 Gbs Infiniband internal network and to 10 Gbs international link.
- The development of new L/S band feed and cryogenic front-end for RT-32 is continued. It will be wide band, dual circular polarization receiver (approx. 1.2 to 2.35 GHz) with expected telescope SEFD in range of 200 - 300 Jy which is 3 times better than the current warm design.

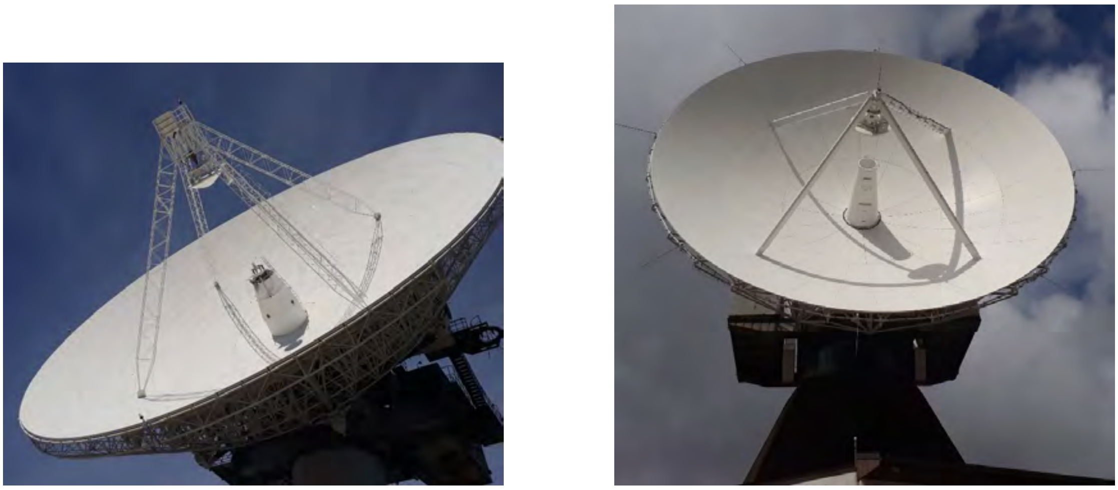

Figure 5.18: Irbene RT-32 and RT-16 radio telescopes

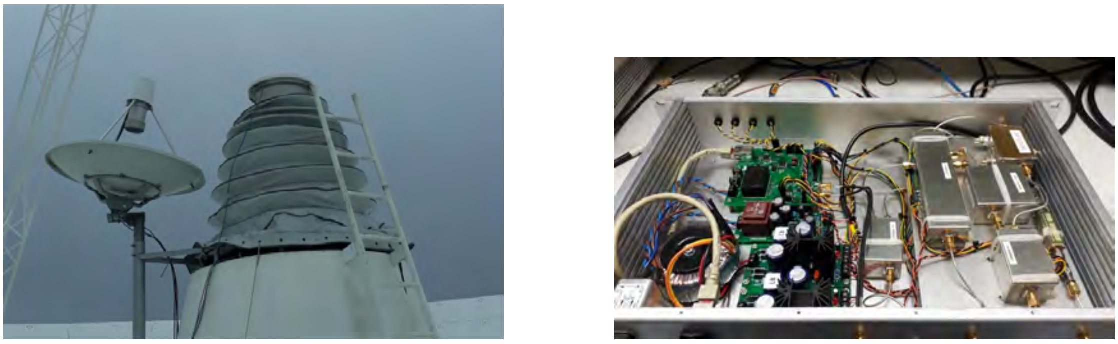

Figure 5.19: The new uncooled L-band receiver – feed antenna at RT-32 secondary focus (left) and IF unit (right)

5.12 Xinjiang Astronomical Observatory, Chinese Academy of Sciences, P. R. China

5.12.1 Nanshan Station

Receiver system

At present, the Nanshan 26-m Radio Telescope (NSRT) is equipped with Q, K, S/X, C, and L band receivers. All the receivers are currently working normally except the Q band receiver, which is still under testing. During 2019 and 2020, the X band receiver was upgraded with the new low-temperature refrigeration unit, the room-temperature microwave frequency conversion unit, and the intelligent power supply system. After the upgrade, the system temperature of the new X band receiver is significantly lower than the previous one. Currently the new X band receiver is working normally on the telescope. A new wide frequency C band (4-8 GHz) receiver was developed completely, and it is now tested in laboratory (Fig. 5.20). A new L band (1- 2 GHz) receiver is also under construction. In addition, we carried out the optical fiber laying in the RF cabin and the compressor room, and a shielded cabinet was also installed in the RF cabin to mitigate the RFI.

Figure 5.20: *The new C band receiver tested in laboratory.*

VLBI terminal System

 

Figure 5.21: Left: The VLBI Observation room at Nanshan station. Right: The two new hydrogen clocks.

Currently, the VLBI terminal system at Nanshan station (Fig. 5.21) includes one DBBC2, one MK5B+, one MK5B, one MK6 and four CDAS2. Among them, the DBBC2 and MK5B+ are mainly used for international joint observations of EVN, IVS, EAVN, etc. The CDAS2 is mainly employed in Chinese VLBI observations served for space missions. The MK6 is still under testing. In June 2020, we signed the purchase contract for a DBBC3 and Flexbuff. The Flexbuff is now on hand under testing, but the delivery of the DBBC3 was delayed due to the COVID-19 epidemic. It is expected to arrive after June 2021. In addition, during 2019 and 2020, we purchased 12 sets of disk packs with a capacity of 384 TB for local usage and EVN circulation.

Time-Frequency System

Two new hydrogen atomic clocks (Fig. 5.21) made by the Shanghai Astronomical Observatory (SHAO) are on active service. In 2020, we re-optimized the configuration of links and equipment of the time-frequency system to improve the performance of the system signal output. The environment of the hydrogen clock room has undertaken an all-round modification to improve the clock operating performance.

Scheduled VLBI Observations at Nanshan Station

In 2019, there were 259 experiments conducted by the Nanshan 26-meter Radio Telescope as served in EVN, IVS, EAVN networks and domestic joint observations for space missions and FAST-VLBI test observations, with a total effective observing time of about 1863 hours. Among them, there were 115 EVN runs with the total time of about 720 hours, including 80 hours of the EVN-FRB program. In 2020, 296 experiments were conducted for all the VLBI networks mentioned above and the total effective observing time is about 3184 hours, including about one-third of the total time serving for Chinese space missions.

6 EVN observatory reports, associated members

6.1 Arecibo Observatory, Puerto Rico, USA

VLBI system status

In early 2020, the VLBI system at the Arecibo Observatory (AO) was upgraded with two Roach Digital Back End (RDBE) units, a Mark6 recorder and a software unit called the Field System (FS) which communicated with the RDBEs, Mark6, and the AO telescope control system (CIMA). The upgrade was implemented by Harro Verkouter, JIVE, Netherlands, with support from EVN and JIVE scientists (Uwe Bach, Bob Campbell, Arpad Szomoru), Arecibo engineering team (Arun Venkataraman, Luis Quintero) and NRAO staff (Matt Luce, Walter Brisken). The system was successfully commissioned in early 2020 (Anish Roshi, Sravani Vaddi, Anna McGilvray, Phil Perrilat). EVN+Arecibo science observations were carried out in June 2020. Images of the dual AGN source Mrk 463 made with the last EVN+Arecibo observations made at 18cm are shown in Fig. 6.1 (S. Vaddi et al. in preparation). In August 2020 successful test observations with VLBA antennas (project ta036d) with the upgraded system were carried out.

Telescope status

On December 1, 2020, the platform hosting the dome and the receivers of the 305-meter telescope collapsed as the cables supporting them snapped leading to the destruction of the reflector surface. The telescope is irreparable and is no longer operational.

Future plan

Currently we are planning to equip the 12m telescope at Arecibo site with a 2.3 to 14 GHz cryogenic receiver. The native polarization of this system will be linear. The signals from the telescope will be connected to the 305-meter backends, including the VLBI system. Example UV plots with the 12m and EVN antennas when observing sources at different declinations are shown in Fig. 6.2. We expect the 12m system to be operational and integrated to the EVN network by early 2022.

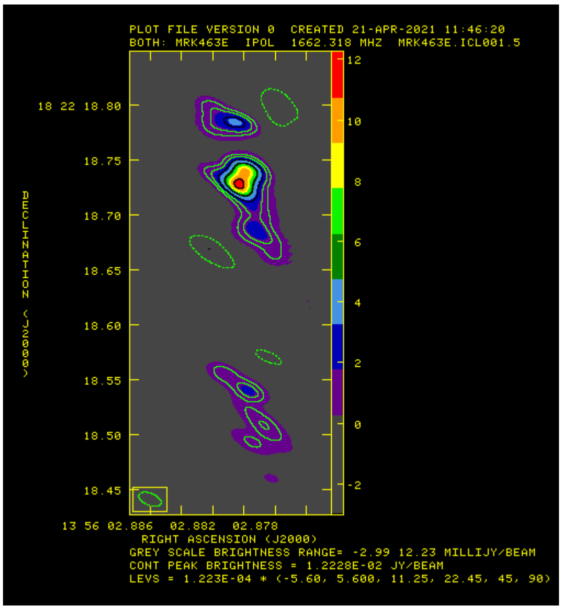

Figure 6.1: *EVN+Arecibo radio map of MRK463E at 18 cm (left) showing the core-jet structure and the detection of MRK463W (right). The contours shown are at 90, 45, 22.5, 11.25, -11.25 percent of the peak value.*

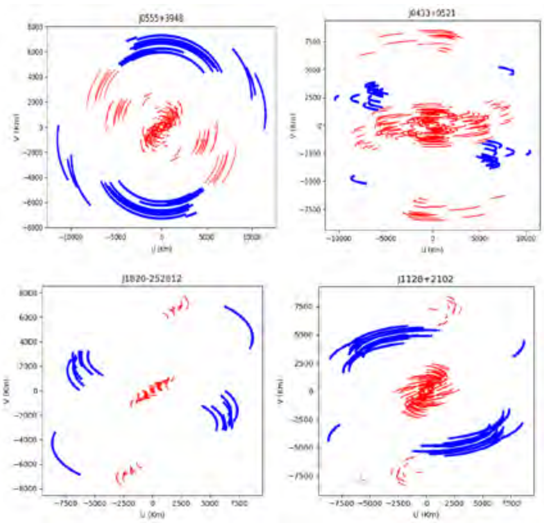

Figure 6.2: *Plot of uv-coverage generated for EVN+12m telescope for four different sources at different declinations for 6 hour scan duration. Baselines with the 12m telescope are shown in blue.*

6.2 Korean VLBI Network (KVN), KASI, South Korea

The 10th Anniversary of the Korean VLBI Network (KVN)

The Korean VLBI Network (KVN; http://kvn.kasi.re.kr), as the first very long baseline interferometry (VLBI) facility in Korea, operated by the Korea Astronomy and Space Science Institute (KASI), celebrated its 10^{th} anniversary since its first fringes in 2009.

The KVN consists of three 21m radio telescopes installed in Seoul, Ulsan, and Jeju Island. Its construction was completed on December 2, 2008 and succeeded in obtaining the first three-baseline fringes on October 16, 2009 (Fig. 6.4). In 2011, the world's first 4-channel receiver that can observe four different frequencies (e.g., 22, 43, 86, 129 GHz) simultaneously was installed. The first simultaneous 22/43/86/129 GHz VLBI fringes were successfully detected in 2012. This receiving system of KVN is particularly effective in millimeter-wavelength VLBI (mm-VLBI) observations by compensating fast atmospheric fluctuations effectively. This technology is now being enhanced with a compact triple-band receiver, becoming easier to adopt in other radio telescopes.

During the ceremony, congratulatory remarks from partner institutes were given (e.g., directors from the National Astronomical Observatory of Japan, the Shanghai Astronomical Observatory, the Joint Institute for VLBI in Europe, Xinjiang Astronomical Observatory, and JIVE etc) and the KASI expressed our appreciation to representatives from domestic and international partners who helped KVN and showed constructive partnership. In addition, two movies about the 10 years of KVN history and a special video were played.

Figure 6.3: *Group photo of the 10th Anniversary of the Korean VLBI Network (October 21, 2019).*

- KVN 10th History Video link

- KVN 10th History Brochure link

Operation

KVN operates 10 months a year except during the summer maintenance period (from mid-June to mid-August). Every year the total time of VLBI observations is around 3500 h. Since the start of the EAVN (http://eavn.kasi.re.kr) in 2018, KVN supports 1000 hours per year. KVN also participates in EVN and GMVA sessions regularly. In 2019, KVN has been used for 12 EVN, 5 GMVA, 4 KVN single dish, 4 KVN key science, 10 KaVA (KVN and VERA Array), 18 EAVN and 13 KVN only programs. In 2020, 16 EVN, 6 GMVA, 2 KVN single dish, 3 KVN key science, 9 KaVA, 17 EAVN and 19 KVN only programs were supported.

Technical Developments

Receivers

The receiver upgrades to widen current bandwidth are underway every year. The frequency range of all KVN receivers are K band (18 to 26 GHz), Q band (35 to 50 GHz), W band (85 to 116 GHz) and D band (125 to 142 GHz) if KVN Ulsan (ku) Q-band receiver upgrade is completed in 2021. The development of the compact tri-band receiver (CTR) for the INAF radio telescopes (Sardinia, Medicina and Noto) is making progress and expected to be shipped to Italy at the end of 2021.

Backends

KVN participates in EVN 2 Gbps and GMVA 4 Gbps sessions using the OCTAD backend system. In 2019, we successfully detected the first simultaneous 22/43/86/129 GHz dual-polarization fringes with 16 Gbps data recording rate by using both FILA10G and OCATD systems. At present, we opened this simultaneous 4-band (22/43/86/129 GHz) and full-polarization mode for two KVN Key Science Projects as an experimental test. The GPU spectrometer was also developed for wideband observations of OCTAD. Together with a simultaneous multi-frequency system of KVN, OCTAD and GPU spectrometer test was conducted. 23 molecular lines at K band (18 to 26 GHz) and 26 lines at W band (85 to 116 GHz) of Orion KL were successfully observed.

e-VLBI

The maximum 32 Gbps e-VLBI test was successfully conducted with KVN and Sejong geodetic telescopes in Korea with great support from Jan Wagner. The KVN and Sejong telescopes are connected by the KREONET (Korea Research Environment Open NETwork) with a bandwidth from 10 to 40 Gbps and the correlation center at the KASI headquarter has a 100 Gbps bandwidth. Using the DiFX cluster at Daejeon correlation center, we tested 2, 4, and 8 Gbps realtime e-VLBI and all fringes were obtained.

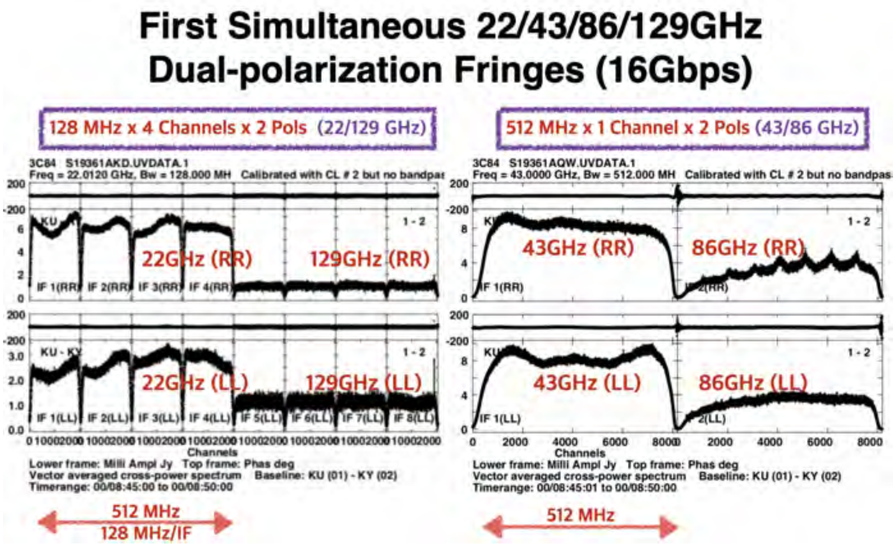

Figure 6.4: *First simultaneous 22/43/86/129 GHz dual polarization fringes (16 Gbps)*

Extended KVN (EKVN) Project

In 2020, we started the extended KVN (EKVN) project to build another KVN telescope in Korea. The new telescope is almost identical to the current KVN telescope, but it will have better surface accuracy to extend operation frequency up to 230 GHz. Seoul National University's Pyeongchang campus has been chosen as a new telescope location. Seoul National University and KASI have signed an MOA on the construction and operation of the new telescope. The Pyeongchang telescope is located about 130 km east of the KVN Yonsei site in Seoul. The basic design of the telescope is complete. Construction and commissioning are expected to be completed by the end of 2022. We will operate KVN as a 4-element array from 2023.

Figure 6.5: *Yonsei, Ulsan and Tanma Observatories*

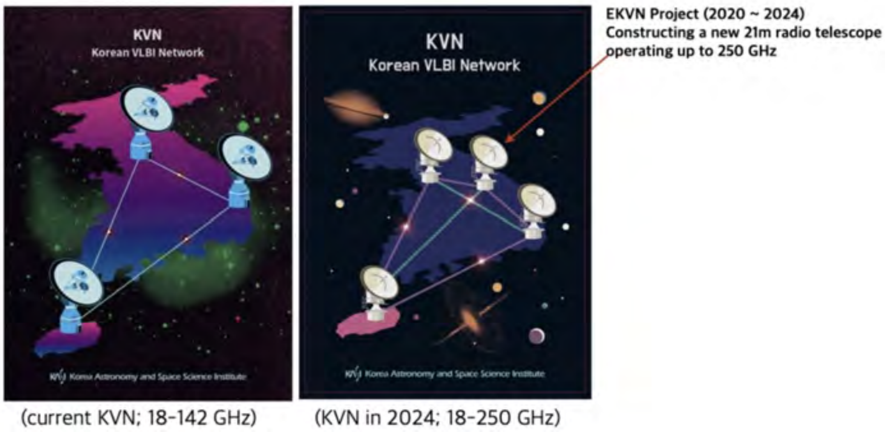

Figure 6.6: *Current and future KVN array*

6.3 Aalto University Metsähovi Radio Observatory, Finland

Metsähovi Radio Observatory has been under major renovations and upgrades in the past years. Despite the ongoing COVID-19 pandemic, the technical team was able to keep the equipment operational, and the maintenance work continued without significant delays even during the local lockdown periods.

Renovation, radome, and antenna steering system

Renovation of the observatory building started in 2019 and continued until the end of 2020. The new observatory premises completed in August 2020 and include a new laboratory wing, and a new wing with social and dining area for the staff as well as office space and a large seminar room to serve better also visitor and student groups. The old UPS-based backup power supply system was replaced by a super-capasitor- and generator-based UPSG system by EATON in December 2019, with the whole observatory and the 14-metre radio telescope now having continuous electricity even during longer power outages.

Also the 14-metre radio telescope experienced major upgrades, when the steering system was refitted. The old DC-servo motors were replaced with a modern AC-servo system in March-April 2020. Simultaneously, high-speed gear boxes and position sensors of the radio telescope were renewed. The work was made by Roll Research International Ltd. In addition to slight improvements in the mechanical performance, the most important improvement is that the need for maintenance is now lower in comparison to the former system.

The protective radome of Metsähovi's 14-metre radio telescope was replaced in June 2020. The new radome was manufactured by LT3-Harris (former ESSCO) and installation was made by Polish Radome Service (PRS). The installation, including dismantling the old radome took only 14 days, which was the fastest radome installation ever according to PRS. The new radome is identical to the old one, and the electromagnetic performances are unchanged. The most critical phase on the project was the removing the old radome and the installation of the radome (shown in Figure 6.7). This took place on 24th June 2020, starting at sunrise, at 3:00 AM, when the general weather conditions were most suitable.

The last renovation work, consisting of thorough maintenance of the concrete base ring supporting the radome and hosting the control room and laboratory space within the radome, will be completed in Summer 2021.

EVN Operations

Metsähovi's main operations are centered around the long-term radio monitoring of active galaxies and the Sun. The solar monitoring program has been going on since 1978, and AGN several lightcurves now cover four full decades. Metsähovi also participates in astronomical sessions at frequencies above 22, 43 and 86 GHz; additionally, geodetic VLBI observations are carried out with a 2/8 GHz receiver by the Finnish Geospatial Research Institute.

Figure 6.7: *Replacement of the 14m radio telescope radome at Metsähovi.*

In 2019-2020 Metsähovi participated in 38 EVN experiments (at 1.3 cm) and three out-of-session or target-of-opportunity observations. Personnel participating and enabling the EVN activities are: Juha Kallunki as the technical VLBI friend and coordinator; Petri Kirves and Ari Mujunen in charge of the receiver and VLBI equipment, respectively; Tuomas Savolainen providing VLBI science and observing time application support; and Joni Tammi, in the role of the director, representing the observatory at the EVN consortium board of directors

All VLBI receivers (2/8, 22, 43, and 86 GHz) are operational and working without problems. The 86 GHz receiver has been slightly upgraded with remote-controlled local oscillator and improved quasi-optics. Our future development focuses on obtaining a triple-band (K, Q, W bands) receiver. In late 2020 we started purchasing a new FlexBuff unit with 0.684 petabytes of hard disk space, a dBBC3, and new disk space. Furthermore, we are currently planning to upgrade the Metsähovi network infrastructure to 100 Gbps optical Ethernet, to match the upgraded 100 Gbps Internet connection.

7 Joint Institute for VLBI ERIC

7.1 Institute news

JIVE has experienced quite an active and challenging 2-year period, with new projects beginning and others closing; exciting technical developments; the continuation of high profile science; as well as facing the challenges of the COVID-19 Pandemic in 2020.

The outbreak of the COVID-19 pandemic has had an enormous worldwide impact, causing abrupt changes in the plans of people and institutions. As of March 2020, the JIVE staff has been working mainly from home, and access to the offices in Dwingeloo has been very restricted. An important challenge, in these circumstances, is to guarantee the well-being of the staff, ensuring that everybody has adequate resources to perform their duties, while taking into consideration the difficulties that many people and their families experience. It is encouraging to note that all staff has remained healthy and safe during this time, and that the JIVE family has proved to be robust and resilient. We all hope that, once the pandemic is over, the best lessons learned will be incorporated into a more flexible and sustainable way to combine work and family life.

The JIVE strategy was revised and approved by the JIVE Council at the beginning of the period. The JIVE mission still highlights on providing data and services by expert support to the EVN and users. In this sense, JIVE aims to enhance the user experience, support continuous innovation, and promote radio astronomy in Europe and beyond. An important focus of the period was to facilitate the development of an updated science vision for the EVN, including its relation with other present and future large scientific facilities covering the whole multi-messenger landscape. Facilitated by the EC H2020 JUMPING JIVE project, it also served as the base for an EVN Technology Roadmap. Both scientific and technological developments in the EVN obviously should be attuned to those at other VLBI networks. In order to create a forum for discussion and transfer of information, a Global VLBI Alliance (GVA) has been formed, including representatives of the EVN, VLBA, EAVN, LBA, and their user and technical communities. The GVA is now formally recognized as a Working Group in the IAU Commission J (radio astronomy), and it will help coordinate some of the opportunities identified in the new EVN science vision, in particular for joint observations with new facilities such as the SKA or for multi-messenger studies.

JIVE and partners have been busy discussing the models to ensure its sustainability after its first five years of existence as a European Research Infrastructure Consortium (ERIC). These discussions resulted in the approval by the JIVE Council in 2020 of the increase of the partners' financial contributions by 15%, starting in 2021. This is especially significant as it happened in the year of the pandemic, with many governments dealing with extreme challenges. It also clearly demonstrates the interest and commitment of the JIVE partners.

The other main action for sustainability is to keep a healthy portfolio of European projects:

- H2020 JUMPING JIVE, has allowed to explore new partnerships to JIVE and the EVN, some technological applications (an upgraded VLBI scheduling program, pySCHED, and progress towards a robust monitoring system for the VLBI networks), many training activities in Africa, and a very strategic development to include the SKA in VLBI arrays (SKA-VLBI).

- H2020 ESCAPE worked to include the EVN archive into the Virtual Observatory and EOSC, and develop VLBI processing tools in Jupyter notebooks.

- The H2020 ASTERICS project brought together researchers, scientists and engineers to work on multi-messenger astronomy challenges. The project came to a successful closing in April 2019.

- The ERIC Forum allows to exploit synergies and solve common challenges, also providing a voice to ERICs in the evolving scenario of EC financing as the new program Horizon Europe is being designed.

- RadioNet provided essential resources to guarantee transnational access to the EVN and JIVE. The project came to a successful closing in December 2020.

- The approval by the European Commission of the OPTICON-RadioNet Pilot (ORP) project, starting in 2021, in which JIVE is the partner receiving the largest share, will provide resources to maintain the highest standard of quality in supporting the EVN and its users.

The final aspect regarding sustainability, namely increasing the number of JIVE partners, is continuously ongoing, and JIVE anticipates the incorporation of Italy as a full member in 2021. This is of course in line with the expectation that all the members of the EVN will eventually join the JIVE ERIC.

JIVE has been also very actively supporting the establishment and growth of new communities interested in VLBI. An important part of the future JIVE strategy lies in attracting new partners to the EVN and JIVE. Significant progress on this front occurred in 2019, including the signing of a collaboration MoU with NARIT for their 40m radio telescope under construction in Chiang Mai (Thailand). This also has been a specific endeavour within the JUMPING JIVE project with the organisation of several workshops in Mexico, Portugal, Thailand, Greece and Ukraine.

JIVE has facilitated or been directly involved in the production of exciting science results using VLBI, like the first even image of the shadow of a supermassive black hole in M87, its charismatic jet, high precision astrometry in our Galaxy, the observations of the afterglow of binary neutron star mergers producing gravitational waves in nearby galaxies, or studying planetary atmospheres.

Regarding communications, on top of preparing press releases of the finest EVN results, preparing and maintaining the new EVN web, and presence in social networks,

Figure 7.1: *Signing of a Memorandum of Agreement between NARIT and JIVE in November 2019.*

JIVE has taken the responsibility of producing the EVN Newsletter. Support from the EVN institutes in this area is actively requested and of course much appreciated. Outreach actions to highlight include the EVN/JIVE booth installed in the 2019 EWASS conference in Lyon (France) and the participation in the public outreach campaign organised at middle and high schools in Ethiopia in conjunction with the IAU Symposium 356 "Nuclear Activity in Galaxies Across Cosmic Time".

7.2 Personnel

During 2019, Dr. Dhanya Nair and Dr. Olga Bayandina joined JIVE as support scientists. Mrs. Cristina Garcia-Miró, SKA-VLBI scientist, moved from the SKAO in Manchester (UK) to JIVE headquarters in the Netherlands in the framework of the H2020 JUMPING JIVE project. In addition, Dr. Waleed Madkour started his role as Frequency Manager for the Committee of Radio Astronomy Frequencies (CRAF). In late 2019, Dr. Arpad Szomoru retired after 19 years of very successful service to JIVE, lately as head of the R&D department. He will continue to be involved in JIVE in an advisory role.

In 2020, Dr. Harro Verkouter was appointed head of the R&D department and Prof. Huib van Langevelde started his role of Program Director of the Event Horizon Telescope (EHT). This year also saw the departure of JIVE's support scientist Dr. Katharina Immer who moved to the ALMA Regional Center (ALLEGRO) at Leiden Observatory (the Netherlands).

Figure 7.2: Farewell Arpad Szomoru as Head of Technical Operations and R&D.

7.3 Research and Development

7.3.1 Data recording and transport

During the period 2019-2020, the FlexBuff capacity grew to seventeen units with a net total of 4.6 PB storage capacity and three Mark6 units. e-VLBI production ran without noticeable data transport issues.

The jive5ab code was reorganized and brought under git version control and its build procedure was modernized to use CMake, improving cross-system support and enabling configuring optional extensions. An optional e-transfer client can be compiled into jive5ab, allowing for direct transfer from jive5ab supported media (Mark5, Mark6, FlexBuff) into a running e-transfer server instance, as developed under ASTERICS WP5/Cleopatra. Both changes were tested in the field and was integrated in jive5ab releases in 2020. Dr Harro Verkouter traveled to Arecibo Observatory to assist with the migration to an RDBE/Mark6 setup for VLBI observations. Together with the technical staff at Arecibo and experts from Effelsberg, NRAO and MIT Haystack a lot of progress was made, and first observations have taken place during the 6 and 18cm NMEs in session 3/2019 (along with one user experiment in each band).

The internal network at JIVE was upgraded and reorganized for the SURFNet8 100 Gbps connection, performing flawlessly through the end of the period. Each FlexBuff and SFXC cluster node is now doubly connected to redundant internal core switches, which, in normal operating circumstances, double the bandwidth to each node and provide redundancy in case of fiber- or switch failures. Two out of the three installed Mark6 units were made operational, requiring a substantial effort since, as delivered by the manufacturer, the units can not read VLBA disk packs sent to JIVE. To facilitate e-transfer of VLBA data from Mark6 disk packs, the FlexBuff manager GUI application was updated to support handling Mark6 formatted diskpacks and recordings.

At the end of 2020, following the regular 2 Gbps e-VLBI session, several EVN telescopes (Tr, Ys, O8, Wb, Ef, Mc, Jb and Hh) continued observing for a short network disruption test by SURF. Four tests were conducted: dynamic routing change, semi fibre cut simulation by disconnecting the Dwingeloo router, fibre cut simulation by turning a port's laser off and interrupting traffic into the Zwolle, which is a city in The Netherlands where traffic gets routed through.

Packet loss at JIVE was monitored throughout the test period. The highest packet loss recorded across the tests was $\simeq$ 4,000 packets per station for the "Link down" test on a data rate of 32,000 packets per station per second. The packet loss for the other tests was an order of magnitude smaller. Even the highest packet loss (12% of a single second) will not affect science. Finding the packet loss connected to the tests in the correlated data file was difficult and without guidance on where to look (time based) would likely have gone unnoticed.

7.3.2 JIVE hardware upgrade

Approximately 30 hard disks failed and were replaced. Several machines required an upgrade to the amount of available disk space: archive, the off-site backup host and the

CASA development host. Four Mark5s were outfitted with new Power Supply Units after these died as a result of an unscheduled power outage of the neighbourhood including the institute.

An LTO8 tape drive and a supply of LTO8 tapes (12 TB / tape) were ordered and installed to replace one of the failing LTO4 tape drives. Side effects of this upgrade are increased backup speed and capacity and much less tape changes required – certainly an advance during restricted access to the premises.

7.3.3 Software correlation

Development of the features, and upgrades, of the EVN software correlator (SFXC) continued throughout 2019 and 2020.

The SFXC version 5.0 was released, which supports "sliced" integrations where correlation of a single output accumulation period is split over multiple CPU cores, resulting in reducing the time it takes for data to make it through the correlator as well as memory requirements. The SFXC's VEX2 support was also improved and SFXC now also provides cross-polarization products for auto-correlations. Further improvements to the geodetic (Mk4) output product were made. The sfxc2mark4 conversion tool now produces proper ovex files that are required by some of the HOPS tools such as aedit. It is now possible to easily specify a mapping between two- and one-letter station codes. It was correlated in Bonn using DiFX using a CALC9 model and in Dwingeloo using SFXC with a CALC10 model. The geodetic observable – total multi-band delay – was compared between the two data sets by M.-E. Gomez (Université de Bordeaux). The results show that with a few exceptions both systems produce "totals" that fall within $\pm 1\sigma$ of each other.

The JIVE Software Correlator was updated to support 4 Gbps e-VLBI and tests were performed. In order to support geodetic and/or astrometric VLBI code was developed to append the model that was applied during correlation to the FITS-IDI files in the EVN archive. A debugging infrastructure was implemented allowing the user to dump the full state of the sfxc processes (slightly less than a thousand are started in parallel for a typical EVN correlation) in machine-readable form. Support for sub-microsecond resolution coherently de-dispersed full-stokes filter bank output. These very high time-resolution data can give important constraints on the emission mechanism of Fast Radio Bursts (FRBs). The mode was used to probe the micro-second polarization structure of repeating FRB 20180916B as shown in Fig. 7.3.

7.3.4 User software

In the context of the ESCAPE project, development of a Jupyter kernel for the upcoming CASA6 release was started. Other Jupyter related work concerned the implementation of a minimal re-computation framework for the Jupyter CASA kernel. Other effort spent on CASA and casacore concerned improved support for im- and exporting VLBI data in FITS-IDI and UVFITS format. The code to do triggered observations at EVN stations was enhanced to produce triggers based on VOEvents. Finally, primary beam

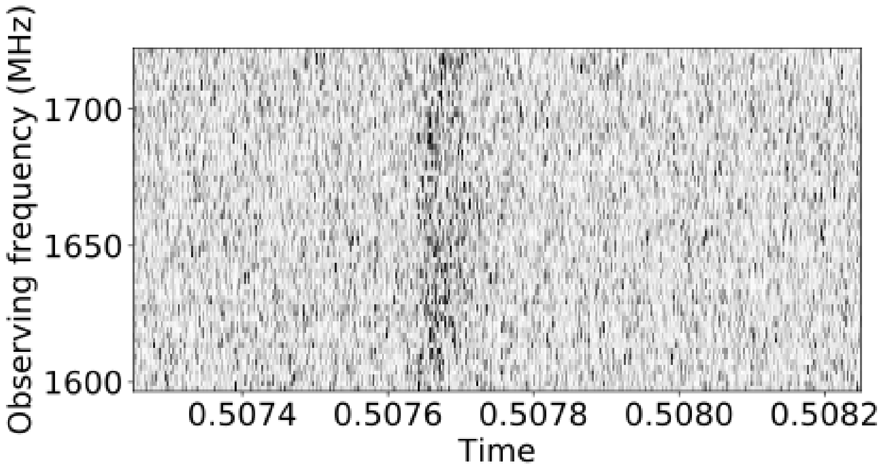

Figure 7.3: Dynamic spectrum of FRB 20180916B at 0.25 μs time resolution.

correction is now part of the EVN pipeline. The CASA fringe fitter task was refactored to allow runtime choice of regular or wide-band fringe fitting. The wide-band mode is being commissioned using EHT data whilst the dispersive fringe fitter was integrated in CASA release 5.7/6.1 and is underway to be demonstrated as a production tool for LOFAR long baseline observations. High memory usage of the fringe fitter for certain data sets reported by users was investigated and a significantly reduced memory footprint version of the code is under test. Finally, full gain curve support is now available in CASA.

The SCHED re-factoring project also continued to make good progress. The correlator control code has been modified to support both VEX1 and VEX2, which will be needed by the correlator to handle multiple data streams for 4 Gbps e-VLBI and e-MERLIN observations with more than one sub-band, or observations with multiple recordings per scan. Other work on pySCHED led to the TSCAL keyword now also being allowed in the frequency catalog as well as in the station catalog. pySCHED was merged with the latest release of SCHED code and catalogs. A methodology for fringe fitting with a source model (from a FITS image's clean components) was developed as well. The code and its documentation were handed over to NRAO for production implementation. A runtime reduction of 30%-50% was achieved by performing a code optimization pass. In order to ease keeping the pySCHED catalogue up-to-date with the latest EVN setups (contained in so-called `setini` files), a script was written to translate and normalize the setini files into new frequency catalogue entries.

7.3.5 SKA and VLBI

In the framework of the H2020 JUMPING JIVE project there were different milestones accomplished related to SKA and VLBI. The Deliverable "Portfolio of SKA-VLBI science cases" were further discussed at the SKA-VLBI Key Science Projects and Operations workshop between 14-17 October 2019, at the SKA HQ. In addition, the Jumping Jive

SKA-VLBI scientist participated in the CDRs for various SKA components and the SKA system CDR as well, where VLBI aspects were also discussed. Most notably, the first Jumping Jive WP10 deliverable D10.1 “Details on VLBI interfaces to SKA Consortia” was formally recognised as an SKA reference document.

In the final year of the ASTERICS project, VLBI fringes between the Dwingeloo telescope (DWT) and several EVN stations (Sardinia, Effelsberg, Jodrell Bank and the WSRT) were demonstrated. This deliverable was for the SKA Signal And Data Transport consortium where JIVE was a member of. The VLBI fringes prove the viability of the White Rabbit time- and frequency transfer technology for use in the SKA telescopes by delivering a performance meeting the SKA standards. The DWT used a digital back end developed in-house by Boven and a White Rabbit (see front cover photo) link to the WSRT H-maser as its phase reference. The WSRT H-maser signal was propagated over 135 km of public, shared, fiber, using COTS equipment. The detection of VLBI fringes clearly demonstrates the ability to achieve a sufficient level of clock stability over such links. The availability of two separate fiber links between WSRT and Dwingeloo (the public, shared route via Groningen and the dark fiber between WSRT and ASTRON) allowed the comparison of the effect of using a public, shared, network instead of a private, dark fiber. The results have been published as ASTERICS WP5/Cleopatra deliverable D5.14.

7.4 Space and Planetary Science

Venus and Mars experiments with PRIDE

ESA’s Jupiter Icy moons Explorer (JUICE) is scheduled to be launched in the third quarter of 2022 and will arrive in the Jovian system by the end of the decade. JIVE and partner organisations continue to prepare for the participation in this mission with PRIDE (Planetary Radio Interferometry and Doppler Experiment), one of eleven science experiments of JUICE.

A group of researchers led by JIVE scientists conducted a series of PRIDE observations of the ESA’s Venus Express mission during several so called radio occultation events, in which the spacecraft was out of direct visibility from Earth for a fraction of its planetocentric orbit. Accurate evaluation of the properties of the refracted signals enabled researchers to estimate parameters of the Venusian atmosphere. The group demonstrated (Bocanegra et al. 2019) that PRIDE is at least as efficient as nominal instrumentation for radio measurements available to space agencies and sometimes can provide even better results, i.e. penetrating deeper in the Venusian atmosphere.

PRIDE was also tested as a support to LaRa, one of the experiments of the ExoMars mission, a joint project of ESA and the Russian space agency Roscosmos, that will launch in the middle of 2022. LaRa, which aims to study the Mars interior, will benefit from an addition of PRIDE observations to its nominal measuring campaign (Dehant et al. 2020). An international collaboration including co-investigators from the JIVE, conducted a series of observations as the EVN project ED045, comprising multi-epoch observations of the NASA InSight lander signal in VLBI and Doppler modes at 8.4

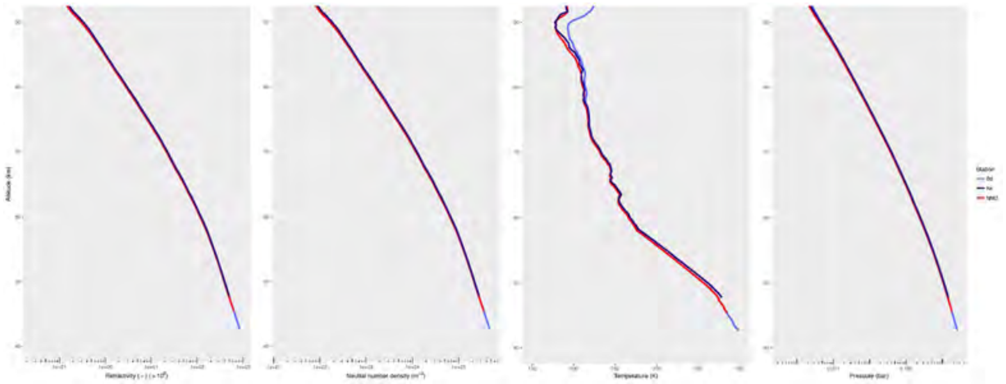

Figure 7.4: *Refractivity, neutral number density, temperature and pressure profiles in the Venusian atmosphere during the session of 2012.04.29 (Bocanegra et al. 2019).*

GHz. The high spatial precision and multi-station Doppler data provided by PRIDE can reduce the estimated uncertainty of the Mars orientation parameters, which are strongly linked to the Martian interior. The experiment served as a fine-tuning exercise in preparation for more intense observations of the ExoMars mission and later – JUICE.

Toward space-borne sub-millimeter VLBI

2019 marked the new beginning in VLBI science by presenting the first direct image of a supermassive black hole shadow in the nucleus of the galaxy M87 obtained by the Event Horizon Collaboration. But the geometrical size of Earth and radio signal propagation properties of the atmosphere make only two sources accessible for this type of studies, M87* and the source in the center of Milky Way, Sgr A*. To overcome these two principle limitations, one must place a sub-millimeter VLBI system in space. A collaboration led by the Radboud University and involving Dr. Leonid Gurvits published results of an investigation of a mission concept tentatively called Event Horizon Imager, EHI (https://doi.org/10.1051/0004-6361/201732423). Implementation of this concept will make possible high fidelity imaging of the black hole shadow in the center of Milky Way as well as studies of other relativistic sources with microarcsecond angular resolution. In a parallel development, a collaboration co-led by Dr. Leonid Gurvits and Dr. Zsolt Paragi and involving representatives of many EVN and other institutes submitted a mission concept entitled TeraHertz Exploration and Zooming in for Astrophysics (THEZA) in response to the ESA's strategic call for future space science programmes Voyage-2050 (https://arxiv.org/abs/1908.10767). Together, the EHI and THEZA studies form a platform for future major steps toward space-borne sub-millimeter VLBI facilities which will revolutionise studies of relativistic processes in the immediate vicinity of super-massive black holes.

The conference "Space VLBI 2020: Science and Technology Futures" held in Charlottesville, VA, USA, in January 2020 brought together researchers from around the world for a brainstorming on the ways to create an interferometric system able to ad-

Figure 7.5: *Participants of the conference "Space VLBI 2020: Science and Technology Futures", Charlottesville, VA, USA, 29 January 2020.*

vance the results obtained by the EHT collaboration in imaging of the immediate vicinity of the SMBH in the nucleus of the radio galaxy M87.

Ultra-long-wavelength interferometry in Space

The ultra-long wavelengths (ULW, corresponding to frequencies lower than the Earth's ionosphere cut-off value of about 20 MHz) remain the last almost unexplored range of the electromagnetic spectrum. It contains crucial information on the cosmological evolution of the Universe. Observations in this frequency regime require space-born radio telescopes which should be involved in interferometric systems for achieving the required angular resolution. Such a system has been proposed in response to the ESA's strategic call Voyage-2050 by a collaboration involving JIVE scientist Dr. Leonid Gurvits (https://arxiv.org/abs/1908.04296). This proposal, entitled "Peering into the Dark (Ages) with Low-Frequency Space Interferometers" is synergistic to the Sino-European study conducted by the group of institutes involving JIVE entitled "Discovering the Sky at Longest Wavelengths with a Small Satellites Constellation" (https://arxiv.org/abs/1907.10853). Together, these studies define a long-term roadmap for developments at the ULW regime for the coming decades.

7.5 EVN Operations

7.5.1 Correlation

The core of JIVE's service is the processing of data from the European VLBI Network(EVN); Tables 1 and 2 below summarise experiments that were correlated at JIVE during 2019 and 2020.

In 2019, a concerted effort, especially over the summer and autumn, was directed towards reducing the size of the correlation queue. From peak to trough (from just after

Table 7.1: Experiments that were correlated at JIVE during 2020.

	User Experiments			Test and Network Monitoring		
	N	Net. (h)	Corr. (h)	N	Net. (h)	Corr. (h)
Correlated	146	1169	1370	28	84.5	88.5
Distributed	138	1074	1251	27	85.5	89.5
e-EVN experiments	33	193.5	193.5			
e-EVN ToOS	10	68.5	68.5			

Table 7.2: Experiments that were correlated at JIVE during 2020.

	User Experiments			Test and Network Monitoring		
	N	Net. (h)	Corr. (h)	N	Net. (h)	Corr. (h)
Correlated	118	959.5	1121.5	22	60	60
Distributed	124	1041.5	1227.5	24	67	67
e-EVN experiments	24	191.5	191.5			
e-EVN ToOS	5	41.5	41.5			

session 2 to just before session 3), the queue to correlate went from 892 to 176 correlator hours. The number of network and correlator hours correlated in 2019 were up by 76% and 71%, respectively, compared to those from 2018. 2019 also saw some records fall for the size of observing: the first time there has been over 1000 network hours of user experiments in a calendar year (1010) and the most disk-based network hours (816.5, previous high was 733.5).

COVID-19 restrictions left footprints in all aspects of correlator operations in 2020. During the first three months, access to the building remained possible for specifically defined tasks as approved on a case-by-case basis. Operators performed correlation remotely, with authorization for an operator to be on-site arranged for the days of real-time e-EVN observations and for handling disk-packs. When restrictions were relaxed starting from June, one operator was in Dwingeloo 2-3 days per week, providing a more normal regime for logistics and routine maintenance. In October, COVID-19 measures were tightened up again, but this quasi-regular operator presence continued. Since March, support scientists have worked entirely remotely. Nonetheless, the number of correlator hours completed in 2020 was the second highest since shifting to SFXC starting in 2011. The number of correlator hours in the queue to correlate was 7.6% lower at the end of 2020 than it was at the beginning. The evolution of the annual EVN network hours fell somewhat in 2020, reflecting the choice of some PIs to defer their experiments from the May/June session because of reduced array composition, given that COVID-19 restrictions at some stations precluded their participation.

In the period reported, there were 17 EVN target of opportunity observations and 10 e-EVN trigger observations, arising from 19 proposals. Scientific topics covered fast-radio bursts (FRBs), extra-galactic nuclear transients, X-ray binary transients, tracing the expansion of gamma-ray bursts, accretion bursts in a young massive star (in 3 different molecular species), shocks in a recurrent nova, and ionization in the coma of an interstellar-visitor comet, blazars from which neutrinos were detected by IceCube, monitoring a short gamma-ray burst, maser outbursts in young massive stars and a new type Ia supernova.

Highlights from the 2019-2020 period are:

- 2 Gbps observations returned by the March e-EVN day and session 2 for disk observations. This marked the end of a period in which bit-rates were limited to 1 Gbps stretching back to session 2/2018, because of the E-series DBBC firmware problems.

- By the autumn there were the first user e-EVN experiments including all three of the Russian QUASAR antennas and the Chinese Kunming antenna, all able to maintain 1 Gbps real-time transfer rates.

- 2019 saw a record for the most triggered e-EVN network hours (56; the previous high was 27)

- GM074 was the first joint Global + LBA observation at 3.6cm, and observing over three days with a rotating overlap among the geographical sub-networks, required building a single 76-hour correlation schedule file from the three separate daily schedules, including reconstituting physically present baselines that did not appear in any of the daily schedules. The resulting 2,612 scans, all less than two minutes, also brought attention to some inefficiencies in starting sub-jobs within SFXC, which led to various speed-ups being developed.

- The first RadioAstron user experiment at L-band was correlated using the normal production system; standard clock-searching saw fringes directly using a null a priori clock model for RadioAstron, without need for an acceleration term. Interestingly, more baselines showed fringes towards the end of the observation, and as one went earlier, fewer and fewer did. Comparison to the RadioAstron ephemeris showed that fringes went away as RadioAstron moved farther from Earth, suggesting that the source was being resolved on such baselines.

- GA043 was the first SiO spectral-line observation at 43 GHz to be correlated at JIVE.

- ER047 is a long project, broken up into six 12-hour epochs, investigating the contributions of AGN and star formation across a large redshift range via the faint ($\sim$few μJy) population of radio sources in the COSMOS two square-degree field. This holds the current record for the most phase centers output in a single correlation at 761. Through the first four epochs, each 12-hr observation has required 102-137 hours to correlate, depending on the number of successfully participating stations. The first two epochs were distributed in 2020, together amounting to 19.5 TB (subsequent epochs with a larger number of stations could reach around 14 TB per epoch).

- The first FRB-burst trigger from the on-going correlation-only project based on observations shadowing CHIME occurred in April.
- The team of ET036, a 72-hr project seeking redshift dependence in the scaling of observed VLBI delays, became the first external users to receive correlated data from SFXC exported in mark4 format. This capability was developed under JUMPING JIVE/WP6 and validated via the K-band EVN geodesy project EC065 led by WP6 members.
- Three 18cm RadioAstron user experiments have been correlated and distributed. Fringes to RadioAstron from the more sensitive ground stations were seen in most scans, with weakening detections as the (non-projected) baseline-length increased – similar to the behavior seen in the previous 18cm observation with fringes. These experiments brought in Australian and Japanese ground stations. Another 18 cm observation was prepared and clock-searched, but with no fringes to RadioAstron seen in any scan.

7.5.2 EVN support

Extensive testing occurred early in 2019 to validate the DBBC firmware v107 that would provide 2 Gbps observing capability lost in 2018. This firmware became operational starting from the 2019 March e-EVN day and the May/June disk session. Initial testing began with some stations for 4 Gbps configurations using tunable BBCs with the same v107 firmware, using modes with 64 MHz filters and modes with 32 channels of 32 MHz filters. Both approaches have issues (band-pass shape for the 64 MHz filters; interaction with scheduling software for 32 channels) for further investigation, as does identifying possible LO settings across the full set of EVN stations to maximize overlap in the resulting 512 MHz frequency range.The cause of the occasional delay jumps of 1 ns in data from e-MERLIN out-stations was identified as the width of the tracking window for fibre delays. Such jumps complicate phase-referencing observations, and this tracking feature was turned off for subsequent VLBI observations. By the end of 2019, the majority of EVN stations used the FlexBuff system to record data and e-shipping to transfer the data to JIVE. Those yet to make this transition include the QUASAR stations and Chinese stations, although activity towards making the transition to FlexBuff operations is underway there as well. There continues to be “unbudgeted” use of FlexBuffs at JIVE for special circumstances (e.g., data from the Australian LBA stations); so far the FlexBuffs at JIVE have been able to accommodate such instances without creating operational bottle-necks. In session 3, NRAO stations sent their data on Mark6 packs, which were also copied onto FlexBuffs in order to be able to recycle the packs timely enough for their logistical requirements. In the 2019 edition of the biennial IVS Technical Operations Workshop, held at Haystack Observatory northwest of Boston, JIVE personnel taught two seminars, with three recitations each: VLBI Data Acquisition, Formats, Transfers, and Tools, and Pointing and Amplitude Calibration Theory and Practice.

4 Gbps modes were tested in various network monitoring experiments (NMEs) within 2020, in order to check empirically the front-end/IF ranges and the tunability of the LOs at the DBBC stations in terms of providing a common 512 MHz frequency range. Wavelength bands tested were 6 cm, 5 cm, and 1.3 cm. All used 32 channels of 32 MHz, except for 5 cm where Effelsberg had a limit of 16 channels in their current DBBC configuration. So that used instead 64 MHz filters, whose pass-band shapes are not as rectangular as are other filter-widths in the current DBBC firmware. By the end of 2020, only the three QUASAR antennas, Urumqi, and Robledo provided data on Mark5 packs; the rest e-ship to FlexBuffs at JIVE, either via the automatic-retrieval process or manually via off-line arrangements. NRAO stations continue to send their data on Mark6 packs, which are promptly copied onto local FlexBuffs.

Prior to the 2020 Feb/March session, JIVE arranged and conducted a couple fringe-test observations for Arecibo in their two-RDBE back-end configuration. During observations within the session itself, there were large delay offsets ($> 200\,\mu$s) between channels containing the two different polarizations. The user experiment with Arecibo (ER047D) was correlated with a special version of SFXC having compensation for this delay difference built in. Arecibo had repaired this condition by the 2020 May/June session. JIVE also arranged and conducted fringe-test observations for investigating the stability of the Westerbork maser prior to the 2020 October/November session. The 6 cm network monitoring experiment in this session saw the first attempt to get fringes to the 32m telescope at Zolochiv, Ukraine, observing two dual-pol 8 MHz subbands within the larger 2 Gbps NME. Problems recording data at the station precluded seeing fringes here. Initial discussions with JPL began about how JIVE can assist in validating aspects of the new DSN digital backend currently under development.

7.5.3 User support

JIVE provides support in all stages of a user's EVN observation, from proposal definition to data analysis. There were 23 first-time PIs in 2019 and 2020 observations, including seven students. JIVE continued to provide PIs with experiment-specific scheduling templates to track the evolving configurations of equipment at EVN stations. A new tactic was the creation of a set of band-specific station catalogs to provide a snapshot of the continuous-calibration situation across the stations, as their development proceeds at their own pace. Observations at 18 and 5cm now regularly have linear-polarization stations. We now correlate all of these with cross-hand polarization products, to enable post-correlation transformation of these linear polarizations back to circular via polConvert. The EVN pipeline now contains the primary-beam correction that fits Gaussians to primary-beam maps provided by the stations (although the collection of such maps remains incomplete). The EVN Data Reduction Guide on the new EVN web page has been cast into parallel guides, covering both the AIPS and CASA analysis packages, and placed side-by-side in columns to facilitate comparison of how each handles the various conceptual stages of analyzing EVN data.

The EVN Archive remains the entry point for users to retrieve their correlated EVN data, and provides open access to others following the one-year proprietary period (six

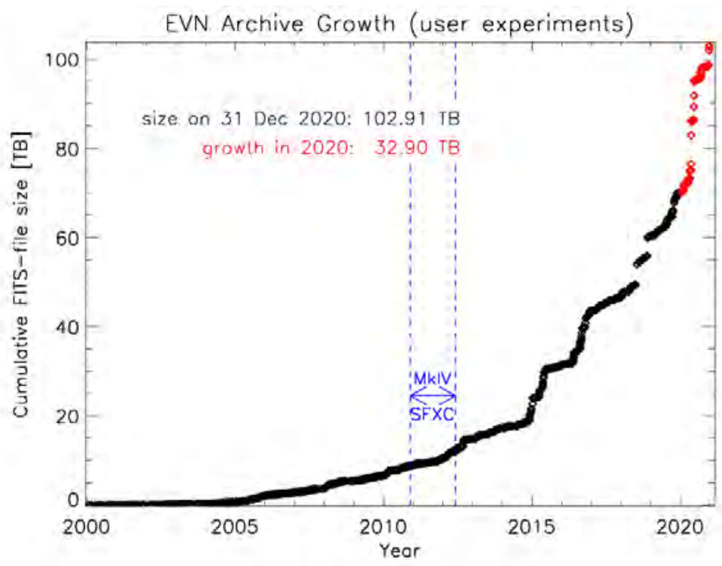

Figure 7.6: *Growth of the EVN archive with time.*

months for ToO projects). The total size of user-experiment FITS files in the Archive passed the 100 TB mark by the end of 2020, increasing by 47% during the year.

Due to the travel restrictions worldwide in most of 2020, there were not many data reduction visits at JIVE in this period. In cases when inexperienced users require, we provide support through Zoom and other remote collaboration tools. As from October 2020 there is a user support contact email (`usersupport@jive.eu`) to facilitate the communication between support scientists and the users in a transparent way for everybody. The R&D and the support groups join efforts in developing software that aid production correlation, and user support.

Data calibration issues reported by users to JIVE are usually related to amplitude calibration, and phase-reference imaging. The former was addressed earlier in 2020 by implementing strict rules in spotting formal errors in ANTAB tables. The issue of poor initial gain values will have to be addressed at both the stations and at JIVE.

Finally, the EVN Programme Committee authorized, upon request, a three-month extension to the one-year proprietary period for PIs who encountered delays in being able to process their data because of COVID-19 restrictions in their countries during 2020.

8 VLBI related meetings with significant participation by EVN institutes and seminars organized by the EVN

Following is a description of the most notable VLBI related meetings organised during the years 2019 and 2020, with a significant participation of the different EVN institutes. It is important to mention that the EVN Symposium and Users Meeting originally planned for 2020 was cancelled due to the COVID-19 pandemic and was postponed until summer 2022. In the meantime a virtual mini-symposium was organised for 2021.

8.1 Young European Radio Astronomers Conference, Dublin, Ireland, 26-29 August 2019

Throughout its 50 year history, the Young European Radio Astronomers Conference (http://www.yerac.org) has brought together postgraduate and early career radio astronomers working at European institutions in order to facilitate networking, raise awareness of new developments in radio astronomy and aide in professional development. Ultimately it is YERAC's objective to properly equip the next generation of radio astronomers, in every manner of the word, to carry the field forward into the future.

Figure 8.1: *Participants in the YERAC, Dublin, Ireland, 26-29 August 2019.*

The last YERAC conference took place in Dublin, on 26-29 August 2019. For a summary of the meeting see the RadioNet report. The meeting web page can be looked up here.

The event received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 730562 [RadioNet].

8.2 European Radio Interferometry School (ERIS), Gothenburg, Sweeden, 7-11 October 2019.

The European Radio Interferometry School (ERIS) is a bi-annual advanced school forming an important part of the training and development of young radio astronomers from Europe, but also from RadioNet partner countries throughout the world. The school has both lectures and in particular advanced practical tutorials that are given by invited specialists in interferometry who have the expertise and experience in using the main European radio astronomy facilities, which include the Atacama Large Millimetre/Submillimetre Array (ALMA), the e-Multi-Element Remotely Linked Interferometry Network (e-MERLIN), the European VLBI Network (EVN), the Low Frequency Array (LOFAR) and the Northern Extended Millimetre Array (NOEMA).

In 2019 ERIS was hosted by Onsala Space Observatory at Chalmers University of Technology in Gothenburg on 7-11 October. The ERIS 2019 was open to all regardless of their ethnicity, gender and academic position. All attendees had to agree to a Code of Conduct during registration, which ensured a harassment-free school experience for everyone, regardless of gender, sexual orientation, disability, physical appearance, race, age, political opinion or religion. Due to size of the venue the number of attendants was limited to 72, from more than 150 applications received.

For a summary of the meeting see the Radionet report.

Figure 8.2: *Participants in the ERIS 2019, Onsala Space Observatory.*

The event received funding from the European Union's Horizon 2020 research and inno-

vation programme under grant agreement No. 730562 [RadioNet].

8.3 SKA-VLBI Key Science Projects and Operations Workshop, Jodrell Bank, United Kingdom, 14-17 October 2019

The Square Kilometre Array (SKA) will deploy its first phase telescopes in the mid-2020s. SKA1-low (50-350 MHz) and SKA1-mid (0.35-15.3[24.0] GHz) will have maximum baseline lengths of about 65km and 150 km, respectively. Some of the highest priority science objectives defined by the SKA Organisation - together with the science working groups - however require an angular resolution that can only be reached by current very long baseline interferometry (VLBI) networks, or the full SKA with baselines extending to thousands of km. To exploit the full potentials of the first phase SKA components for very high resolution applications, it has been proposed to coherently phase-up the core of SKA1-LOW and SKA1-MID, and make these powerful telescopes available for global VLBI observations.

The aim of the workshop was to introduce the VLBI capabilities and observing modes of the SKA to the community, and present the latest results in the SKA high priority science areas where VLBI will make an impact. Ideas and possible strategies for major SKA-VLBI Key Science observing programmes, and the impact of global VLBI observations for astronomical research in the future in general were discussed. In addition, a discussion was held seeking for input regarding the SKA-VLBI requirements for the future SKA Regional Centres.

For a summary of the meeting see the Radionet report.

Figure 8.3: *Participants in the SKA-VLBI key science and operations workshop at Jodrell Bank in October 2019.*

This event received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 730562 [RadioNet].

8.4 8th International VLBI Technological Workshop, Sydney, Australia, 18-20 October 2019

The International VLBI Technology Workshops have evolved from the highly successful 10-year series of International e-VLBI workshops. The scope of the technology workshops aims to encompass all areas of hardware and software development relevant to VLBI. The 8th workshop in this series was hosted by CSIRO in Sydney, Australia. As well as talks on traditional VLBI talks one day was dedicated to "cross discipline" talks with invited speakers from non VLBI backgrounds including, but not limited to, pulsars, connected element interferometry and SETI.

Figure 8.4: *The eighth International VLBI Technological Workshop meeting in Sydney, 9-11 October 2019.*

8.5 IUCAF 5th School on Spectrum Management for Radio Astronomy, Stellenbosch, South Africa, 2-6 March 2020

This summer school attracted the largest number of participants to date for the IUCAF spectrum management summer school. Some of these participants are experienced spectrum managers, but the majority were not. This represents a significant transfer of knowledge to a wider group at a time when scientific use of the radio spectrum is under pressure from commercial interests.

The 5th IUCAF 5th School on Spectrum Management for Radio Astronomy was held in Stellenbosch in South Africa from March 2nd to March 6th 2020. The event website is at http://www.iucaf.org/sms2020/ and a summary of the meeting is publicly available here.

Figure 8.5: *Participants to the IUCAF 5th School on Spectrum Management for Radio Astronomy.*

The event received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 730562 [RadioNet].

8.6 European Astronomical Society Annual Meeting, virtual meeting, 29 June 2020

The European Astronomical Society (EAS) celebrated a special session called: Registering the Universe at the highest spatial accuracy on 29 June 2020. This session was within the European Astronomical Society Annual Meeting which took place virtually between 29 June and 3 July 2020. The aim of the session was to demonstrate the power of VLBI observations when combined with other wavelengths and/or other carriers.

The spectacular black hole image released in 2019 has shown the wonder of high-resolution radio astronomy to the world. Observations at high spatial resolution from different observing frequencies are fundamental to study complex astrophysical phenomena. This special session brought together experts in a range of topics to present the synergies between observations across the electromagnetic spectrum. Special focus was on how the micro-arcsecond accuracy achievable with Very Long Baseline Interferometry (VLBI) can help tackle the major science questions in high-energy astrophysical phenomena, and exploit the synergies of VLBI with multi-wavelength and multi-messenger astrophysics. This is an exploding field with the next generation large facilities, such as the ELT and SKA, coming soon online. Talks and posters were accepted following an equal opportunity policy regarding diversity and non-discrimination.

A summary of this special session can be found at Jumping JIVE repository.

The event received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 730562 [RadioNet].

8.7 Radionet Workshop on Future Trends in Radio Astronomy Instrumentation, Bonn, Germany, 21-22 September 2020

Despite the all-dominating Corona Virus crisis the RadioNet Technical Dissemination Workshop on new trends in Radio Astronomy instrumentation was celebrated and explicitly organized as a virtual event. Two days of virtual coming together, presenting new ideas by Zoom, and discussing future trends via web-chat took place on 21-22 September 2020 organized by the Max Planck Institute for Radio Astronomy in Bonn (Germany).

This meeting was the last in a series of technical workshops combining several aspects of engineering and operational issues at radio observatories all over Europe and beyond.

The Workshop was fully sponsored (no participation fees) and organized by the EU Consortium RadioNet within the Horizon2020 Program of the European Commission, continuing a very successful series of engineering workshops and telescope operation - oriented meetings organized within the Sixth and Seventh Framework Programme. Engineers and scientists working at various observatories to get and keep their radio telescopes running were welcome to present their interesting projects in an oral presentation tailored to a virtual presentation. Due to internal visitor restrictions and the purely virtual format of the workshop no poster presentations were shown.

A summary of this meeting can be found at this Radionet report.

Figure 8.6: *The Radionet Workshop on Future Trends in Radio Astronomy Instrumentation: a Zoom meeting on 21-22 September 2020.*

The event received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 730562 [RadioNet].

8.8 CASA-VLBI Workshop, Dwingeloo, the Netherlands, 2-6 November 2020

The CASA data processing package is growing in its use for VLBI. In the last years VLBI functionality in CASA has significantly expanded and improved, and this has been advertised globally in meetings, schools and tutorials.

To educate new and existing VLBI astronomers in the use of CASA for data processing, JIVE hosted a second CASA-VLBI workshop from 2-6 November. This was a fully online event, due to the COVID-19 situation which did not allow to host participants locally. Zoom and Mattermost were used.

No registration fee was charged for this workshop, but registration was required to obtain access to the live lectures, interactive sessions and discussion platform. To access the recorded lectures and online materials after the workshop, no registration is needed. Participants were responsible for ensuring sufficient internet bandwidth, and having access to the latest CASA release for their platform of choice (see the CASA homepage). Prior experience with the CASA package and/or VLBI data processing was helpful, but not mandatory.

The workshop consisted of four days of which the first one was devoted to the basics of CASA and the three subsequent days covered VLBI data processing in CASA. For a summary of the event see the Radionet report.

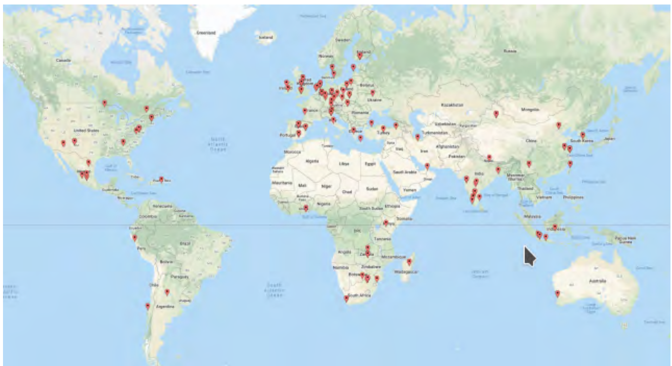

Figure 8.7: *Geographical location of the registered participants.*

This event received funding from the European Union's Horizon 2020 research and innovation programme under grant agreements No 730562 [RadioNet] and No 7308844 (JUMPING JIVE).

8.9 EVN virtual seminars

After the cancellation of the planned EVN Symposium and Users Meeting in 2020 due to the pandemic situation, the EVN adapted to the new scenario and organised a successful series of virtual seminars under the name "The sharpest view of the radio Universe. VLBI: Connecting astronomers worldwide".

The seminars were focused on how Very Long Baseline Interferometry (VLBI) observations can significantly contribute to different astronomical fields. The talks were oriented to the broad astronomical community and provided an engaging introduction to cutting-edge research from different groups across the world. During 2020 four seminars were organised, followed by a numerous number of participants that hold very interesting discussions. The seminars were recorded and are accessible at the EVN/JIVE Youtube channel.

Figure 8.8: *Poster for the EVN virtual seminars "The sharpest view of the radio Universe".*

8.9.1 Using Strong Gravitational Lensing to Zoom in on High-Redshift Galaxies

Seminar by Cristiana Spingola, University of Bologna & INAF Istituto di Radioastronomia. 8 July 2020.

The centres of galaxies are powerful laboratories to test models of galaxy formation, as well as the interplay between supermassive black holes and their host galaxies. While these sub-galactic scales can be directly investigated in the local Universe, it is observationally extremely difficult to access them at high redshift. In this talk, we will exploit the combination of strong gravitational lensing and multi-wavelength high angular resolution observations to directly study the parsec scale emission in active galaxies at z ¿ 1. The magnifying effect of strong lensing and the milliarcsecond angular resolution of HST, Keck AO and VLBI observations allow us to spatially resolve the central parts of distant lensed galaxies, especially if they are located in the regions at highest magnification. Therefore, it becomes possible to unveil dual and offset AGN candidates, but also faint extended jets embedded in massive molecular gas reservoirs at cosmological distances. Nevertheless, this kind of study is currently limited by the small number of radio-loud lensed sources. We will conclude by discussing the current efforts to search for more lensing systems in wide-field VLBI surveys.

This seminar is available at the EVN/JIVE Youtube channel.

8.9.2 VLBI as a key to the origin of high-energy neutrinos

Seminar by Yuri Kovalev, Astro Space Center. 4 September 2020.

Observational information on high-energy astrophysical neutrinos is being continuously collected by the IceCube observatory. However, the sources of the neutrinos are still unknown. We studied a large complete VLBI-selected sample of extragalactic radio sources and found that AGN positionally associated with IceCube events have typically stronger parsec-scale cores. Moreover, we see an increase of radio emission at frequencies above 10 GHz around neutrino arrival times. We conclude that AGNs with bright Doppler-boosted jets observed at small viewing angles constitute an important population of neutrino sources. High-energy neutrinos are produced in their central parsec-scale regions, probably in proton-photon interactions.

This seminar is available at the EVN/JIVE Youtube channel.

8.9.3 Pin-pointing the positions of repeating Fast Radio Bursts

Seminar by Kenzie Nimmo, University of Amsterdam & ASTRON. 19 October 2020.

Fast radio bursts (FRBs) are bright pulses of coherent radio emission with durations of only a few milliseconds, and unknown extragalactic origin. Some FRBs have been observed to repeat, whereas others appear as one-off events. Currently it still remains unclear whether all FRB sources have the ability to repeat, or if there are multiple populations with different physical mechanisms. Recently, the Galactic magnetar SGR 1935+2154 emitted a very bright radio burst (orders of magnitude brighter than typical Galactic radio bursts from pulsars/magnetars) unveiling a bridge between Galactic sources of radio bursts and FRBs. With the European VLBI Network (EVN) we can precisely localise FRBs to milli-arcsecond precision, identifying not only the host galaxy, but the region within the host that the bursts are originating from. This will help in understanding the FRB progenitor(s) and how FRBs link to Galactic sources. In addition to the real-time correlation observing mode (e-EVN), baseband data can be buffered to study fine time and frequency structures of the bursts, as well as their polarisation properties. In this talk I will discuss our approach to localising repeating FRBs using the EVN, present the localisation of a second repeater, FRB 180619.J0158+65, and present recent results on SGR 1935+2154.

This seminar is available at the EVN/JIVE Youtube channel.

8.9.4 Galactic Maser Astrometry with Very Long Baseline Interferometry: Current Status and Beyond

Seminar by Mareki Honma, National Astronomical Observatory of Japan. 9 December 2020

I will present the most recent results of high-resolution maser astrometry with Very Long Baseline Interferometry (VLBI). Maser astrometric surveys have been conducted with the Japanese VERA array and the Bar and Spiral Structure Legacy (BeSSeL) project, aimed at exploring the dynamic structure of the Milky Way. I will present recent results from these surveys, mainly covering topics on the determination of fundamental parameters, rotation curve measurement, tracing spiral structures, comparisons/calibrations of GAIA astrometry, and so on. I will also cover some topics related to individual maser sources (star forming regions and AGB stars) revealed by VLBI astrometry in combination with other arrays such as the Atacama Large Millimeter Array (ALMA). Finally, I will briefly discuss the future prospects of VLBI astrometry for forthcoming global VLBI in the SKA era.

This seminar is available at the EVN/JIVE Youtube channel.

9 EVN publications

9.1 EVN related referred publications (in alphabetical order) 2019

Journal Articles

1. P. Atri, J. C. A. Miller-Jones, A. Bahramian, R. M. Plotkin, P. G. Jonker, G. Nelemans, T. J. Maccarone, G. R. Sivakoff, A. T. Deller, S. Chaty, M. A. P. Torres, S. Horiuchi, J. McCallum, T. Natusch, C. J. Phillips, J. Stevens, S. Weston: *Potential kick velocity distribution of black hole X-ray binaries and implications for natal kicks*, 2019, Monthly Notices of the Royal Astronomical Society, 489, 3116-3134 (**EM101**)

2. T. M. Bocanegra-Bahamón, G. Molera Calvés, L. I. Gurvits, G. Cimò, D. Dirkx, D. A. Duev, S. V. Pogrebenko, P. Rosenblatt, S. Limaye, L. Cui, P. Li, T. Kondo, M. Sekido, A. G. Mikhailov, M. A. Kharinov, A. V. Ipatov, W. Wang, W. Zheng, M. Ma, J. E. J. Lovell, J. N. McCallum: *Venus Express radio occultation observed by PRIDE*, 2019, Astronomy and Astrophysics, 624, id.A59 (**V0427, V0429, V0430, V0501, V0323**)

3. Hong-Min Cao, Sándor Frey, Krisztina É. Gabányi, Jun Yang, Lang Cui, Xiao-Yu Hong, Tao An: *The loud and the quiet: searching for radio counterparts of two radio-weak BL Lac candidates with VLBI*, 2019, Monthly Notices of the Royal Astronomical Society, 482, L34-L39 (**EC061**)

4. P. Castangia, G. Surcis, A. Tarchi, A. Caccianiga, P. Severgnini, R. Della Ceca: *Water masers in Compton-thick AGN. II. The high detection rate and EVN observations of ¡ASTROBJ¿IRAS 15480-0344¡/ASTROBJ¿*, 2019, Astronomy and Astrophysics, 629, id.A25 (**EC047**)

5. K. É. Gabányi, S. Frey, S. Satyapal, A. Constantin, R. W. Pfeifle: *Very long baseline interferometry observation of the triple AGN candidate J0849+1114*, 2019, Astronomy and Astrophysics, 630, id.L5 (**RS09B**)

6. G. Ghirlanda, O. S. Salafia, Z. Paragi, M. Giroletti, J. Yang, B. Marcote, J. Blanchard, I. Agudo, T. An, M. G. Bernardini, R. Beswick, M. Branchesi, S. Campana, C. Casadio, E. Chassande-Mottin, M. Colpi, S. Covino, P. D'Avanzo, V. D'Elia, S. Frey, M. Gawronski, G. Ghisellini, L. I. Gurvits, P. G. Jonker, H. J. van Langevelde, A. Melandri, J. Moldon, L. Nava, A. Perego, M. A. Perez-Torres, C. Reynolds, R.

Salvaterra, G. Tagliaferri, T. Venturi, S. D. Vergani, M. Zhang: *Compact radio emission indicates a structured jet was produced by a binary neutron star merger*, 2019, Science, 363, 968-971 (**GG084, RG009, EP105**)

7. N. V. Gusinskaia, J. W. T. Hessels, N. Degenaar, A. T. Deller, J. C. A. Miller-Jones, A. M. Archibald, C. O. Heinke, J. Moldón, A. Patruno, J. A. Tomsick, R. Wijnands: *Quasi-simultaneous radio and X-ray observations of Aql X-1 : probing low luminosities*, 2019, Monthly Notices of the Royal Astronomical Society, doi:10.1093/mnras/stz3420 (Used published **EVN** data)

8. P. Hartley, N. Jackson, D. Sluse, H. R. Stacey, H. Vives-Arias: *Strong lensing reveals jets in a sub-microJy radio-quiet quasar*, 2019, Monthly Notices of the Royal Astronomical Society, 485, 3009-3023 (**EJ016A, EJ016B**)

9. J. W. T. Hessels, L. G. Spitler, A. D. Seymour, J. M. Cordes, D. Michilli, R. S. Lynch, K. Gourdji, A. M. Archibald, C. G. Bassa, G. C. Bower, S. Chatterjee, L. Connor, F. Crawford, J. S. Deneva, V. Gajjar, V. M. Kaspi, A. Keimpema, C. J. Law, B. Marcote, M. A. McLaughlin, Z. Paragi, E. Petroff, S. M. Ransom, P. Scholz, B. W. Stappers, S. P. Tendulkar: *FRB 121102 Bursts Show Complex Time-Frequency Structure*, 2019, The Astrophysical Journal, 876, id.L23 (**RP024,RP026**)

10. Z. X. Li, Z. Z. Wu, Y. J. Chen, L. Chen, M. F. Gu, L. G. Mi: *The Radio Properties for BL Lac Object S5 2007+777*, 2019, Acta Astronomica Sinica, 60, id. 20 (**EZ028???**-paper not open access)

11. D. S. MacMillan, A. Fey, J. M. Gipson, D. Gordon, C. S. Jacobs, H. Krásná, S. B. Lambert, Z. Malkin, O. Titov, G. Wang, M. H. Xu: *Galactocentric acceleration in VLBI analysis. Findings of IVS WG8*, 2019, Astronomy and Astrophysics, 630, id.A93 (Based on VLBA/**EVN**/VERA data)

12. B. Marcote, K. Nimmo, O. S. Salafia, Z. Paragi, J. W. T. Hessels, E. Petroff, R. Karuppusamy: *Resolving the Decades-long Transient FIRST J141918.9+394036: An Orphan Long Gamma-Ray Burst or a Young Magnetar Nebula?*, 2019, The Astrophysical Journal, 876, id.L14 (**RM015**)

13. B. Marcote, Y. Maan, Z. Paragi, A. Keimpema: *Probing the origin of the off-pulse emission from the pulsars B0525+21 and B2045-16*, 2019, Astronomy and Astrophysics, 627, id.L2 (**EM127**)

14. S. E. Motta, R. P. Fender: *A connection between accretion states and the formation of ultrarelativistic outflows in a neutron star X-ray binary*, 2019, Monthly Notices of the Royal Astronomical Society, 483, 3686-3699 (Using data from the 1999 VLBA/**EVN**/LBA campaign; Fig. 2)

15. Suma Murthy, Raffaella Morganti, Tom Oosterloo, Robert Schulz, Dipanjan Mukherjee, Alexander Y. Wagner, Geoffrey Bicknell, Isabella Prandoni, Aleksandar Shulevski:

Feedback from low-luminosity radio galaxies: B2 0258+35, 2019, Astronomy and Astrophysics, 629, id.A58 (**ES070**)

16. Gelu M. Nita, Aard Keimpema, Zsolt Paragi: *Statistical Discrimination of RFI and Astronomical Transients in 2-bit Digitized Time Domain Signals*, 2019, Journal of Astronomical Instrumentation, 8, id. 1940008 (Used **RP024** data)

17. M. Olech, M. Szymczak, P. Wolak, R. Sarniak, A. Bartkiewicz: *6.7 GHz variability characteristics of new periodic methanol maser sources*, 2019, Monthly Notices of the Royal Astronomical Society, 486, 1236-1254 (**EB040, EB052, EO014**)

18. J. A. Paice, P. Gandhi, P. A. Charles, V. S. Dhillon, T. R. Marsh, D. A. H. Buckley, M. M. Kotze, A. Beri, D. Altamirano, M. J. Middleton, R. M. Plotkin, J. C. A. Miller-Jones, D. M. Russell, J. Tomsick, W. Díaz-Merced, R. Misra: *Puzzling blue dips in the black hole candidate Swift J1357.2 - 0933, from ULTRACAM, SALT, ATCA, Swift, and NuSTAR*, 2019, Monthly Notices of the Royal Astronomical Society, 488, 512-524 (**RM010**)

19. A. V. Plavin, Y. Y. Kovalev, L. Y. Petrov: *Dissecting the AGN Disk-Jet System with Joint VLBI-Gaia Analysis*, 2019, The Astrophysical Journal, 871, id. 143 (Used earlier published VLBA and **EVN** maps)

20. Jack F. Radcliffe, Robert J. Beswick, A. P. Thomson, Michael A. Garrett, Peter D. Barthel, Thomas W. B. Muxlow: *An insight into the extragalactic transient and variable microJy radio sky across multiple decades*, 2019, Monthly Notices of the Royal Astronomical Society, 490, 4024-4039 (**EG078, GG053**)

21. M. J. Reid, K. M. Menten, A. Brunthaler, X. W. Zheng, T. M. Dame, Y. Xu, J. Li, N. Sakai, Y. Wu, K. Immer, B. Zhang, A. Sanna, L. Moscadelli, K. L. J. Rygl, A. Bartkiewicz, B. Hu, L. H. Quiroga-Nuñez, H. J. van Langevelde: *Trigonometric Parallaxes of High-mass Star-forming Regions: Our View of the Milky Way*, 2019, The Astrophysical Journal, 885, article id. 131 (Based on VLBA/VERA/**EVN**/LBA data)

22. C. Spingola, J. P. McKean, D. Massari, L. V. E. Koopmans: *Proper motion in lensed radio jets at redshift 3: A possible dual super-massive black hole system in the early Universe*, 2019, Astronomy and Astrophysics, 630, id.A108 (**GP030**)

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2. P. Benke, S. Frey, K. É. Gabányi, L. I. Gurvits, Z. Paragi, T. An, E. Kun, P. Mohan, D. Cseh, Gy. Mező: *The rise and fall of a binary AGN candidate: the story of PSO J334.2028+1.4075*, 2019, arXiv e-prints (**RSF08**)

3. Michael F. Bietenholz, Norbert Bartel: *Recent VLBI Results on SN 1986J and the Possibility of FRBs Originating from Inside the Expanding Ejecta of Supernovae*, 2019, arXiv e-prints (Based on earlier **EVN** and US VLBI network observations)

4. F. Colomer: *What can VLBI do for your research? The EVN and JIVE*, 2019, Highlights on Spanish Astrophysics X, p. 290-295 (**EVN** and user support)

5. Francisco Colomer, Mark Kettenis, Robert M. Campbell, Patrick Charlot, Arpad Szomoru: *Geodetic Capabilities at the JIVE SFXC Correlator*, 2019, International VLBI Service for Geodesy and Astrometry 2018 General Meeting Proceedings: "Global Geodesy and the Role of VGOS - Fundamental to Sustainable Development, p. 117-120 (**EVN** SFXC geo-VLBI developments)

6. Jonas Flygare, Miroslav Pantaleev, John Conway, Michael Lindqvist, Leif Helldner, Magnus Dahlgren, Rüdiger Haas, Peter Forkman: *Ultra-wideband Feed Systems for the EVN and SKA - Evaluated for VGOS*, 2019, International VLBI

Service for Geodesy and Astrometry 2018 General Meeting Proceedings: "Global Geodesy and the Role of VGOS - Fundamental to Sustainable Development, p. 42-46 (Broadband **EVN** developments)

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11. B. Marcote, Z. Paragi: *Localizations of Fast Radio Bursts on milliarcsecond scales*, 2019, arXiv e-prints (FRB VLBI results with the **EVN**)

12. P. Mohan, T. An, J. Yang: *The nearby luminous transient AT2018cow: a magnetar formed in a sub-relativistically expanding non-jetted explosion*, 2019, arXiv e-prints (**RY007, EY033, EM137**)

13. S. Murthy, R. Morganti, T. Oosterloo, R. Schulz, D. Mukherjee, A. Y. Wagner, G. Bicknell, I. Prandoni, A. Shulevski: *VizieR Online Data Catalog: B2 0258+35 VLA and VLBI HI absorption spectra (Murthy+, 2019)*, 2019, VizieR Online Data Catalog, (From **EVN** data; **ES070**)

14. Zsolt Paragi, Antonio Chrysostomou, Cristina Garcia-Miro: *SKA-VLBI Key Science Programmes*, 2019, arXiv e-prints (**e-EVN** as SKA pathfinder; SKA-VLBI)

15. Anish Roshi, L. D. Anderson, E. Araya, D. Balser, W. Brisken, C. Brum, D. Campbell, S. Chatterjee, E. Churchwell, J. Condon, J. Cordes, F. Cordova, Y. Fernandez, J. Gago, T. Ghosh, P. F. Goldsmith, C. Heiles, D. Hickson, B. Jeffs, K. M. Jones, J. Lautenbach, B. M. Lewis, R. S. Lynch, P. K. Manoharan, S. Marshall, R. Minchin, N. T. Palliyaguru, B. B. P. Perera, P. Perillat, N. Pinilla-Alonso, D. J. Pisano, L. Quintero, S. Raizada, S. M. Ransom, F. O. Fernandez-Rodriguez, C. J. Salter, P. Santos, M. Sulzer, P. A. Taylor, F. C. F. Venditti, A. Venkataraman, A. K. Virkki, A. Wolszczan, M. Womack, L. F. Zambrano-Marin: *Arecibo Observatory in the Next Decade*, 2019, Bulletin of the American Astronomical Society, 51, id. 244 (Arecibo as part of the **EVN**)

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17. G. Tuccari, W. Alef, S. Dornbusch, R. Haas, K. -Å. Johansson, L. La Porta, H. Rottmann, A. L. Roy, J. Wagner, M. Wunderlich: *DBBC3 Towards the BRAND EVN Receiver*, 2019, Proceedings of the 24th European VLBI Group for Geodesy and Astrometry Working Meeting, p. 27-30 (VLBI backend for the **EVN**)

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9.2 EVN related referred publications (in alphabetical order) 2020

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2. Saghar Asadi, Erik Zackrisson, Eskil Varenius, Emily Freeland, John Conway, Kaj Wiik: *The case against gravitational millilensing in the multiply-imaged quasar B1152+199*, 2020, Monthly Notices of the Royal Astronomical Society, 492, 742 (archival and new data: **EJ010**, **EZ024**, **GA036**)

3. P. Atri, J. C. A. Miller-Jones, A. Bahramian, R. M. Plotkin, A. T. Deller, P. G. Jonker, T. J. Maccarone, G. R. Sivakoff, R. Soria, D. Altamirano, T. Belloni, R. Fender, E. Koerding, D. Maitra, S. Markoff, S. Migliari, D. Russell, T. Russell, C. L. Sarazin, A. J. Tetarenko, V. Tudose: *A radio parallax to the black hole X-ray binary MAXI J1820+070*, 2020, Monthly Notices of the Royal Astronomical Society, 493, L81 (**EA062**)

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10. Lulu Fan, Wen Chen, Tao An, Fu-Guo Xie, Yunkun Han, Kirsten K. Knudsen, Jun Yang: *The Hyperluminous, Dust-obscured Quasar W2246-0526 at $z = 4.6$: Detection of Parsec-scale Radio Activity*, 2020, Astrophysical Journal, 905, L32 (**EY034**)

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12. E. C. Kool, T. M. Reynolds, S. Mattila, E. Kankare, M. A. Pérez-Torres, A. Efstathiou, S. Ryder, C. Romero-Cañizales, W. Lu, T. Heikkilä, G. E. Anderson, M. Berton, J. Bright, G. Cannizzaro, D. Eappachen, M. Fraser, M. Gromadzki, P. G. Jonker, H. Kuncarayakti, P. Lundqvist, K. Maeda, R. M. McDermid, A. M. Medling, S. Moran, A. Reguitti, M. Shahbandeh, S. Tsygankov, V. U, T. Wevers: *AT 2017gbl: a dust obscured TDE candidate in a luminous infrared galaxy*, 2020, Monthly Notices of the Royal Astronomical Society, 498, 2167 (**RP028B**)

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3. Michael F. Bietenholz, N. Bartel, M. Argo, R. Dua, S. Ryder, A. Soderberg: *The Radio Luminosity-Risetime Function of Core-Collapse Supernovae*, 2020, arXiv:2011.11737 (reusing previously published **EVN** data as well)

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6. F. Colomer: *VLBI20-30: A scientific roadmap for the next decade*, 2020, XIV Scientific Meeting (virtual) of the Spanish Astronomical Society, 221 (about the **EVN Vision Document**)

7. B. Boccardi, M. Perucho, C. Casadio, P. Grandi, D. Macconi, E. Torresi, S. Pellegrini, T. P. Krichbaum, M. Kadler, G. Giovannini, V. Karamanavis, L. Ricci, E. Madika, U. Bach, E. Ros, M. Giroletti, J. A. Zensus: *Jet collimation in NGC 315 and other nearby AGN*, 2020, arXiv:2012.14831 (**ES049B**)

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