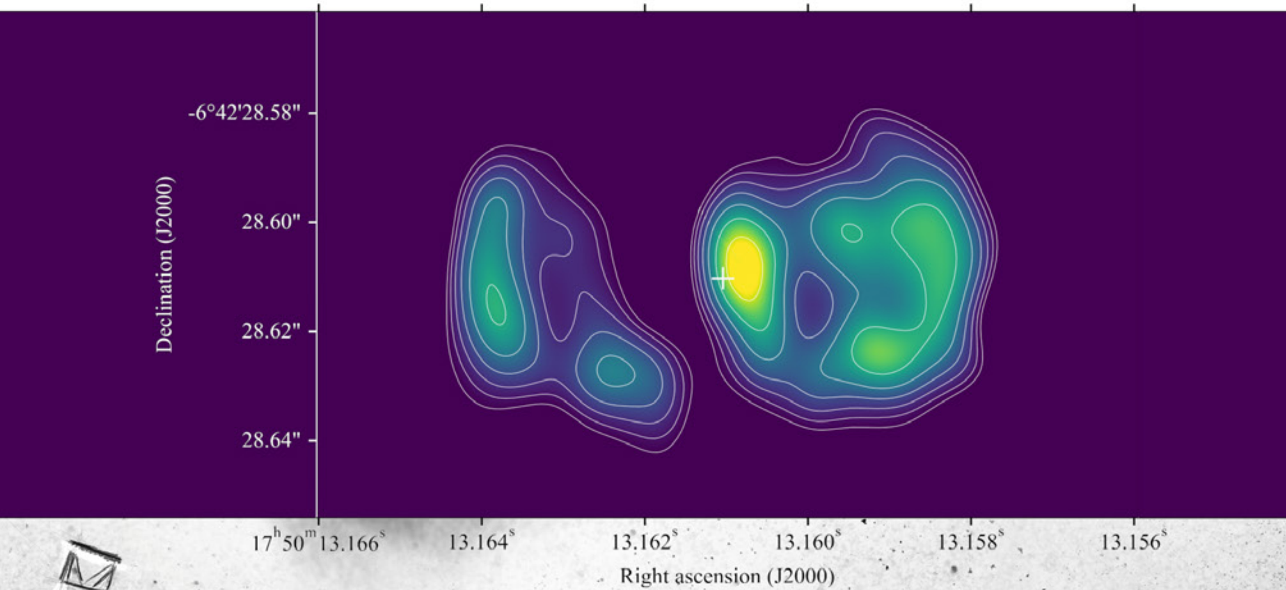
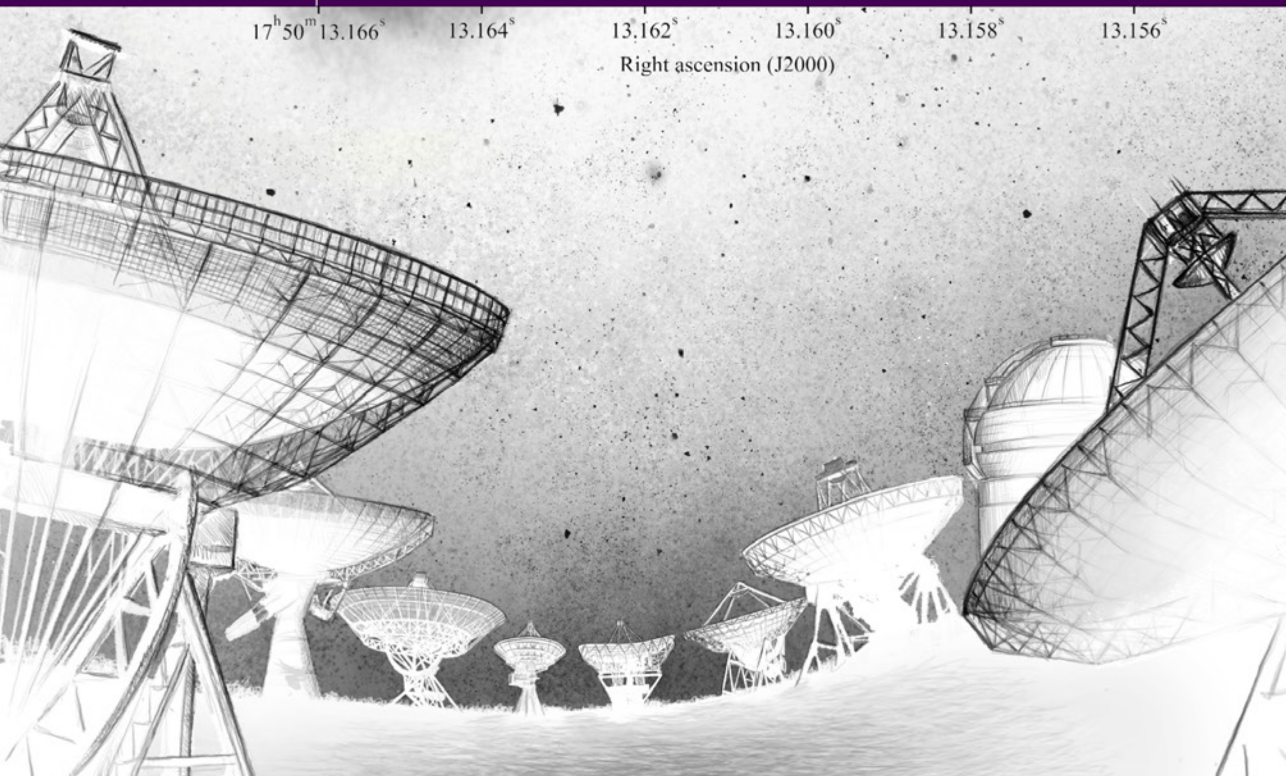
EUROPEAN VLBI NETWORK

2021-2022 Biennial Report





EUROPEAN VLBI NETWORK

2021-2022 Biennial Report

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1. Foreword

Foreword, from the EVN Consortium Board of Directors Chairperson

It is a pleasure and a privilege to introduce the 2021-2022 EVN Biennial Report. It has been a very dense biennium, during which the EVN has delivered exciting science and has implemented new capabilities.

Two major events have impacted on the EVN activities. The limitations due to the COVID-19 pandemic continued throughout 2021 to mid-2022, affecting the CBD and PC meetings, which were held online until Autumn 2022. As already happened in 2020, the dedication and expertise of the personnel at each observatory allowed that smooth operations and observing sessions could take place regularly. The second tragic event has been the Russian invasion of Ukraine. This has been, and still is, a shock for the whole world, and it is a major challenge to the collaborative and supportive nature of radio astronomy in general, and VLBI in particular. The EVN condemns the invasion and stands next to the Ukrainian colleagues and collaborators. At the same time, deciding not to correlate the data from the Quasar antennas in session 1-2022 and not to include them in the following VLBI sessions has been a painful decision for the CBD. As any sanction, this one is harmful to all parties involved. We have to do without three stations of an EVN member country, and the EVN Users will miss three stations in the array for an indefinite time. From a scientific point of view, this loss comes at a time when the requirement of improved sensitivity and (*u, v*)-coverage is as compelling as never before.

To avoid skipping entirely the biennial appointment of the EVN symposium, the scientific outcome of the EVN was presented at the mini-symposium held in July 2021 fully online, which was attended by an average of 100 participants each session, with a full 4-day programme which included 39 talks. Finally, the 15th EVN Symposium was held in person in Cork in July 2022. It has been a most enjoyable symposium, both for the quality of the talks and for the warm and friendly atmosphere, which has always been a key feature of the VLBI community. I wish to thank Denise Gabuzda for all the energy and work she has put in the organisation of both events, and for ensuring their success. The EVN online seminars have continued throughout 2021 and 2022 and have turned out to be extremely successful in reaching the astronomical community at large, well beyond the radio boundaries.

While the EC project JUMPINGJIVE finished in the summer of 2021, the two new projects ORP (Opticon Radio Pilot) and RADIOBLOCKS (started in 2021 and approved in 2022 respectively) now provide continuation of the cooperation between the radio astronomical partners in Europe (and beyond) on the operations and technological developments, to ensure that the EVN can develop to meet the scientific challenges of the present and next decade.

On the technological front, the implementation of the technological roadmap as outlined in the EVN Science Vision Document has continued. 4Gbps observations are being offered, even though flexbuff storage capacity has to be kept in mind. Solutions for a more flexible array have been implemented, to meet the needs of transient science without impacting other types of observations and taking into account the workload at each station: a second eVLBI day has been approved for each run, to be used for trigger observations if needed. Waiting for the BRAND receiver to become available, the development of broadband (C-X) receivers is making progress. Finally, the three-band (K-W-Q) receiver has been either purchased or developed by 7 stations in the array, making the EVN suitable for high-frequency observations in the near future. These forthcoming capabilities have triggered a remarkable enthusiasm on the scientific potentials of frequency phase transfer. Finally, one important outcome of the technological roadmap is the quest for the inclusion of more antennas in the array, to improve sensitivity and (u, v)-coverage. A lot has happened in this area. The **40m NARIT radio telescope** in Thailand has made amazing progress and operability is expected in the near future. The **uGMRT** expressed interest to join the EVN, carried out successful fringe tests during session 1-2022, and is now offered for observations at L-band. We all look forward to the official EVN membership of both radio telescopes.

This biennial report covers all the above, and much more. It consists of nine chapters, which report only a selection of the scientific productivity of the EVN and a very concise summary of the technological progress.

As clear from the EVN PC report, the EVN science spans over an increasingly broader range of areas. The selection made for this report is representative of such range. The two classical EVN areas, i.e. AGN studies and stellar maser science, are now only a fraction of the global scientific output, and the focus of the research has evolved considerably over the years. We will find multiband studies of AGNs, which are now mandatory for a complete understanding of the nature of the phenomena observed. Observations of very distant AGNs are providing clues on the formation and cosmological evolution of supermassive black holes. At the same time, we can finally gain insight on the black hole closest to us, SgrA*, thanks to the breathtaking results of EHT. Polarisation studies keep our attention high on the structure and role of magnetic fields in the AGN phenomenology. The discovery of recurrent maser flares, as well as the role of magnetic fields in such objects has important implications for our understanding of stellar evolution. Transient science is one of the most remarkable novel areas of interest. It actually includes very different phenomena and relates to very different types of objects, from fast radio bursts, to gamma-ray bursts, to extreme variable emission in AGN. The investment in making the EVN as flexible as possible (in relation to its nature as consortium of several different observatories with individual commitments beyond the EVN itself) is paying off. Observations of a sizeable sample of gravitational lenses for cosmological studies are needed to allow progress unveiling the dark matter properties. A novel application of VLBI using the ESA Mars mission has provided interesting results in the study of solar coronal flares.

All this and much more is reported here. I wish to remind that the EVN Newsletter provides regular updates on the EVN scientific and technological achievements, and I thank JIVE for taking the responsibility to prepare and distribute it to the whole community.

During the past two years, the collaboration between JIVE and the EVN has been most fruitful. I wish to thank Paco Colomer for his full dedication to the JIVE mission, hence ensuring the best possible outcome of the EVN science. It has been great to work with him. Dr. Agnieszka Słowikowska, former Deputy Director of Torun Radio Astronomical Observatory, is now the Director of JIVE. I wish to congratulate and reassure her that the EVN CBD will continue to collaborate tightly with JIVE in the interests of the EVN and its users.

Finally, I wish to warmly thank the CBD Secretary, Marcello Giroletti, for his support throughout the past two years, and for assembling this remarkable report.

Tiziana Venturi

Chair, EVN Consortium Board of Directors (January 2021 – December 2022)

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 2021-2022 is given in Tables 2.1 and 2.2.

2.2 EVN Consortium Board of Directors meetings

Regular meetings of the CBD happen 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 other individuals who may be invited to address topical meeting agenda points. The locations and dates of the regular CBD meetings during 2021-2022 are given in Table 2.3. Due to the COVID-19 pandemic three out of four meetings in the biennium took place via videoconference.

In addition, an online CBD meeting was held on 2022 March 9th, to discuss the position of the consortium following the dramatic events unfolding in Ukraine.

Name	Institute
Aleksejs Klokovs	Ventspils International Radio Astronomy Centre, Ventspils, Latvia
Pablo de Vicente	National Astronomical Observatory, Instituto Geográfico Nacional, Madrid, Spain
Fernando Camilo	South African Radio Astronomy Observatory, Hartebeesthoek, South Africa
John Conway	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
Agnieszka Slowikowska	Institute of Astronomy of Nicolaus Copernicus University, Toruń, Poland
Na Wang until April 2022, **Cui Lang** since May 2022	Xinjiang Astronomical Observatory, Xinjiang, China
Tiziana Venturi – Chair of the CBD	INAF 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 2.1: Full EVN CBD members, 2021-2022

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
Wang Min	Yunnan Observatories, Chinese Academy of Science, China

Table 2.2: EVN associate CBD members, 2021-2022

Place	Date
Remote meeting	12 May, 2021
Remote meeting	9 November, 2021
Remote meeting	9 March, 2022†
Remote meeting	10 May, 2022
Dwingeloo, the Netherlands	16 November, 2022

Table 2.3: CBD Meetings during 2021-2022. †The 9 March, 2022 meeting was devoted to the dramatic events unfolding in Ukraine.

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: transient phenomena and stellar compact objects, AGN, galaxies and (non-stellar) black-hole systems, galactic science, gravitational lensing, and development of new techniques and software.

3.1 Transient phenomena and stellar compact objects

VLBI localisations of Fast Radio Bursts

by F. Kirsten, J. W. T. Hessels, B. Marcote, et al.

Fast Radio Bursts (FRBs) are bright and brief (lasting milliseconds or less) flashes of radio light of unclear nature and cosmological origin. Firstly discovered in 2007, we have now detected hundreds of FRBs. Among those, only a small fraction are known to repeat, although it still remains unclear if there are different types of FRBs or all belong to the same population.

During the last years, a group led by F. Kirsten, B. Marcote, and J. Hessels has used the EVN to localize repeating FRBs to milliarcsecond precision, with studies that led to the first ever localization of a FRB, the first known repeating FRB, 20121102A, and the localisation of the second repeating FRB, 20180916B. These two localisations revealed surprising scenarios and only thanks to the accuracy of the localisations, the researchers could constrain the local environments where the bursts were produced. However, the physical conditions found in these two FRBs were radically different, and they did not allow the

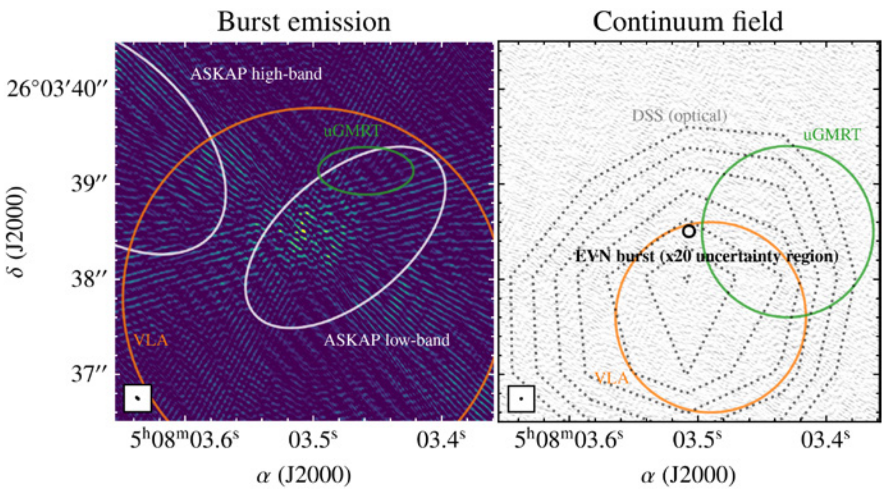

Figure 3.1: Localization of FRB 20201124A performed within the PRECISE project, from Kirsten et al. (2022). Left: the dirty map (color scale) compared to the previous localisations of the bursts performed by ASKAP, uGMRT, and VLA (ellipses). Note that the VLBI localization is about thousand times more precise (down to 4 mas). Right: the continuum map (gray scale), showing absence of significant radio emission and confirming that the previously reported one by the VLA and uGMRT (circles) is actually associated with star formation within the optical galaxy (dotted contours), and not to FRB 20201124A (Marcote et al. 2021; Nimmo et al. 2022).

team to trace a common scenario where these events are produced. To fully understand where FRBs can be found, a large number of localisations is clearly required. However, this also implies a large amount of observing time.

Pinpointing **R**Epeating **C**h**I**me **S**ources with **E**VN dishes (PRECISE) is a project to monitor repeating FRBs, aiming at localising them with milliarcsecond accuracy. By using an ad-hoc array of EVN dishes upon availability, it is possible to target a large number of known repeating FRBs. The data recorded from the individual dishes are searched for the presence of FRB emission and, in case of detection, are correlated at JIVE through an accepted correlation-only proposal.

During the last couple of years the team has been able to observe for hundreds of hours with up to ten antennas on each run. In 2021, the production of the first results within PRECISE started, localizing new repeating FRBs to milliarcsecond precision.

FRB 20200120E was found in a radically different environment than the previous FRBs: inside a globular cluster associated to the M81 galaxy (Kirsten et al. 2022), and with burst components as narrow as 60 ns (Nimmo et al. 2022), the narrowest features observed to date in a FRB. While most FRB models predicted very young objects, the presence of this FRB inside a globular cluster challenges most of these scenarios.

On the other hand, the localization of 20201124A (see Figure 3.1) clearly demonstrated the importance of milliarcsecond-precision localizations. This FRB was already localized to the arcsecond level with ASKAP, FAST, GMRT, and the VLA, allowing the identification of the host galaxy. Furthermore, a persistent radio source, detected by the VLA and GMRT, was coincident with such position. However, the VLBI localization allowed the researchers to pinpoint the bursts with a precision over thousand times better than the previous ones, clarifying that FRB 20201124A is placed outside the center of the host galaxy.

Additionally, the persistent emission is completely resolved out on these scales, implying that its origin is related to galactic star formation, and thus unlikely to be associated to FRB 20201124A.

FRB 121102: drastic changes in the burst polarisation contrasts with the stability of the persistent emission

by A. Plavin, Z. Paragi, B. Marcote, et al.

Fast radio bursts (FRBs) are bright millisecond-duration transients of an extragalactic origin. A great number of theories has been developed to explain this phenomenon in the past decade, many of those invoking neutron stars. Some FRBs are repeating, making it possible to organize detailed follow-up observations that include interferometers, so that to probe the emission regions with extreme resolution and sensitivity.

FRB 121102 is the first repeater discovered, and its properties make the source unique among FRBs. It lies within a star-forming region of a dwarf galaxy at a redshift of 0.19. The high rotation measure (RM) exceeding 10^5 rad m^{-2} indicates dense, highly magnetized plasma around the emitter. This plasma is likely related to the persistent radio source co-located with the bursts. The persistent source also has multiple alternative explanations, including an AGN or a young nebula. More focused studies of the source properties on milliarcsecond scales, and its relation to the bursts' RM, would let us constrain all these models better. Plavin et al. (2022) present such studies, including both EVN and single-dish observations, and discuss the results.

The brightest burst of FRB 121102 within the observation campaign was caught on 2016 September 20. Thanks to the VLBI backend at Effelsberg, the authors reanalysed the data at the highest spectral resolution of 4 kHz; this became crucial for the polarisation studies. They detected a significant linear polarisation of FRB 121102 bursts for the first time at a low frequency of 1.7 GHz. The rotation measure was the highest to date at $1.27 \cdot 10^5$ rad m^{-2}, qualitatively consistent with the falling trend on the years timescales. Linear polarisation fraction

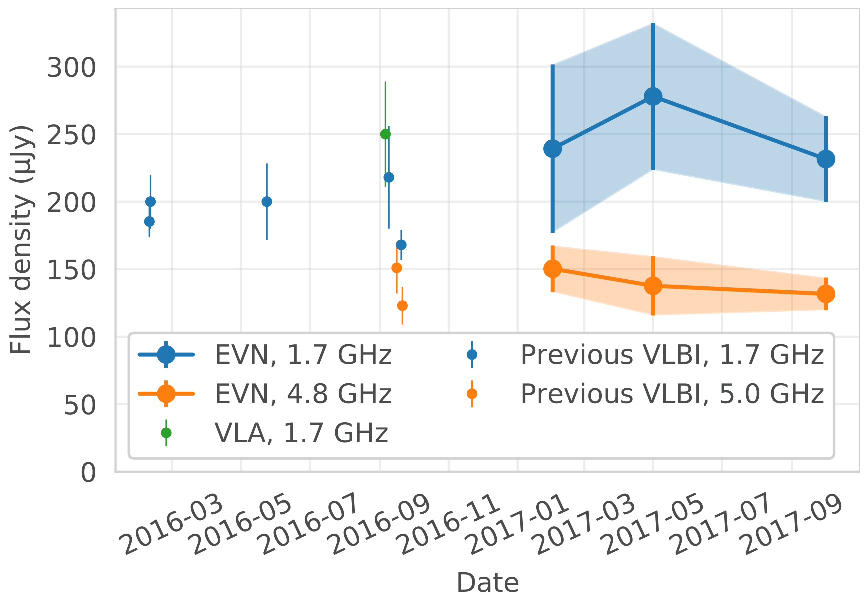

Figure 3.2: Measured fractional polarisation of bursts at different frequencies, from Plavin et al. (2022). The phenomenological model assumes 100% intrinsic polarisation with an effective width of 150 rad m^{-2} in the RM space. This model is consistent with measurements at 1.7 GHz and with higher 3–5 GHz measurements.

turned out to be much lower at 1.7 GHz: only 15%, compared to almost 100% observed at 5 GHz. This low fraction, combined with the requirement of a high spectral resolution, is the likely reason why no burst polarisation was detected at 1–2 GHz before. The authors explain this striking difference between frequencies with minor substructures in the screen, leading to spatial depolarization: the emission Faraday width of just 150 rad m^{-2}, or 0.1% of the total RM, is enough.

Dedicated EVN observations throughout 2017 caught no bursts, but this dataset provides invaluable information about the persistent radio counterpart. The observations included more telescopes than previous studies, leading to a better spatial frequencies coverage and a higher sensitivity. The radio source flux density is only 0.2 mJy, so both a regular phase-referencing calibrator, and a secondary in-beam one for relative comparisons were used. As it turns out, the persistent emission is surprisingly stable: flux variations are less than 10% over a year; the apparent position stays the same up to 0.1 mas, and is consistent between 1.7 and 4.8 GHz. The upper limits on the source size of 1 pc further constrains the maximal potential expansion rate to $\sim 10^4$ km s^{-1}. The lack of variations in observed parameters of the persistent emission, combined with changes in the bursts rate and

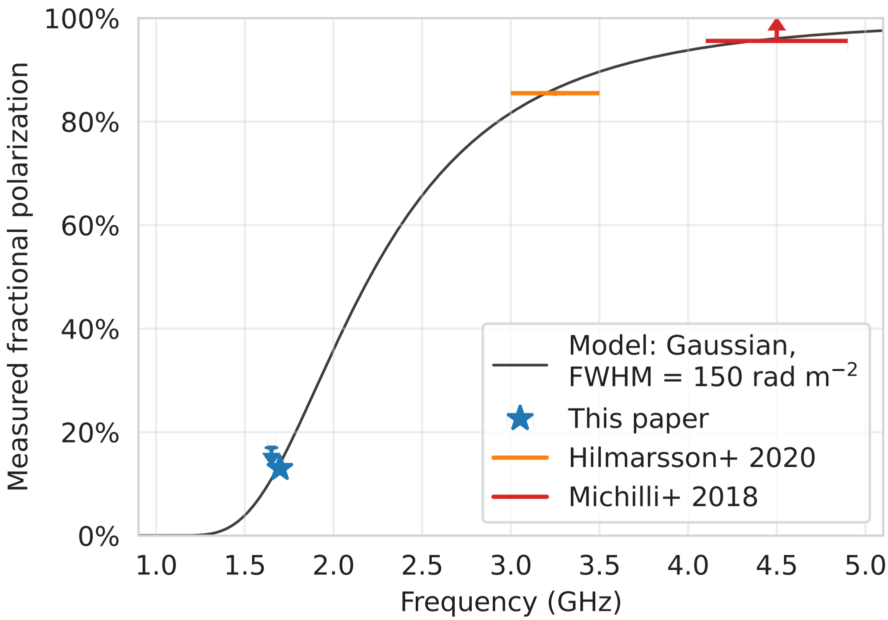

Figure 3.3: Flux density measurements of the persistent radio counterpart. EVN measurements in 2017 are show in comparison with earlier VLA, VLBA, and EVN observations. Variability within each frequency band is insignificant and lies below 10%.

their RM, put strong constrains on models explaining the environment of FRB 121102. For example, an expanding supernova would show a decaying luminosity trend; an AGN could have frequency-dependent apparent positions, or a general flux variability; a nebula inflated by a magnetar outflow would lead to a correlation between the burst rate and the persistent emission.

Unique dedicated observations of FRB 121102 performed by the EVN and the Effelsberg telescope lead to the results presented in Plavin et al. (2022). More observations, including polarisation, simultaneously at a wide frequency range and consistently over multiple years, would further help understanding the FRB environment evolution and the mechanisms underlying the bursting and persistent emission.

SN 2014C: Shell structure resolved in a complex supernova

by M. Bietenholz

Bietenholz et al. (2021) report on the very unusual supernova (SN) 2014C. Over the course of a few months, it evolved from an H (hydrogen)-poor Type Ib to an H-rich Type IIn, showing strong interaction with dense circumstellar medium. Intense observations at radio, optical and X-rays have led to the conclusion that the supernova exploded in a

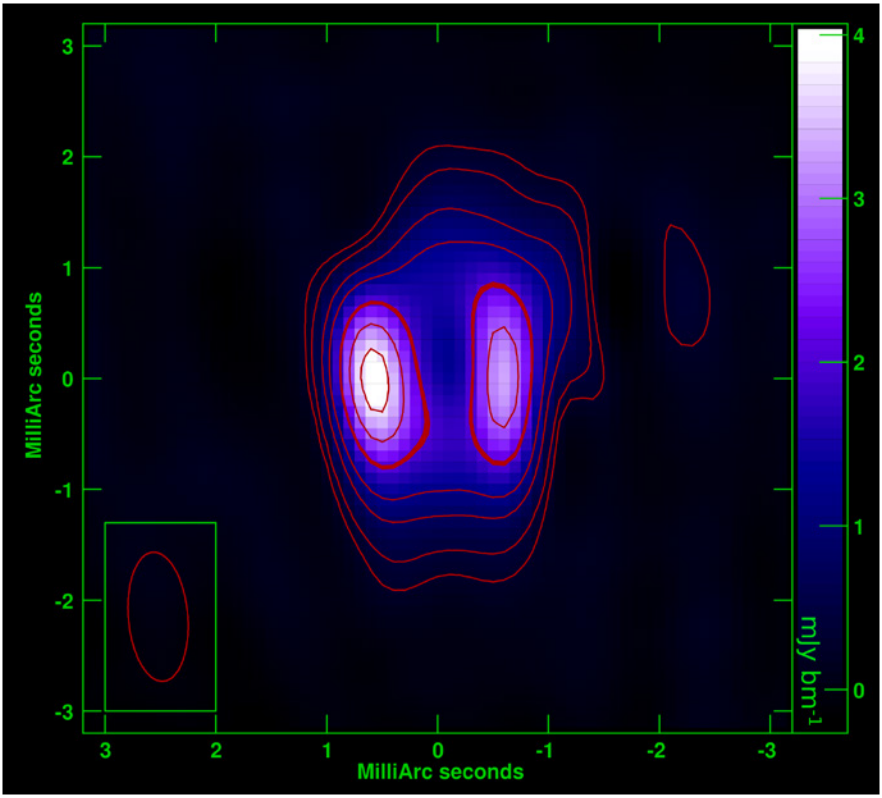

Figure 3.4: The VLBI image of SN 2014C on 2018 Oct 31, at age, t = 4.8 yr after the SN explosion, from Bietenholz et al. (2021). Both the contours and colour scale show the brightness. The contoures are at –6, 6, 10, 30, 50 (emphasized), 70, 90% of the image peak brightness of 4080 μJy beam^{-1}. The rms background brightness is 51 μJy beam^{-1}. The full-width at half-maximum (FWHM) resolution of (1.17 $\times$ 0.54) mas at p.a. 5° is indicated at lower left. North is up and east is to the left. Our observations were phase-referenced to VCS1 J2248+3718 and subsequently self-calibrated in phase. Imaging and deconvolution was done with multi-scale CLEANing using the AIPS task IMAGR.

low-density cavity as a Type Ib originating from a progenitor that had lost most of its H envelope. As the shock moved outward a few months after the explosion, it encountered a dense, H-rich shell of circumstellar medium. This shell, with a mass of $\sim 1 M_{\odot}$, was the product of an episode of intense mass-loss from the progenitor, which must have occurred in the period a decade to a few centuries before the explosion.

They obtained new, 8.4-GHz, VLBI observations of SN 2014C on 2018 Oct. 30 and 31, using 13 stations of the EVN, resulting in the image displayed in Figure 3.4. It shows a structure that is at least approximately circular in outline, with a minimum in the centre, and with enhancement to the east and west, with the one in the east being about 25% brighter. The enhancements to the east and west are largely due to the convolution of an intrinsically circular structure with the north-south elongated beam (see Bietenholz et al. (2021) for details), although the east-west asymmetry is real. The minimum in the centre suggests a spherical shell morphology, which has not clearly been seen for this SN before. Since only about 10 SNe are close enough and bright enough that the morphology can be clearly resolved with VLBI, the addition of SN 2014C represents a significant increase to this group of supernovae of which the size, shape and morphology and expansion can be studied in detail.

To determine parameters of the shell of SN 2014C, the researchers fit a geometrical, spherical-shell model in the Fourier transform or $u-v$ plane and found that the shell of emission is relatively thin. The angular outer radius is 0.89 ± 0.08 mas, corresponding to a linear radius of $(20.1 \pm 1.7) \times 10^{16}$ cm at a distance of 15.1 Mpc. Along with radii measured with VLBI at previous epochs, the new measurement implies that SN 2014C has been significantly decelerated since its explosion. There is a suggestion that the deceleration is increasing since the previous measurement at $t \sim 3$ yr. New EVN observations already planned will help to shed more light on the development of this supernova.

SN 2014C joins a growing list of SNe that show complex patterns of mass-loss before the SN explosion. VLA measurements show that SN 2014C's flux density has remained relatively constant since $t \sim 1$ yr (Bietenholz et al. (2021)). The sustained radio emission since then suggests that the progenitor went through a period of steadily decreasing mass-loss before ejecting the dense shell and then subsequently exploding as a SN. The mass-loss history of SN 2014C was therefore quite complex, with a period of likely 1000's of years of decreasing mass-loss rate, followed by a period of very high mass-loss rate in the decades to centuries before the explosion, which produced the dense CSM shell, followed by a period of very low mass-loss for the remaining time till the explosion finally occurred.

High-resolution VLBI observations and modelling of the radio emission from the TDE AT2019dsg

by P. Mohan, T. An, Y. Zhang, et al.

A tidal disruption event (TDE) involves the cataclysmic shredding of a star that approaches the vicinity (at or within the tidal radius) of a galactic supermassive black hole (SMBH of $10^6 - 10^8$ $M_\odot$, e.g. Rees (1988). The accreting stellar debris powers a predominantly optical — X-ray flare (thermal blackbody emission) during the early phase (timescale of days). An outflow (relativistic/collimated or non-relativistic/wider angled) can be subsequently produced and accelerated. Synchrotron radio emission is produced by electrons accelerated by an expanding shock over timescales of months to years. The shock can originate (1) from the interaction between the outflow and the surrounding circum-nuclear medium, or (2) intrinsically in the outflow (e.g. injection events, magnetic re-connections in the relativistic jets of active galactic nuclei AGN). Monitoring the radio emission can address its origin, outflow nature (relativistic or non-relativistic), constrain the density and distribution of the surrounding environment, and help discern the TDE physical and geometric properties.

AT2019dsg is a TDE discovered on 9th April 2019 by the Zwicky Transient Factory at a redshift $z = 0.051$ (distance of $\sim$230 Mpc; van Velzen et al. (2021). It is highly luminous (peak optical luminosity of $\approx 3.5 \times 10^{44}$ erg s^{-1}) and the first TDE with a potential neutrino association (peta-electron volt, PeV) based on the detection by the IceCube neutrino observatory (IC191001A $\approx$ 180 days post TDE; Stein et al. (2021)). The study of non-thermal emission (evolution of flux density and source structure) and its origin, either from activity associated with a relativistic jet (collimated, beamed emission) or a non-relativistic outflow (wider angled) is key to understanding the origin of the PeV neutrino from this source. Multi-wavelength and interpretative studies of AT2019dsg provided divergent views on the nature of the emission and hence on the neutrino origin (e.g., Stein et al. (2021), Cendes et al. (2021)).

Mohan et al. conducted VLBI high resolution C-band (5 GHz) radio observations with EVN, which can resolve emitting structures a few tens of light-years in the host galaxy situated $\approx$ 750 million light-years away. This included three sessions (RSM04, EM140A and EM140B covering $\approx$ 4 months during 2019/20) and involved up to 20 participating radio telescopes across the UK, Europe, Russia and China. The objectives were: 1. To detect and monitor the radio emitting component and its evolution (in brightness and structure), 2. To potentially detect a relativistic jet (putative driver of the production of neutrinos and cosmic rays in blazars), 3. Inputs to discern the TDE properties and address the neutrino association. The observations successfully imaged the compact fading emission structure in all three sessions (see Fig. 3.5), enabling the integration with previous C-band studies in order to aid

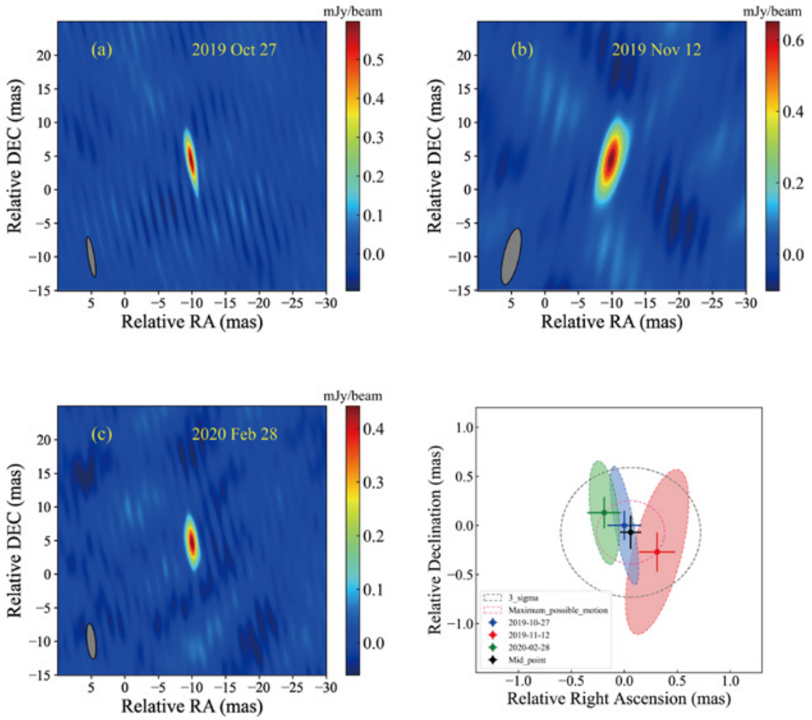

Figure 3.5: Top row and bottom left: high-resolution images from the three EVN 5 GHz observations showing a compact, unresolved source. Bottom right: constraints on the source; emission centre from astrometric measurements the inner red circle denotes the maximum relative position change, and the outer black circle denotes the 3-σ error on this, indicating no significant proper motion. See Mohan et al. (2022) for the reported VLBI observations and analysis.

in the modelling of the emission and understanding its origin.

The EVN astrometric measurements (precise position of the emission peak) and flux density evolution provide less evidence for a relativistic component in AT2019dsg (at the 3-σ uncertainty level, see Fig. 3.5). This and modelling the evolution of the 5 GHz radio flux densities indicate a decelerating shock produced by a fast outflow with a speed of $\approx 0.1\ c$ that had interacted with a dense surrounding medium. The transient involved the disruption of a $\approx 2\ M_{\odot}$ star. The base of the outflow is found to offer suitable conditions for the production and acceleration of cosmic ray protons and neutrinos. The findings, published in Mohan et al. (2022 promote an expanded inventory of multi-messenger (electromagnetic, particles: cosmic rays and neutrinos, gravitational waves) producing transients, not necessarily requiring a powerful accelerating mechanism such as a relativistic jet.

Resolving the 3D structure of RS Oph, the fastest repeater among symbiotic recurrent-novae

by U. Munari, M. Giroletti, B. Marcote, et al.

An EVN monitoring campaign of the 2021 outburst of the symbiotic recurrent nova RS Oph, in combination with high-resolution ground-based spectroscopy and the accurate astrometric position by Gaia, provided an unprecedented 3D view of the pre-existing circumstellar environment and of the nova ejecta expanding through it Munari et al. (2022): launched at an initial velocity > 8000 km/s, the ejecta have been rapidly decelerated into a bipolar shape by the density-enhancement laying on the orbital plane, with strong non-thermal emission originating from the shock interface with the slow and thick wind of the red-giant (RG) companion to the erupting white dwarf (WD).

A nova eruption is rather violent, with 10^{-6} to $10^{-4} M_{\odot}$ of material being expelled at high velocity (10^3 km/s), as consequence of a thermonuclear runaway (TNR) igniting in the accreted and electron-degenerate shell of a WD. The binary system survives the eruption, and shortly after it the donor companion resumes transferring material to the WD. The refuelling time to the next eruption stretches over various orders of magnitudes, reaching the shortest recurrence times for the most massive WD accreting from cool giant companions (which are powerful mass-losers). Such kind of binary is known as "symbiotic", and RS Oph is undoubtedly the most famous and best studied example of a symbiotic recurrent-nova, with eruptions recorded in 1898, 1933, 1958, 1967, 1985, 2006, and 2021, and possibly many other passed unnoticed during Solar conjunctions and the early years of only sparse monitoring.

In a "classical" nova, the donor is a tiny lower-main sequence star, orbiting the WD in a few hours at a separation of about one Solar radius, and the recurrence time is usually vastly longer than historical records. The rapidly advancing ejecta quickly overtake the orbital separation, after which they keep expanding in the surrounding void. A nova outburst developing in a symbiotic binary is a much more spectacular and dynamic show, thanks to the presence of the pre-existing, slow, thick and massive wind of the cool giant companion that permeates the circum-binary space for hundreds of AUs. Such wind plays two main roles during a symbiotic nova eruption: (1) it offers an absorbing medium for the initial UV-flash of the TNR, gets ionized glowing brightly, and recombines over time-scales of a few days, and (2) decelerates, shocks, and reshapes the ejecta that try expanding through it, which is the phenomenon targeted with the EVN monitoring campaign of the 2021 eruption of RS Oph.

The 2021 EVN image at 5 GHz for RS Oph on day +34 (counted from maximum optical brightness) is shown in the top panel of Figure 3.6,

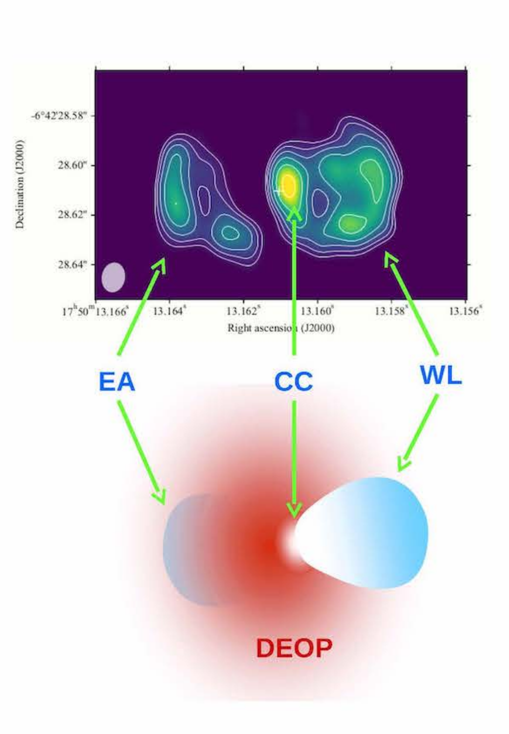

Figure 3.6: Top: EVN image at 5 GHz of RS Oph on day +34 of its 2021 nova eruption. The radio emission is elongated over the east–west direction for a total extension of $\sim$ 90 mas ($\sim$ 240 AU). The central component CC lies within a few mas of the Gaia position (white cross) extrapolated to the observing epoch. Emission is present on either side of the CC, brighter on the western side and forming a circular lobe. Fainter emission is present also to the east of CC, in the shape of an arc. Bottom: simple sketch of the expanding and bipolar arrangement of the ejecta. The diffuse and reddish component represents the DEOP. From Munari et al. (2022).

with the sketch in the bottom panel illustrating the interpretation of the observed structure. In addition to a massive accretion disk (AD) around the WD, 3D hydro-dynamical simulations of symbiotic stars show that much of the mass loss from the RG is gravitationally focused by the companion towards the orbital plane, creating a strong and disk-like density enhancement with the binary at its centre. In Figure 3.6 the density enhancement on the orbital plane (DEOP) is represented by the diffuse and reddish component. During a nova eruption, the combined effect of the AD and the DEOP is to confine the ejecta primarily within a bipolar structure, which expands perpendicular to the orbital plane. The non-thermal radio emission originates at the shock interface between the fast expanding lobes and the pre-existing slow wind of the RG. The circular western lobe (WL) component in Figure 3.6 is the projection on the plane of the sky of the lobe moving towards the observer, in the foreground to the DEOP. The Easter Arch (EA) is the visible outer portion of the lobe expanding opposite the WL, moving away from the observer and located behind the DEOP. The projected surface density of the DEOP, and probably also its ionisation degree, radially declines moving away from the central binary, which implies that the free-free opacity exerted by the DEOP also reduces as a function of the increasing projected distance from its centre.

For its synchrotron radiation (of frequency ν) to be able to reach the Earth, the EA component has to move to a projected distance from the central binary that is large enough to cross the DEOP where the optical depth turns $\tau_\nu < 1$, a condition occurring three weeks past optical maximum. The compact central component CC is interpreted as the interface between the DEOP and the impacting fast ejecta. Its much higher density turns the DEOP into a decelerating medium that is far more efficient than the diffuse wind of RG: a lot of kinetic energy is transformed within a small volume of space, leading to the bright non-thermal central emission spike.

The 2021 EVN observations of RS Oph, coupled with high-resolution optical spectroscopy and Gaia astrometric position, resulted in the most detailed 3D-view to date of a symbiotic recurrent-nova and its dynamical evolution: comparing with optical spectroscopy, the inclination of the orbital plane is constrained to $54° \pm 1$ and the average velocity of the leading edge of both WL and EA to 7550 ± 150 km/s. They offer a complementary view to the one obtained - again with EVN - of the symbiotic Mira V407 Cyg during its nova eruption of 2010, and provides a stimulating term of comparison for the imminent and much anticipated eruption of T CrB, which one hopes to similarly image with EVN.

Multiwavelength View of the Close-by GRB190829A Sheds Light on Gamma-Ray Burst Physics

by O.S. Salafia, M. Ravasio, J. Yang, et al.

Gamma-ray bursts have been serendipitously discovered in the late 1960's (see Kumar & Zhang 2015 for a recent review), but our understanding of the underlying physical processes is still far from complete. We have solid evidence that the main ingredient is a relativistic jet, a narrow surge of plasma that travels almost at the speed of light. The short duration (seconds to minutes) and extremely large energy of these jets points to the central 'engine' being a black hole or a neutron star. Indeed, some supernovae have been identified in association to gamma-ray bursts, which clearly indicates that these formed following the core-collapse of a massive star. When the fast and energetic jet material expands into the interstellar medium, it drives a shock wave that propagates outwards, which is referred to as the 'forward shock'. Soon the energy of the swept-up material, becomes comparable to the rest mass energy of the jet itself: the latter then starts to decelerate significantly because of energy and momentum conservation. The deceleration starts off in the outermost layers of the jet, but this leads to a supersonic collision with the layers behind (which have not slowed down yet): this produces a second shock wave, called the 'reverse shock'. Both shocks are thought to be places of particle acceleration through the 'Fermi process'. The

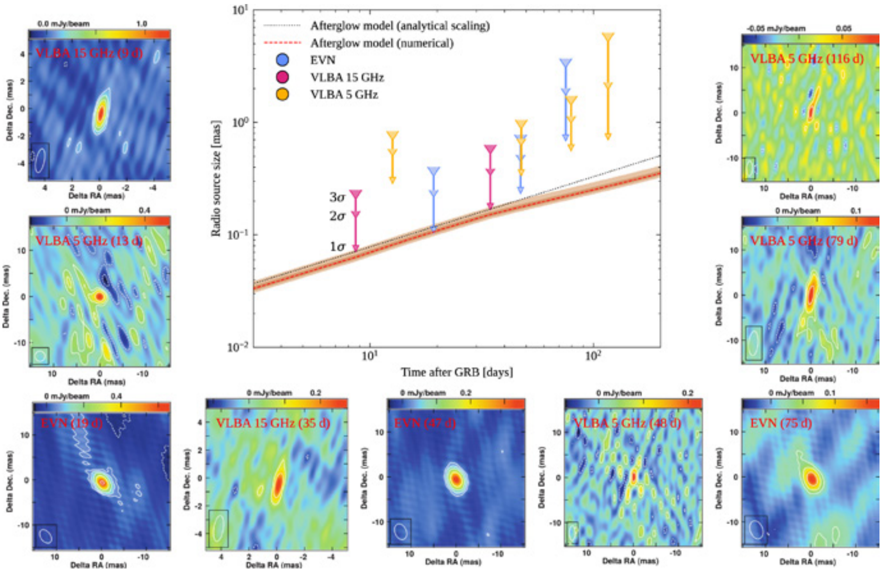

Figure 3.7: Constraints on the projected size of the forward shock from high-resolution EVN and VLBA imaging (from Salafia et al. 2022). The downward arrows in the main panel show the projected size constraints (in milliarcseconds, each relative to the observation time shown on the horizontal axis) obtained from EVN (blue) and VLBA (purple and orange) observations. Each has three arrowheads, corresponding to three levels of confidence that the true size should lie below (1σ, 2σ, 3σ). The dotted and dashed lines represent the size entailed by our best-fitting model, with the band showing the associated uncertainty. The smaller panels show the images of the sources obtained from the data of each observing epoch.

accelerated particles radiate their excess energy by synchrotron and inverse Compton processes. In suitable conditions, the main source of seed photons for the inverse Compton process is the synchrotron radiation from the particles themselves, which leads to 'synchrotron-self-Compton'.

Emission from the forward and reverse shocks is referred to as the gamma-ray burst afterglow. The whole process is rather complicated, but mathematical models exist which can be used to compute the expected behaviour (luminosity, spectrum, evolution) of the radiation as a function of the underlying physical conditions.

The gamma-ray burst GRB190829A represented a fantastic test-bed for this kind of physics. Discovered by the Fermi satellite on 29 August 2019, it was observed by an impressive number of facilities spanning five orders of magnitude in time (from 10^{-3} days to more than 100 days after the initial gamma rays) and 18 orders of magnitude in frequency (from radio to the TeV). The very-high-energy observations, performed by the High Energy Stereoscopic System (HESS), attracted particular attention: only a handful of gamma-ray bursts had been detected at such frequencies before.

High-resolution observations of the source were taken with the EVN and the VLBA and combined with multi-wavelength data in optical, gamma-ray, X-ray and Ultraviolet, Salafia et al. (2022) delved into its analysis and interpretation. The EVN and VLBA data analysis led to meaningful constraints on the size of the forward shock at the time of our observations (see Figure 3.7). It allowed a self-consistent interpretation of all the observations with a model that includes emission from both the forward and reverse shocks, whose synchrotron-self-Compton emission is also in agreement with the HESS observations, and whose forward shock projected size is compatible with the EVN and VLBA constraints (Figure 3.7). The success of the model requires a `special effect': the magnetic field generated by the reverse shock must decay rapidly after the shock crosses the jet, which is reasonable but not entirely settled, and thus sheds light on a poorly understood part of the physics involved.

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

Tracing HI outflows in radio galaxies down to the parsec scales

R. Morganti, R. Schultz et al.

Supermassive black holes (SMBH) are ubiquitous in the centre of massive galaxies and play an important role in the evolution of galaxies. When active, they can release huge amounts of energy which affects the gas around them and, as result, the evolution of the host galaxy. One of the manifestations of this energy release is the presence of fast and massive gas outflows that can be traced also by the cold component of the gas (atomic neutral hydrogen and molecular gas). In fact, these components are found to be the most massive. A growing number of radio galaxies are found to have outflows of atomic hydrogen (HI), detected by observing this gas in absorption. This gives us the unique possibility to explore the properties of the outflows down to the smallest scales thanks to HI observations using VLBI. In this way, the location, extent and physical properties of the outflowing gas can be derived.

Some of the best low-redshift cases of HI outflows in radio galaxies have been studied using broad-band, spectral-line observations with the Global VLBI network. The latest additions are the sources 4C 52.37 and 3C 293 where the distribution of HI on pc scales has been observed with 16 MHz band and 512 channels. The radio galaxy 3C 293 is a well-studied object in VLBI, but never before HI observations were done with such a broad band, tracing the HI outflow. Figure 3.8 shows the results for 4C 52.37. This object, like most sources where HI outflows are observed, is a young radio galaxy. The depth of the VLBI observations shows the entire structure of the radio lobes (Figure 3.8 on the right), only a few hundred pc in size. The position-velocity plots (left in the figure) show that features blueshifted up to 500 $\mathrm{km\,s^{-1}}$ compared the systemic velocity – and therefore tracing the outflowing HI - are observed in a nuclear region just a few tens of pc (in projections) in size. The outflowing HI appears to be distributed in clouds with masses in the range of $10^4 - 10^5 M_{\odot}$. This indicates that the outflow is, at least to some extent, clumpy. This is an important result because numerical simulations predict that the coupling of the radio jet with the surrounding ISM (and therefore its impact) is highly enhanced when the jet enters a clumpy medium.

Combining the results for these two objects with the other sources previously studied as part of this project (Schulz et al. 2018), some general trends could be derived about the properties of the HI outflows for radio galaxies at different stages in the evolution. Thanks to the high spatial resolution and sensitivity, a trend has been found with

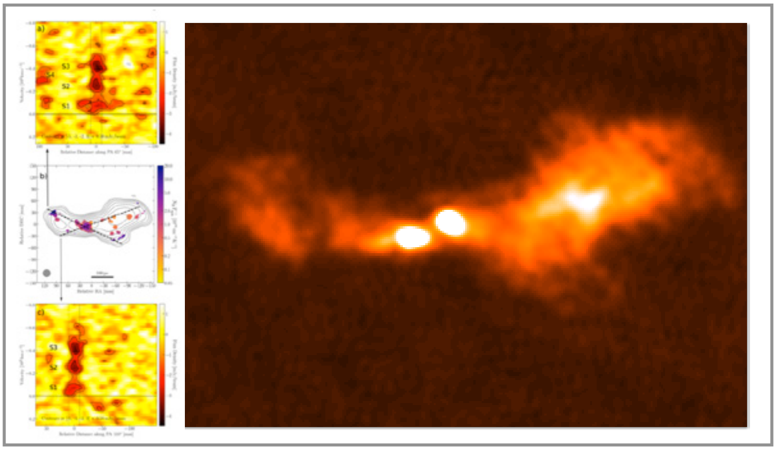

Figure 3.8: Right: high spatial resolution (6 mas) continuum image of 4C52.17. Left - Top panel: position-velocity (PV) diagram of 4C 52.37 along a cut aligned with the largest extent of the central absorption feature. The solid, horizontal line corresponds to the systemic velocity. The dashed, vertical lines mark the size of the synthesized beam. Middle panel: The contour lines show the continuum radio emission at lower resolution (20 mas) the colormap corresponding to column density x spin temperature. The dashed lines represent the cuts for the PV diagram. Bottom panel: same as top panel, but a cut along a different position angle.

the clumpy component of the outflow decreasing as the jet evolves. A diffuse component of the HI outflow becomes more prominent in larger sources (often associated to restarted sources like 3C 236 and 3C 293), i.e. when the jet has interacted for a longer time with the surrounding medium. Also this is consistent with what predicted by numerical simulations (e.g. Mukherjee et al. 2018). More details on the observations and the results are given in Schulz et al., (2021).

Potential magnetic pole inversion in a changing look Active Galactic Nucleus

Sibasish Laha et al.

Recent discoveries of so-called changing-look AGN (CL-AGN), have given us a rare view of extreme changes in the AGN state spanning a few months to years, which may give insight into major open questions about the nature of AGN fueling. CL-AGN are rare, with only a few dozen candidates in the literature. One of the most dramatic cases is 1ES 1927+654, a nearby (74.2 Mpc) and previously well-studied type 2 AGN which was observed to undergo a dramatic optical outburst beginning in December 2017. Laha et al. (2022) report the evolution of the radio, optical, UV and X-rays from the pre-flare state

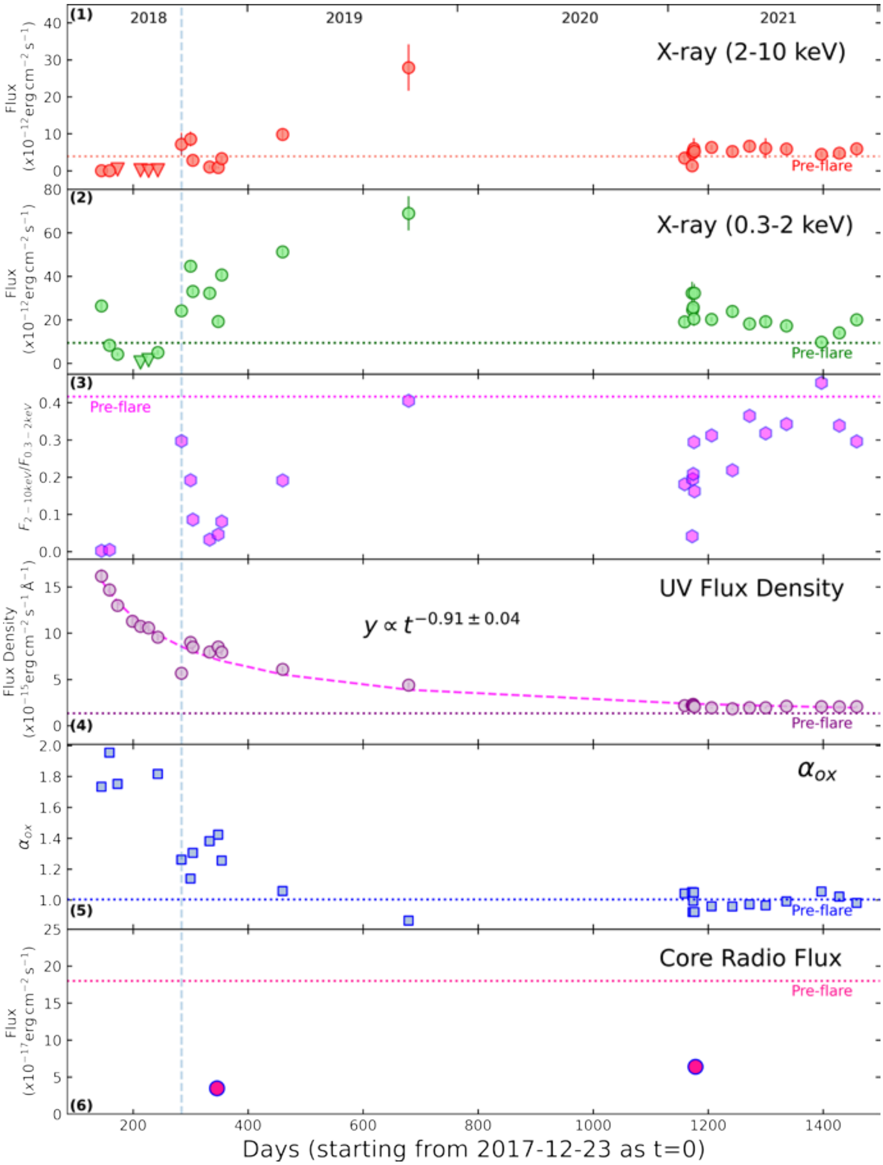

Figure 3.9: The light curves of the X-ray, UV and Radio parameters of the central engine of the AGN 1ES1927+654, as observed by Swift, VLBI and VLBA (see Laha et al. (2022)).

through mid-2021 with a suite of new and archival multiwavelength observations, including archival EVN and new VLBA observations.

During the outburst of 1ES 1927+654 which peaked in March 2018, the optical and UV fluxes increased by four magnitudes, and broad

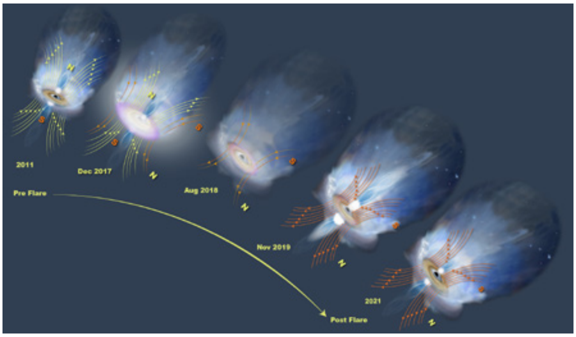

Figure 3.10: Cartoon representing the magnetic flux inversion event. From left to right are the pre-flare to postflare states of the central engine. The initial direction of the magnetic field is depicted by yellow lines, while the reversed polarity is shown by red lines.

emission lines newly appeared for the first time in the optical/UV. By July 2018 the X-ray coronal emission (2 – 10 keV) had completely vanished, only to reappear a few months later in October 2018. Interestingly, the optical and UV emission dropped monotonically after the peak in 2018, following a power-law with $t^{-0.91\pm0.04}$ (see Figure 3.9). After around 1200 days since the start of the flare, the UV and X-rays reached their pre-flare values (as observed in 2011). New and archival VLBI observations spanning this period show that the core radio flux (at ≤ 1 pc scale) was at its minimum at the time when the X-ray emission was also at a minimum.

Although the initial papers reporting this unique event suspected a TDE as the source of the CL event due to the power-law decay signature, multiwavelength observations spanning a period from pre- to post-flare states suggest otherwise. Clearly the event was triggered by a sudden change in the accretion rate. But what made the accretion rate change? Laha et al. (2022) conjecture that it could be a unique case of magnetic polarity inversion in the accretion disk surrounding the SMBH (Scepi et al. 2021). See Figure 3.10. We see a similar phenomenon in the Sun every 11 years.

The uncorrelated evolution of the optical/UV and X-ray suggests that two separate physical parameters are changing during this event. We suggest that the optical/UV are related to a change in the mass accretion rate at some large radii, $\dot{M}(r_{\rm opt})$, and that the X-rays come from very close to the black hole and are related to a change in the magnetic flux onto the black hole, $\Phi_{\rm BH}$.

One of the most crucial observations supporting the conjecture is the dip in the core-radio flux, occurring nearly at the same time as that of the X-ray dip, favouring the flux inversion scenario.

Changes in the radio structure after major γ-ray flares in the blazar S5 1803+784

by R. Nesci, S. Cutini, C. Stanghellini, et al.

S5 1803+784 is a BL Lac object characterised by large variations

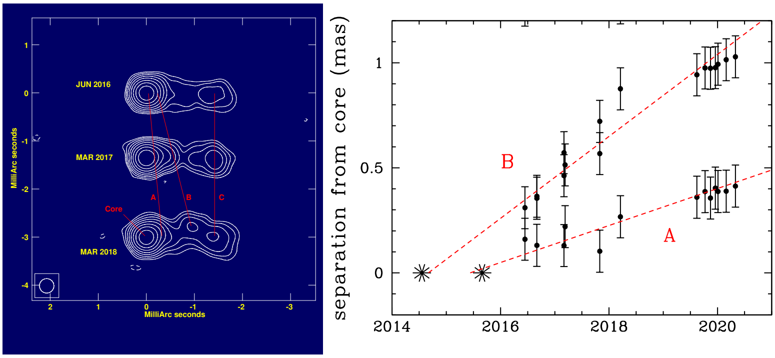

Figure 3.11: Left: EVN images at 22 GHz with components A, B, C as identified by model fit of the visibilities with Gaussian components. Right: evolution of separation from the core with time for components A and B; the epochs of the two large γ-ray flares are marked with asterisks located at the core position. From Nesci et al. (2021).

in the optical range, well detected at γ-ray energies by the Fermi Large Area Telescope (LAT), from the first LAT Catalog of AGN up to the most recent one. The γ-ray light curve shows a flat, oscillating behaviour and several large flares, irregularly spaced, whereas the largest flares are up to 10 times brighter than the quiescent state and range between 20 and 90 days.

The morphological radio structure of S5 1803+784 at milliarcsecond scale can be described as a diffuse emission from an opening jet, directed East-West, with knots and brightness enhancements in several locations along the jet. The interpretation of the radio structure as a helical jet has also been suggested by Britzen et al. (2010) and Kun et al. (2018), following a long-term monitoring at different frequencies.

To further understand if the strong γ-ray flares of the years 2014 and 2015 produced detectable changes in the structure of the inner part of the source, observations of this object have been performed with the EVN at 22 GHz on June 2016, March 2017, and March 2018 (Fig. 3.11, left), and with the VLBA at 15 and 43 GHz on September 2016, March 2017, and November 2017. Fourteen antennas participated to the EVN observations, including the three antennas of the Korean VLBI Network (KVN) which provided the longest baselines. Seven additional epochs (2019/2020) of VLBA data at 15 GHz from the MOJAVE project were added to the analysis.

Fitting discrete Gaussian components to the visibilities the following components have been identified: component A, very close to the dominant core; component B, further away; and component C, at about 1.4 mas West of the core. Despite the difficulty to relate such components at different epochs, with differing (u,v) coverage and different observing frequencies, the overall results show components

A and B with a clear outward motion with respect to the core. This is already seen from the EVN images at 22 GHz (Fig. 3.11, left) and is more clearly noticeable taking into account all the frequencies and epochs (Fig. 3.11, right). As to components C, it is stationary or oscillating around a fixed position, well in agreement with previous studies on this radio source (Roland et al. 2008).

The derived proper motion of component A is (0.088±0.011)mas/yr, corresponding to an apparent velocity of (4.18±0.54)c and an estimated epoch of passage through the core at 2015.44±0.44 (i.e. between January and November 2015), consistent with the epoch of a γ-ray flare seen on August 2015. Component B is moving at (0.195±0.014)mas/yr, corresponding to an apparent velocity of (9.27±0.67)c, and the estimated epoch of passage through the core at 2014.67±0.28 (i.e. between May and December 2014), consistent with a γ-ray flare seen on July 2014.

Therefore, the scenario suggested by the VLBI radio observations covering a span of several years, indicates that the two more recent γ-ray flares have generated radio components moving along the jet at relativistic speed. This strongly supports a causal connection between the mechanisms producing the high-energy and the radio-band radiation in blazars. More details and a general discussion on the light curves at different bands can be found in Nesci et al. (2021).

Radio-loud Quasars above Redshift 4: VLBI Imaging of an Extended Sample

M. Krezinger, K. Perger, K. Gabányi, et al.

Quasars in the early Universe ($z > 4$) provide excellent tools to study the evolution of galaxies and supermassive black holes. These high-redshift sources are tracers of processes from early-time star forming activity to primordial active galactic nuclei (AGN). The latter are powered by accretion onto supermassive black holes (SMBH) with masses of up to 10^{10} $M_{\odot}$ ((Sbarrato, 2021). In recent years, a couple of high-redshift jetted sources were revealed by various radio sky surveys. Because only about 10% of the AGN have jets (radio quasars) and distant quasars tend to be faint, these sources are harder to detect and the high-redshift domain will not be as populated with well-studied objects as the more nearby Universe. To date, we know ∼200 radio quasars at above redshift 4 (Perger et al., 2017). From these sources, only ∼60 were imaged with very long baseline interferometry (VLBI). With VLBI, we can better classify the already known high-redshift radio sources, since the technique can distinguish between a compact core and a more extended radio emission. For blazars, we expect to find compact radio cores with flat spectrum and Doppler-boosted emission. In some cases, high-resolution milliarcsecond (mas) scale observations of blazar candidates – identified via X-ray observations – reveal some

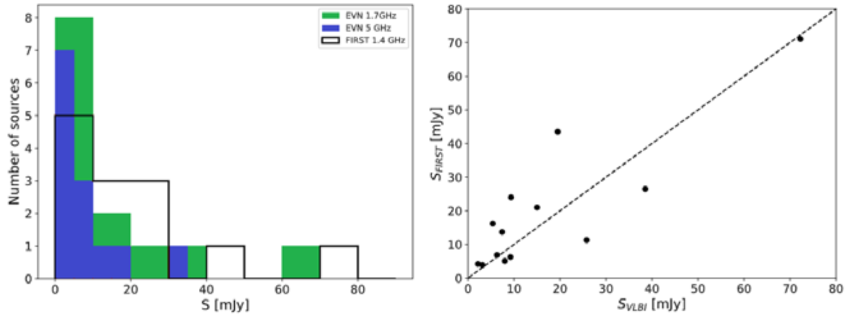

Figure 3.12: Left: Histograms of the flux density distribution of the target sources. Open columns with black outline: FIRST 1.4 GHz flux densities. Green: EVN 1.7 GHz flux densities. Blue: EVN 5 GHz flux densities. Right: FIRST 1.4 GHz flux density vs. VLBI flux density extrapolated to the same frequency from 1.7 GHz. The measurements were non-simultaneous, the sources located below the dashed line are certainly variable because the flux density in their mas-scale structure appears higher than the total value measured in FIRST at another epoch.

extended, or even symmetric radio structures with steep spectra which indicates that there are misaligned sources misclassified as blazars. To observe and classify more and more sources is essential to examine a more complete sample than we have now.

To extend the sample of VLBI imaged high-redshift quasars, we chose 13 radio-loud quasars from the list of Sbarrato et al. (2013) which contains 31 $z > 4$ blazar candidates with radio loudness $R > 100$. This way, the list of the VLBI imaged sources has been increased by 25%. They are all detected in the 1.4 GHz Very Large Array (VLA) Faint Images of the Radio Sky at Twenty-centimeters (FIRST) survey, with flux densities in the range $1 - 100$ mJy (see Figure 3.12). Phase-referenced dual-frequency (1.6 and 5 GHz) observations were carried out with the EVN. EVN provides the best angular resolution and the highest sensitivity needed to image these distant and faint sources. Under the project code EG102, a total of 12 observing sessions were scheduled, started in 2017 December and ended in 2020 November. In addition to the elements of the EVN, antennas of the e-MERLIN were occasionally included in the observing network to trace the possible extended emission of the target sources. Most observing networks included long east–west baselines for the finest resolution.

Krezinger et al. (2022) derived physical properties for the target sources in order to classify the radio quasars in the sample as blazar or non-blazar sources. The radio structure revealed by the EVN images and the fitted brightness distribution model parameters was studied to describe the continuum radio spectra and to find possible flux density variability. Six targets were found to be variable. Additionally, the Gaia

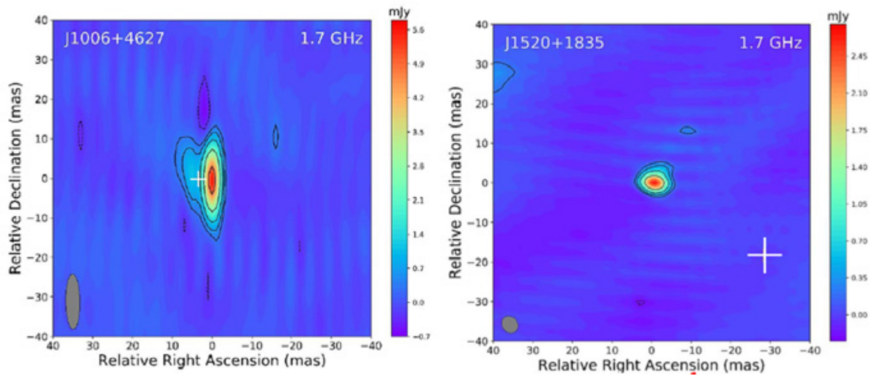

Figure 3.13: Naturally weighted 1.7 GHz EVN clean images of J1006+4627 (left) and J1520+1835 (right). The white cross marks the Gaia position. The length of the cross not represent the uncertainties of the position. From Krezinger et al. (2022)

EDR3 optical coordinates were used to obtain more morphological information. Figure 3.13 shows EVN images of two example sources, one blazar and a compact symmetric object. Krezinger et al. (2022) found that half of the sources are blazar-like objects with compact core–jet structures and flat spectrum, while the rest are unbeamed gigahertz-peaked spectrum sources or CSOs. Conducting further high-resolution VLBI surveys of high-redshift quasars is essential to achieve a more complete sample to study.

Radio properties of the OH megamaser galaxy IIZw 096

Wu Hong, Wu Zhongzu, Sotnikova Yu, et al.

IIZw 096 is classified as a LIRG, and is one of the most luminous known OH-Megamaser (OHM) galaxies. This particular source is the second system to host formal megamasers involving both OH and H_2O species. Optically, IIZw 096 shows complex morphology. It contains four main regions, denoted A, B, C, and D (see Fig. 3.14); sources A and B are possibly two spiral galaxies. Near-IR imaging and spectroscopic observations show that source D is a powerful starburst not associated with the primary nuclei (sources A and B), which could be a starburst in the disturbed disk of source A, or even the nucleus of a third galaxy.

Wu et al. (2022) analysed two-epoch EVN archival data of the OH 1667 MHz line emission of IIZw 096 and confirmed that this source's OH 1667 MHz line emission is mainly from two regions. They found no significant variations of the OH 1667 MHz line emission from the two areas, including the integrated flux densities and peak positions. The OH 1665 MHz line emission is detected at the 6 σ level, with a peak of about 0.42 mJy/beam from the OH1 region. The OH emission regions

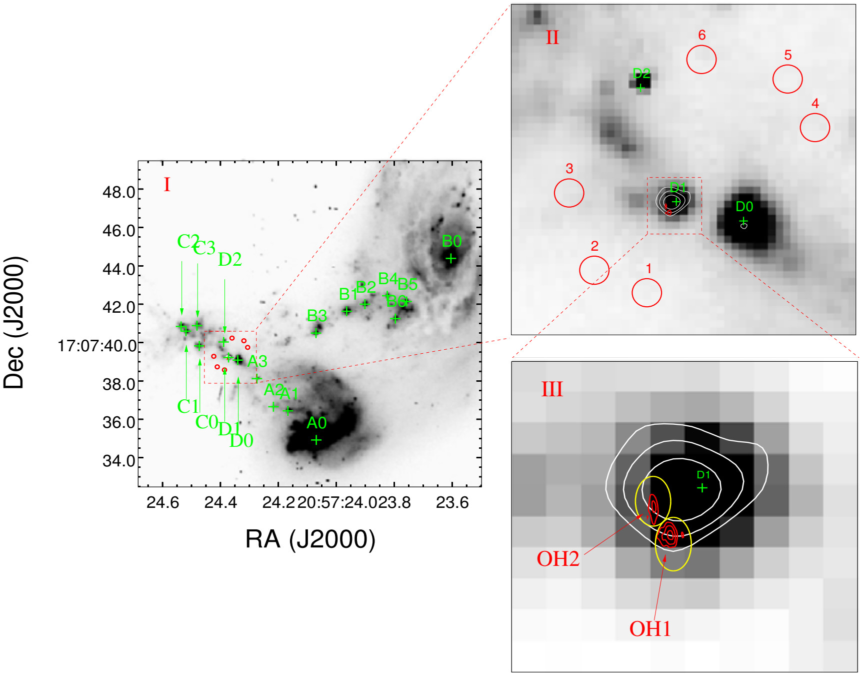

Figure 3.14: Particular spots, regions, and contours superimposed on an HST image of IIZw 096 (Wu et al. 2022)). Panel I: HST-ACS F814W image (grey scale) for IIZw 096. The green crosses indicate the bright spots in this optical image. Panel II: VLA (A configuration) contour map at 33 GHz (white line) overlaid on the HST image; the contour levels are 0.0000441 $\times$ (1, 2, 4, 8) Jy/beam and the Beam FWHM is 82.4 $\times$ 59.5 (mas) at -69.1°. The red circles show the regions around the comp D1, and the radius is about 0.1 arcsec. The red contour stands for the OH megamaser emission (red) from EVN archival data (project ES064B). Panel III: Zoomed map of the D1 region from panel II. The yellow ellipses are the two regions where we extracted the integrated OH emission lines.

reside in comp D1, which shows the brightest CO and HCO+ emission. The molecular mass in the central part (~130 pc) is about 2.5× 10^9 $M_\odot$, which is consistent with the view that there is a high mass concentrated in the central region.

By using archival data from the VLBA, VLA, and ALMA observations, the team investigated the properties of the environment of this component through H I, CO(3-2), and HCO+(4-3) lines and the multi-band radio continuum emission. Component D1 shows the brightest CO, HCO+ line emission, as well as multi-band radio continuum emission. The environment around D1 shows no clear velocity structure associated with circular motions, making it different from most other OHMs in the literature, which might have been caused by an effect during the merger stage. Meanwhile, the CO emission shows three velocity structures around D1, including the central broad full width at half maximum region, the double-peak region where the CO line profile shows two separated peaks, and the region of the high-velocity clouds where the CO line peaks at a high velocity ($\sim 11000\ \mathrm{km\,s^{-1}}$). Similarly, H I observations in absorption also show high-velocity clouds around the D1 region, which might be due to inflows caused by the merging of two or more galaxy components.

Based on the high-resolution K-band VLA and L-band VLBA observations of the radio continuum emission, Wu et al. (2022) constrained the brightness temperature in the range 10^5 to 10^6 K, consistent with other starburst dominant OHM sources in the literature. The multi-band radio continuum emission shows that the radio SED of component A can be well fitted with the power-law equation, while component D might contain contributions from the free-free emission. As a consequence, these results support a starburst origin for the OHMs, without the presence of an active galactic nucleus (AGN).

VLBI observations reveal the nuclear jet properties of Fanaroff-Riley type 0 radio galaxies

Xiaopeng Cheng, Tao An, B. W. Sohn, et al.

Radio galaxies are divided into two groups according to their morphology, namely Fanaroff-Riley type I (FRI) and type II (FRII). FRIIs generally have higher jet power than FRIs. According to evolutionary models of FRII and FRI galaxies, each radio source starts as a compact symmetric object (CSO), grows gradually through a medium-sized symmetric object (MSO) phase, and then a fraction of MSOs successfully evolve into large symmetric objects (LSOs), including FRII and FRI galaxies. The practical radio galaxy evolution of individual FRII or FRI is very complex and depends on several factors such as the initial jet power, the duration of the nuclear activity, the recurrence of the radio activity, and the loss of jet kinetic energy due to the jet-ISM interactions.

A class of radio sources, which have a compact morphology in arcsec-scale resolution images and lack extended jets (larger than 5 kpc), was recently discovered and cannot be directly classified as FRIs or FRIIs, and is therefore treated as a separate class named FR0 radio galaxies (Baldi & Capetti 2009). The number density of FR0s in the local Universe ($z < 0.05$) far exceeds that of FRIs and FRIIs, making this class important for a complete understanding of the radiative properties of radio galaxies and the radio feedback to the host galaxy. In terms of galactic nuclei and host properties, FR0s are not significantly different from FRIs, indicating that both classes have the same type of central engines and that the jet provides the main contribution to the overall radio power. Based on these commonality between FR0s and FRIs, it is thought that FR0s may be early-stage FRIs, but it is still not clear whether FR0s can eventually evolve into FRIs. Although FR0s lack extended jets of tens of kpc, sub-arcsec resolution imaging observations show the presence of kpc-scale jets in at least a fraction of FR0s. In addition, some FR0s (and candidates) have been detected in the gamma-ray band and have been suggested as possible sources of cosmic neutrinos and high-energy cosmic rays, indicating the presence of relativistic jets in FR0s. One of the direct ways to detect the relativistic jet in FR0s and to explore the connection of FR0s with other FR galaxies is to study the pc-scale radio emission with VLBI observations.

Cheng & An (2018) selected 14 FR0s with highest radio flux densities to study their radio properties on pc scales based on VLBA observations. Pc-scale jets were detected in 80% of the sample sources (at higher resolutions, this percentage may reach 100%). The jets show a variety of characteristics: lower bright temperatures than typical radio-loud quasars, slow structure and flux density variations, compact structures with two-sided jets or one-sided jet, steep spectra, and moderate jet velocities, implying that these FR0s may be mixed with CSOs and MSOs. The team continued to observe eight of 14 FR0s using the EVN and VLBA at 5 and 8 GHz (Figure 3.15; Cheng et al. 2021), determining the jet kinematics and radio spectral properties, and found that the jets are mildly relativistic with velocities between -0.08c and 0.51c, and that the jets have low bulk Lorentz factors and large viewing angles. Detection of mildly relativistic jets in FR0s provides important information for discerning the nature of FR0s.

The above VLBI research is focused on brightest FR0s. In a recent work, Baldi, Giovannini & Capetti (2021) selected a sample of 15 FR0s with lower radio luminosities and carried out observations with the EVN and eMERLIN. Parsec-scale jets were detected in 11 sources (73%), suggesting that although FR0s lack extended emission, pc-scale jets are prevalent. The low brightness of the pc-scale FR0 jets requires high-sensitivity VLBI imaging observations.

The jet luminosity detected by VLBI is more representative of the jet power because the pc-scale radio emission region is closer to the jet launching zone. By investigating the correlation between radio jet

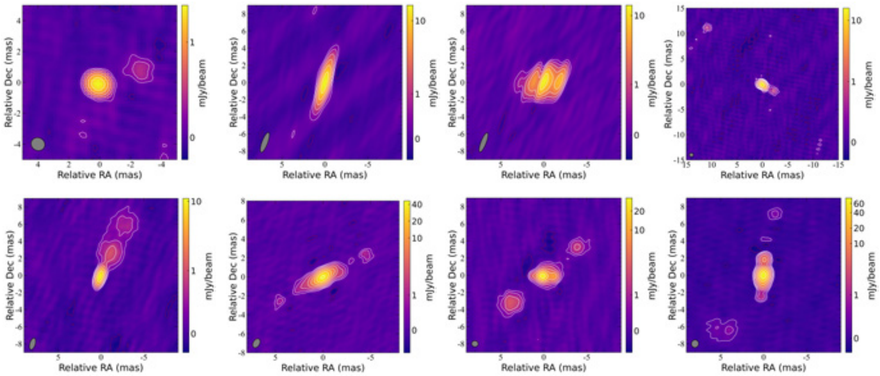

Figure 3.15: 8-GHz EVN images revealing fine structure of the pc-scale jets of eight FR0 galaxies (from Cheng et al. 2021).

power, optical spectroscopic luminosity, and black hole mass, a disc-jet link in FR0s similar to FRIs is explored to establish a homogeneous class with a common accretion-jet coupling mode, revealing a continuous population distribution from the low-luminosity radio-loud AGN to the powerful FRIs.

The similarities and differences between FR0s and FRIs can be explained in the framework of radio galaxy evolution. FR0s reside in moderately host environments, powered by low-spinning BHs and low accretion rates. This scenario predicts that FR0s are characterized by low jet velocities, consistent with the observations. Most FR0s have a jet structure in which the outer mildly relativistic spine is more easily disrupted by the gas in the host galaxies, leading to their inability to develop extended jets like FRIs.

Future high-resolution and high-sensitivity radio facilities, such as the SKA and ngVLA, offer promising opportunities to discover large numbers of FR 0s, and follow-up VLBI observations enable to place tighter constraints on the jet velocities, thus improve the understanding of this rich population of compact radio galaxies.

First RadioAstron view of the quasar 3C 345 in polarisation

F. Pötzl

A fraction of active galactic nuclei (AGN) produce collimated, relativistic outflows, termed jets. They are visible across the electromagnetic spectrum, and their synchrotron emission can most prominently be seen in the radio. In the case of the archetypical quasar 3C 345, the jet has a small viewing angle (∼5 degrees) with the line of sight, leading to significant relativistic boosting of the observed emission.

3C 345 has been observed with the space VLBI mission RadioAstron in March 2016 at a frequency of 1.6 GHz. The observations included

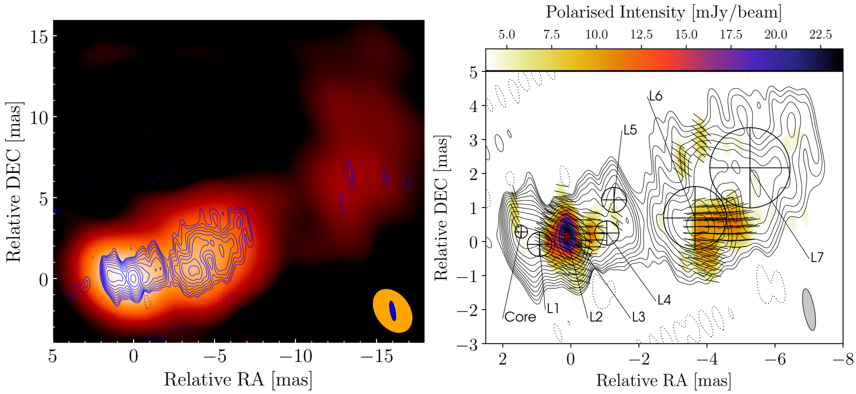

Figure 3.16: Left: total intensity image of 3C 345 at 1.6 GHz with the ground array data (orange colour scale) and all data including the space baselines (blue contours). The different beam sizes are displayed in the bottom right corner. We reach a for this source unprecedented resolution of 1.25×0.32 mas with RadioAstron (3.0×2.1 mas with the ground-array). Right: Total intensity contours as in the left panel, with overlaid linearly polarised intensity in colour-scale. The lines show the EVPAs the length of which is proportional to the polarised intensity. The jet seems to display a predominantly toroidal magnetic field configuration.

the 10 m antenna on board the *Spektr-R* spacecraft together with a ground array comprised of the VLBA as well as several EVN stations. The source was observed in full polarisation, enabling the study of magnetic fields at the smallest possible scales to date in the source at this frequency.

The reconstructed image in total intensity, with a resolution of $\sim$300 microarcseconds along the jet direction, can be seen in the left panel of Fig. 3.16. This marks an improvement of a factor of about 7 compared to the ground-array image, displayed in orange colour scale. The right hand size panel shows the linearly polarised intensity in colours overlaid onto the total intensity in contours, as well as our best Gaussian component representation as crossed circles. The core is identified at the jet base, and appears self-absorbed and largely depolarised, with a polarisation fraction of $\sim$1%. A visibly curved jet then extends further downstream. At $\sim$2 mas from the core, the peak in total and polarised intensity is observed in the jet, reaching $\sim$5% fractional polarisation. The electric vector position angles (EVPAs) seem to largely follow the jet direction, indicating a predominantly toroidal magnetic field in the jet on the scales we observe here. Together with our brightness temperature analysis, which indicates jet regions above the inverse-Compton limit, this suggests a shock travelling down the jet.

A second paper (currently in preparation) will deal with the RadioAstron data in conjunction with a multi-frequency VLBI dataset,

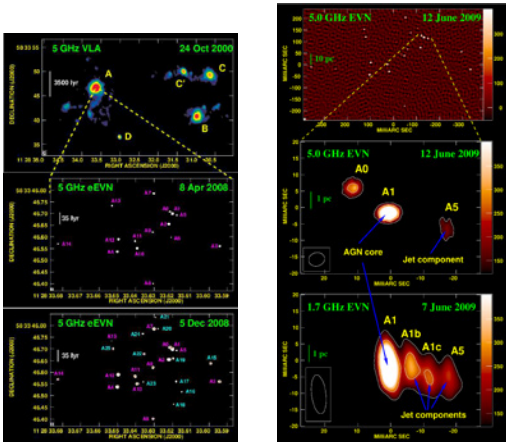

Figure 3.17: Left: 5 GHz VLA archival observations of Arp 299 (top) and 5.0 GHz EVN images of the central 200 pc of Arp 299-A (bottom). Right: EVN image at 5 GHz of the central 200 pc region of Arp 299-A (top), and blow-ups of the inner 8 parsecs as imaged with the EVN at 5.0 GHz (middle) and 1.7 GHz (bottom).

suitable to investigate the spectrum, core shift and rotation measure in the source. This will give further insight into the underlying jet physics in 3C 345.

Star formation and nuclear activity in luminous infrared galaxies: An infrared through radio review

M. Pérez Torres

Nearby galaxies offer unique laboratories allowing multi-wavelength spatially resolved studies of the interstellar medium, star formation and nuclear activity across a broad range of physical conditions. In particular, detailed studies of individual local luminous infrared galaxies (LIRGs) are crucial for gaining a better understanding of these processes and for developing and testing models that are used to explain statistical studies of large populations of such galaxies at high redshift for which it is currently impossible to reach a sufficient physical resolution.

In a recent review, Pérez-Torres et al. (2021) provide an overview of the impact of spatially resolved infrared, sub-millimetre and radio observations in the study of the interstellar medium, star formation and active galactic nuclei as well as their interplay in local LIRGs. They also present an overview of the modelling of the spectral energy distributions using state-of-the-art radiative transfer codes. Those codes are also a powerful 'workhorse' tools for the study of LIRGs (and their more luminous counterparts) at higher redshifts, and whose morphology cannot be spatially resolved. They also show how spatially-resolved

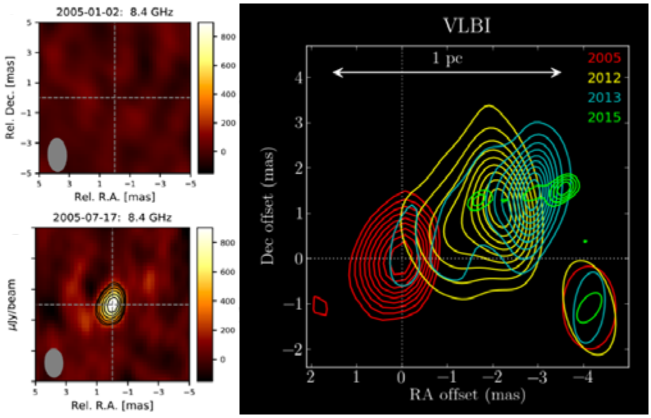

Figure 3.18: unresolved 8.4 GHz radio source in the nuclear region of Arp 299-B (left panels: pre-discovery image (top) and discovery image (bottom), develops into an expanding jet structure as a fraction of the accretion power is channeled into a relativistic outflow (right panel).

time domain observations have recently opened a new window to study the nuclear activity in LIRGs.

Finally, the review describes in detail the observational characteristics of Arp 299, one of the best studied local LIRGs, to exemplify the power of combining high-resolution observations at infrared to radio wavelengths, together with radiative transfer modelling used to explain the spectral energy distributions of its different components.

Radio interferometric observations at the highest angular resolution, i.e., VLBI, play a very relevant role in the review. This role is summarised in Figures 3.17 and 3.18, all of them of the iconic LIRG Arp 299. Figure 3.17 (left panel) shows 5 GHz VLA archival observations of Arp 299 (top), displaying the five brightest knots of Arp 299, while the bottom panels show 5.0 GHz EVN images of the central 200 pc of Arp 299-A on 8 April 2008 and 5 December 2008. The EVN clearly reveals a large population of compact, non-thermal emitting sources (white contours), mostly identified with young radio SNe and SN remnants (Pérez-Torres et al. 2009; Bondi et al. 2012). On the right panel of Figure 3.17, we show an EVN image at 5 GHz of the central 200 pc region of Arp 299-A (top panel), and blow-ups of the inner 8 parsecs, as imaged with the EVN at 5.0 GHz (middle panel) and 1.7 GHz (bottom panel). The morphology, spectral index and luminosity of the A1–A5 region are very suggestive of a core-jet structure. Finally, in Figure 3.18 we show the first observations of a resolved radio jet in a TDE ever, obtained using VLBI observations. The initially compact, unresolved 8.4 GHz radio source in the nuclear region of Arp 299-B (left panels: pre-discovery image (top) and discovery image (bottom), develops into an expanding jet structure as a fraction of the accretion power is channeled into a relativistic outflow (right panel).

The review summarises previous achievements obtained using high-spatial resolution observations and provides an outlook into what is expected to be achieve with future facilities. The authors hope the article is of use to the whole community, but especially for undergraduate and graduate students interested in the diversity of phenonema that take place in LIRGs, and how VLBI can help, sometimes in truly unique ways, to solve puzzling mysteries.

3.3 Galactic science

6.7 GHz CH_3OH masers polarization in massive star-forming regions: the Flux-Limited Sample

Gabriele Surcis

One of the still open questions of modern astrophysics is the formation process of high-mass stars, which have masses greater than 10 solar masses. The observational and theoretical efforts made in the last decades have shown that a common and essential component in the formation of high-mass stars is the presence of molecular outflows during the protostellar phase, similarly to what is observed during the formation of low-mass stars. Theoretically, it has been convincingly demonstrated that the magnetic field plays an important role in launching molecular outflows in massive young stellar objects. Here, for instance, the presence of a magnetic field helps the formation of early outflows that can reduce the radiation pressure through cavities; this partially solves the well-known radiation problem of high-mass star formation allowing the protostar mass to grow further. In addition, the intensity of the magnetic field may influence the collimation of the outflows. Although there is a large consensus on the theoretical importance of magnetic fields in launching the outflows, there are still some open issues from an observational point of view. For instance, the alignment of the magnetic field lines with the outflows. Therefore, providing new measurements of magnetic fields close (10s-100s astronomical units) to massive young stellar objects is of great importance. This can be achieved only by observing the polarized emission of molecular masers by using the VLBI technique. Indeed, dust polarimetric observations towards massive star-forming regions are often limited to low density regions and/or envelopes at scales of several thousands astronomical units making them not suitable for probing the full structure of the magnetic field close to the protostars where the outflows are launched. Among the different maser species, the best probes for this purpose are the methanol masers, and in particular the 6.7 GHz transition.

After the successful pilot observations of the polarised emission of 6.7 GHz methanol maser made with the EVN in 2009 (Surcis et al. 2009), we started a large EVN campaign to measure the magnetic field orientation and strength towards a sample of 30 massive star-forming regions. This is called the "flux-limited sample". The flux-limited sample is composed of massive star-forming regions with declination greater than $-9°$ and with a total methanol single-dish flux density $>$50 Jy, as reported in the catalogue of 6.7 GHz methanol masers compiled by Pestalozzi et al. (2005). The EVN campaign lasted more than ten years and the results have been published in a series of papers. In the last one, Surcis et al. (2022), besides reporting the results of the last five sources, we have presented the statistical analysis of the entire sample.

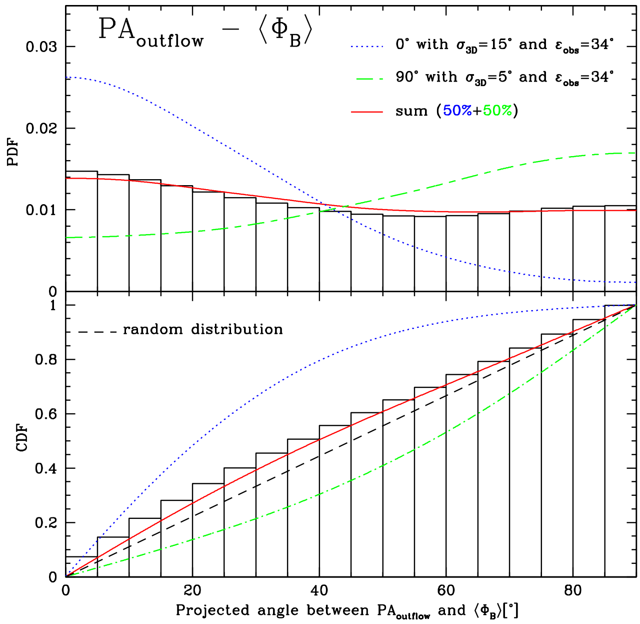

Figure 3.19: Probability distribution function (PDF, top panel) and the cumulative distribution function (CDF, bottom panel) of the projected angle between the magnetic field and the outflow axes ($|PA_{outflow} - \langle \Phi_B \rangle|$). The dotted blue line is the result of a Monte-Carlo simulation of the projection on the plane of the sky of two random 3D parallel vectors with a Gaussian uncertainty of 15° and with a projected Gaussian error of 34°. The dot-dashed green line is the result of a Monte-Carlo simulation of the projection on the plane of the sky of two random 3D perpendicular vectors with a Gaussian uncertainty of 5° and with a projected error of 34°. The red line is the best combination of the previous two Monte Carlo simulations to fit the observed data, each contributing for the 50%. The black dashed line is the CDF for completely random orientation of outflows and magnetic fields, i.e., all angular differences are equally likely.

We were able to measure the magnetic field orientation in all sources but one. This allowed us to compare the orientation of the magnetic field ($\langle \Phi_B \rangle$) with the orientation of the outflows ($PA_{outflow}$) on the plane of the sky. The probability distribution of the angles $|PA_{outflow} - \langle \Phi_B \rangle|$ is shown in Fig.3.19. To investigate the distribution of these angles in the 3D space we have performed two Monte Carlo simulation runs, one considering the outflow and the magnetic field parallel in the 3D space and then projected on the plane of the sky (dot-dashed green line in Fig. 3.19) and the other when they are perpendicular in the 3D space and then projected on the plane of the sky (dotted blue line in Fig. 3.19). We found that only a combination of the two distributions (50%-50%, red line in Fig. 3.19) represents what we observe. Therefore, we see a perfect bimodal distribution in the difference between the 3D magnetic field direction and the outflow axis. A slightly similar distribution was observed by Zhang et al. (2014) on scales greater than 1000 AU obtained by observing dust polarized emissions, although due to their small sample size they concluded that the data were consistent more with a random distribution.

Furthermore, because we measured in total linear polarisation fraction (P_l) and circular polarisation fraction (P_V) for 233 and 33 6.7 GHz methanol maser features towards the sources of the flux-limited sample, we were also able to determine for this maser transition the typical values of P_l, P_V, and of the Zeeman-splitting (ΔV_Z). These are $P_l = 1.0 - 2.5\%$, $P_V = 0.5 - 0.75\%$, and $\Delta V_Z = 0.5 - 2.0\ \mathrm{m\,s^{-1}}$ (see Fig.2) that would correspond to 9 mG $< |B_{||}| <$ 40 mG if $F = 3 \rightarrow 4$ is the hyperfine transition that contributes most to the 6.7 GHz methanol maser emission.

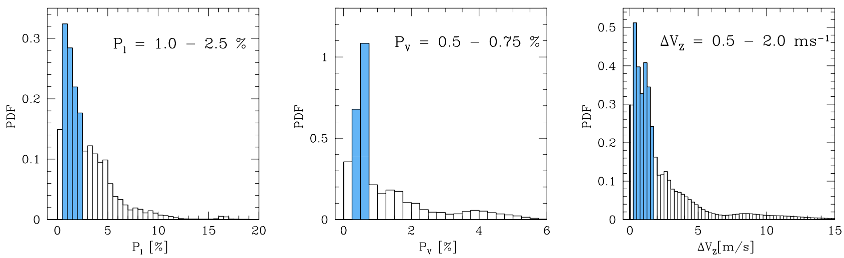

Figure 3.20: Probability distribution function (PDF) of the linear polarisation fraction (P_l, *top panel*), of the circular polarisation fraction (P_V, *middle panel*), and of the Zeeman-splitting (ΔV_Z, *bottom panel*) of the 6.7 GHz CH_3OH maser emission. The interval width of the histograms is 0.5%, 0.25% and 0.25 $\mathrm{m\,s^{-1}}$ for the P_l, the P_V, and the ΔV_Z plots, respectively. Typical values of P_l, P_V, and ΔV_Z for the 6.7 GHz CH_3OH maser emission is highlighted in blue.

Snapshot of a magnetohydrodynamic disk wind traced by water maser observations

L. Moscadelli

The formation of astrophysical objects of different nature and size, from black holes to gaseous giant planets, involves a disk-jet system, where the disk drives the mass accretion onto a central compact object and the jet is a fast collimated ejection along the disk rotation axis. Magnetohydrodynamic (MHD) disk winds (DW) have been proposed to account for the link between mass accretion and ejection, which is essential to ensure that the excess angular momentum is removed

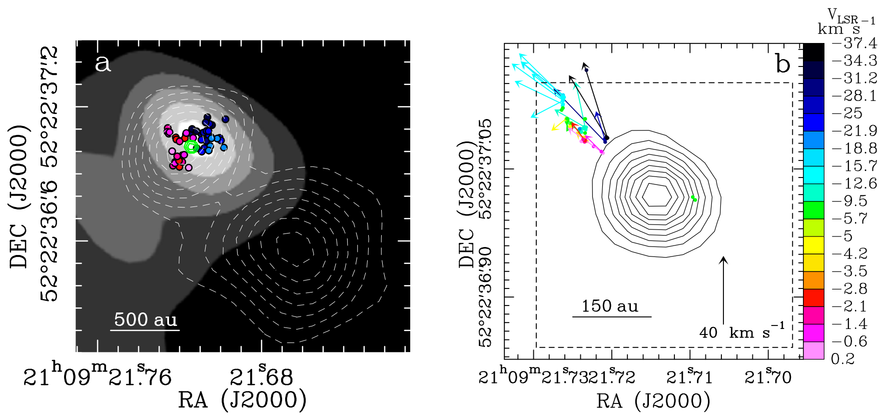

Figure 3.21: The disk-jet system in IRAS 21078+5211 from previous NOEMA, JVLA and VLBA observations. (a) The core: NOEMA 1.37 mm continuum emission (grey-scale); the disk: channel emission peaks of the CH_3CN and HC_3N lines (colored dots, with colors denoting blue- and red-shifted LSR velocities); the jet: JVLA A-Array continuum at 5 cm (white contours) and 1.3 cm (green contours). (b) The jet root: absolute positions (colored dots) and proper motions (arrows) of the 22 GHz water masers determined with multi-epoch (2010-2011) VLBA observations, and the JVLA A-Array continuum at 1.3 cm (black contours). The dashed rectangle delimits the field of view plotted in Fig. 3.22-a.

from the system and accretion onto the central object can proceed. So far, the best observational evidence for a MHD DW towards several low- and few high-mass young stellar objects (YSO) has been the finding, through high-angular resolution ALMA observations, of line of sight velocity gradients transversal to the YSO's jet axis, which are interpreted in terms of jet rotation and the imprint of the magneto-centrifugal acceleration. However, that is an indirect evidence and the derivation of key parameters, as the launch radius and the magnetic lever arm, can be seriously affected by systematic biases (Tabone et al., 2020).

Recently, sensitive global VLBI observations of the 22 GHz water masers toward the intermediate luminosity, 5×10^3 $L_\odot$, and mass, 5.6 ± 2 $M_\odot$, YSO IRAS 21078+5211 (see Fig. 3.21) have resolved, for the first time, the kinematics of a MHD DW on length scales of 1–100 au (Moscadelli et al. 2022). On scales of a few 100 au, by employing the NOrthern Extended Millimeter Array (NOEMA), a rotating disk is observed in high-density molecular tracers (CH_3CN and HC_3N, see Fig. 3.21-a). Interferometric observations at radio wavelengths (5 cm) using the VLA have revealed a jet directed NE-SW (PA≈44°) emerging from the YSO, whose position at the center of the disk is pinpointed by compact thermal emission observed with the VLA at 1.3 cm. During 2010–2011 we have performed multi-epoch VLBA observations of the water maser emission at 22 GHz. These observations have discovered

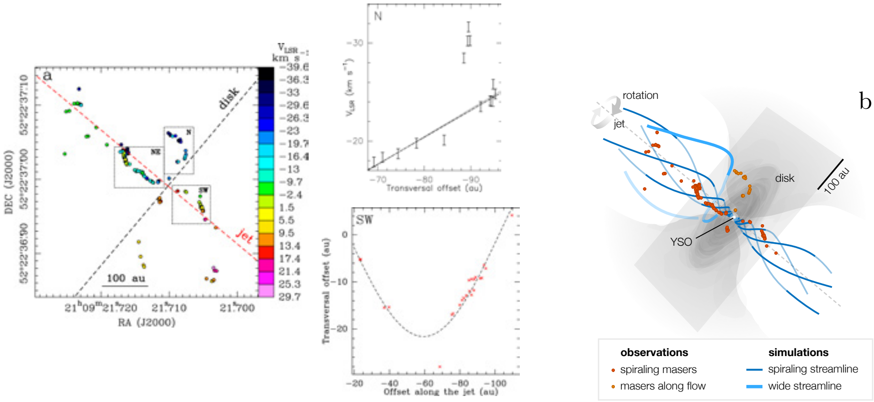

Figure 3.22: Global VLBI observations of the 22 GHz water masers and 3D view of the proposed kinematical interpretation (Moscadelli et al. 2022). (a) Absolute positions (coloured dots) of the 22 GHz water masers. The black dotted rectangles encompass the three regions, to the N, NE and SW, where maser emission concentrate. The red and black dashed lines mark the sky-projected jet and disk axis, respectively. (SW) Sinusoidal fit of the transversal versus longitudinal (parallel to the jet) offsets for the masers in the SW region. (N) Plot of LSR velocities versus transversal offsets for the masers in the N region. (b) Observed maser positions (red and orange dots) overlaid on top of streamlines (blue lines) computed from resistive-radiative-gravito-MHD simulations of a jet around a forming massive star.

a cluster of masers placed ≈100 au NE from the YSO, whose proper motions are collimated NE-SW (PA = 49°) and trace the base of the jet from the YSO (see Fig. 3.21-b). The analysis of the three-dimensional (3D) maser motions, specifically the local standard of rest (LSR) velocity gradient transversal to the jet axis and the constant ratio between the toroidal and poloidal velocities, suggested that the jet could be launched from a MHD disk wind.

Fig. 3.22-a shows the water maser distribution from the novel (October 2020), sensitive global VLBI observations of the 22 GHz water masers toward IRAS 21078+5211. The water masers are mainly found within 100 au from the YSO and trace magnetized streams of gas emerging from the YSO's disk (see Fig. 3.21-b). Specifically, close to the disk rotation axis, in the SW and NE regions, the masers trace sinusoidal patterns in the plane of the sky (see Fig. 3.21-SW), which are univocal signatures of a spiraling motion along the jet axis. At larger separation from the rotation axis, in the N region, the maser LSR velocity changes linearly with the radial distance (till reaching the Alfvén point, see Fig. 3.21-N), which indicates that the maser stream co-rotates with its launch point from the disk as predicted by magneto-centrifugal acceleration. This interpretation is supported by (resistive-radiative-

gravito-) MHD simulations of the formation of a star starting from the gravitational collapse of a rotating cloud core threaded by a magnetic field. In these simulations, a magneto-centrifugally launched jet (see Fig. 3.21-b) develops around the forming star which has properties matching many features of the maser and thermal (continuum and line) observations of IRAS 21078+5211.

Discovery of recurrent methanol maser emission flares in Cepheus A HW2 at 6.7 GHz

M. Durjasz, M. Szymczak, M. Olech & A. Bartkiewicz

6.7 GHz methanol maser emission is one of the most significant markers of high-mass star formation. It originates relatively close to the protostar and is sensitive to the variations of its environment's physical conditions - these properties make it a decent marker of protostellar activity.

Extensive methanol maser monitoring provided a handful of discoveries, like the periodic variability or accretion bursts. Since current maser monitoring projects have lasted for over a decade, new long-period activity is likely to be detected – like the discovery of the recurrent flares in Cep A HW2.

Cep A is a high-mass star-forming region located 700 pc away that hosts a cluster of YSOs, with the HW2 being the brightest continuum source in the cluster. HW2 is an HMYSO with a mass of approximately ten solar masses and bolometric luminosity of $2 \times 10^4 L_\odot$.

Durjasz et al. (2022) carried out an extensive maser monitoring which revealed the appearance of the low-amplitude red-shifted (compared to the 6.7 GHz maser centroid velocity) flares in 2010, 2015 and 2020, implying 5-year variability. The flare profile is not well conserved from cycle to cycle, and only its general shape (sharp rise and more gradual decay) is maintained between the periods of activity. EVN observations of the 6.7 GHz masers in June and October 2020 revealed that the flaring emission originates from the edge of a dust disc. The team tested many periodic-variability scenarios to determine the causes of the observed variability, but none worked flawlessly. The authors also noted the quasi-periodic activity of the most blue-shifted spectral (–4.7 km/s) feature of the 6.7 GHz spectrum anti-correlated with the brightest 6.7 GHz feature at –2.6 km/s with a delay of 6 to 8 days.

The EVN observations and inclination angle of the system constrained the distance between the cloudlets that host –2.6 and –4.7 km/s emission to about 800 AU - this is well within an order of magnitude with the light-crossing time between the cloudlets, what suggests that the radiative connection scenario, proposed by Cesaroni (1990) remains the valid explanation of this phenomenon.

3.4 Gravitational lensing

SMILE: Searching for MIlli-LEnses

by C. Casadio

One of the most compelling mysteries in both cosmology and particle physics is the nature of Dark Matter (DM). Its elusive detection coupled with unsolved discrepancies between some standard cosmological (Lambda-CDM) model predictions and observations have paved the way to alternative DM models. A critical prediction of the CDM paradigm is the number of DM halos at sub-galactic scales ($\lesssim 10^{11} M_{\odot}$). Constraining this number would help discarding many currently viable DM models. This problem can be investigated using strong gravitational lensing of active galaxies on the key but poorly-explored milli-arcsecond scales, i.e. milli-lenses. Gravitational lensed images with angular separation on milliarcsecond scales probe gravitational lens systems where the lens is a compact object with mass in the range $10^6 - 10^9 M_{\odot}$. Compact objects in this mass range could be i) sub-galactic DM halos (in the surroundings of galactic DM halos or in the field), ii) primordial black holes, also considered an alternative candidate to DM particles, (iii) supermassive BHs hosted by galaxies.

The most direct way to explore these small angular scales is through the high-resolution of radio VLBI. We performed a pilot search for milli-lenses with angular separation < 150 mas, using the publicly available multi-frequency VLBI data in the Astrogeo VLBI FITS image database, containing data of 13828 sources. For our search, we visually inspected all images creating a web page based on the idea of citizen-science projects. 5 PhD scientists and 9 undergraduate Physics students from the University of Crete were involved in the search and asked to mark as *Lens* sources showing multiple compact components in at least one of the available observing bands, and as *No Lens* the rest of the sources. Each source in the database was inspected by one user and the corresponding choice was recorded. After many visual selection steps, we finally use the surface brightness preservation criterion to obtain the list of 40 best milli-lens candidates. Since gravitational lensing preserves the surface brightness of the background source, we expect the lensed images to have all the same intrinsic brightness.

The 40 best milli-lens candidates, presented in Casadio et al. (2021), have been followed up with EVN observations at 5 and 22 GHz (Project ID: EC071; PI: C. Casadio). New EVN images of two (J1143+1834, and J0616-1957) of the best milli-lens candidates are shown in Figure 3.23. The two sources confirm their double structure, but while the two components in J1143+1834 are slightly resolved, in J0616-1957 we clearly distinguish two jet-like features that may indicate a different nature for this object. Further analysis will allow us to reject or confirm the milli-lens candidates. Any source rejected as milli-lens candidate

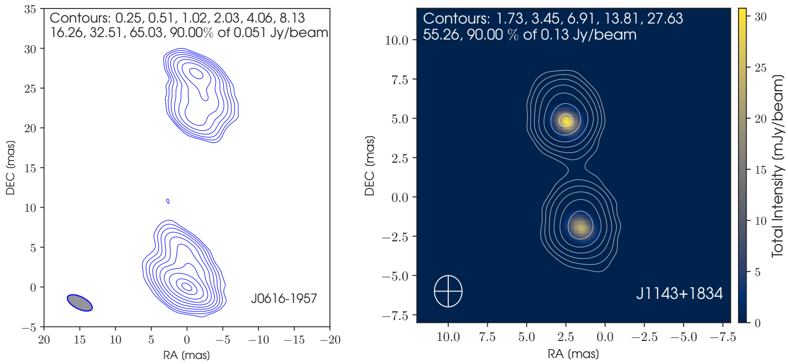

Figure 3.23: New 5 GHz (contours) and 22 GHz (colours in J1143+1834) EVN images of two milli-lens candidates (Casadio et al. 2021).

can still be investigated as either a supermassive black hole or a compact symmetric object candidate.

Secondarily lensed Einstein arc by the companion galaxy discovered in a galaxy lens

by Ming Zhang et al.

A team from the Galaxy & Cosmology Research Group at Xinjiang Astronomical Observatory, Chinese Academy of Sciences, detected and verified the existence of a secondarily-lensed Einstein arc caused by its companion galaxy in the CLASS lens B1152+199, by analysing the Hubble Space Telescope (HST) optical-to-near-infrared tricolour images and the 8.4 GHz global VLBI data. The results were published in Zhang et al. (2022).

In the previous HST image analysis, the looming diffuse emission close to the companion galaxy was speculated to be part of the galaxy's spiral arms, so its role in the lensing macromodel was not emphasised. In this study, researchers analysed the tri-band images from optical to near-infrared captured by the wide-field planetary camera (WFPC2) and near-infrared camera (NICMOS) carried by the HST, and found that after subtracting the light model of the foreground galaxy and background quasars, in the residual image, the Einstein light arc is consistently visible, and its convergence centre is just at the position of the companion galaxy.

At the same time, researchers used the latest 8.4GHz global VLBI observations to successfully resolve the corresponding jet components in the secondary image. Together with the jet components in the primary image, those components constitute a dual-image-three-component constraint on the lens system, which gives the strongest point source location and flux constraints for this lens system.

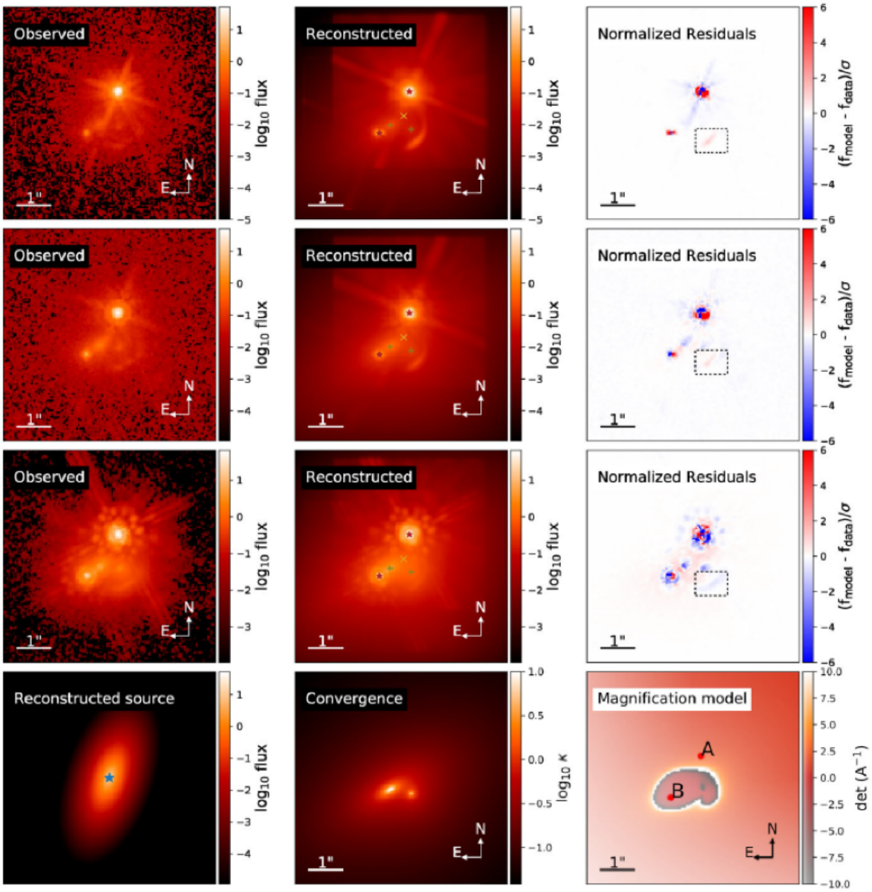

Figure 3.24: HST tri-band images and model reconstructions, HST tri-band images and model reconstructions, from Zhang et al. (2022).

The researchers applied the optimized macromodel constrained by the VLBI point source to the HST tricolor images, further optimized the photometric model of the foreground lens galaxy and the background quasar, and obtained the consistent optimization of the lens model for both optical and radio observations (Fig. 3.24). The model can perfectly produce the Einstein arc, which indicates it is from the extended structure of the background quasar host galaxy. It also shows that the power-law slope of the lens host galaxy is steeper than that of the isothermal ellipsoid model, and the weak curvature of the jet in the secondary image is also within the tolerance of the model.

A lensed radio jet at milli-arcsecond resolution: Bayesian comparison of parametric lens models

D. M. Powell, S. Vegetti, J. P. McKean, C. Spingola, et al.

Strong gravitational lensing by galaxies is a powerful astronomical tool, as the lensing effect is sensitive to the total surface mass density in the lens galaxy. This provides an observational window, independent from and complementary to light-based modelling, into the complex physical processes that shape the distribution of mass in galaxies. For instance, gravitational lensing observables are sensitive to different baryonic processes, such as adiabatic contraction or AGN feedback, that can cause galaxies to become more or less concentrated. Gravitational lensing can also reveal the presence of low-mass dark matter haloes in several lens systems, which are detectable only through their gravitational effect. Measurements of the Hubble constant are possible using time-delays between multiple images of a lensed quasar.

The success of such aforementioned studies depends on the level of detail that can be detected in the mass distribution of a gravitational lens galaxy, which in turn is strongly dependent on the angular resolution of the observation. So far, most existing gravitational lens systems have been observed with Hubble Space Telescope ($\sim$ 120 mas resolution), with some followed up using the W.M. Keck adaptive optics system ($\sim$ 70 mas), and still fewer with ALMA ($\sim$ 25 mas). These observations are sufficient to constrain the slope of an elliptical power-law mass model, or to detect dark subhaloes as small as 10^8 solar masses. Pushing the field of gravitational lens modelling into the milli-arcsecond (mas) regime drastically increases the amount of astrophysical information we can extract from gravitational lens observations; at present, global very long baseline interferometry is the only observational tool which can provide such high angular resolution.

Powell et al. (2021) present the first analysis of a gravitational lens system observed at $<$ 5 mas resolution using global VLBI, in which both a detailed model for the mass of the lens galaxy and a pixellated source surface brightness map are jointly inferred. The analysis was done using the Bayesian visibility-space lens modelling technique. This observation of the lensed radio jet MG J0751+2716 exhibits extremely long, thin lensed arcs covering a wide range of angular and radial positions around the lens galaxy, which are perfect for revealing the underlying gravitational landscape. In Figure 3.25, one can clearly see the jet morphology of the reconstructed source, with bright knots of radio continuum emission stretching several hundred parsecs (in projection) from the host galaxy (shown in white contours modelled from Keck AO data).

The authors found during the modelling process that significant lens model complexity is needed to recover such a clearly reconstructed source. In addition to a basic elliptical power-law mass distribution,

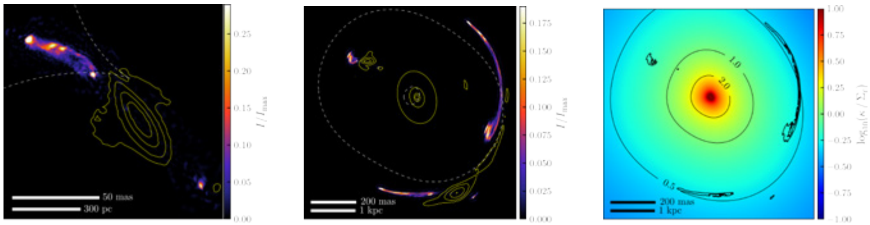

Figure 3.25: Best-fit source (left) and lens-plane (centre) surface brightness reconstructions, as well as the surface mass density (right) for the smooth lens model of MG J0751+2716 from Powell et al. [0]. Caustics and critical curves are plotted as dashed white lines. The colour maps, which are normalised to the peak surface brightness, show the continuum radio emission, while the overlaid yellow contours show the source and sky emission reconstructed from a 2.12 μm Keck AO observation. The convergence map is in units of critical density Σ_C. The middle panel illustrates the long, thin gravitational arcs resolved with VLBI which are highly sensitive to detailed features in the gravitational potential.

extra angular structure in the form of multipole perturbations was added, as well as higher-order terms in the potential corresponding to gradients in the external convergence and shear. It is important to include sufficient complexity in smooth gravitational lens models: Searches for dark substructures and line-of-sight halos around the main lens can be biased by inaccurate knowledge of the large-scale mass distribution; this is also a concern for flux-ratio analyses and time-delay cosmography. VLBI observations can therefore play a key role in informing several types of gravitational lens analyses, by revealing structure in the gravitational potential that is otherwise inaccessible with current optical telescopes.

3.5 Development of new techniques and software

Corona radio-sounding observations of Martian spacecraft using very long baseline interferometry radio telescopes

Maoli Ma, et al.

Almost every planetary probe is used to study the solar corona. Usually, a single radio telescope is enough to characterise the electron density variation of solar wind in the corona radio-sounding observation. Ma et al. (2021, 2022) make strong cases for using multiple VLBI radio telescopes to study the solar wind. They detected the oscillation and propagation of the solar wind within 10 solar radii (Rs) by observation of ESA's Mars Express (MEX) and China's Tianwen with VLBI radio telescopes. The study confirms that the ground station-pairs are able to form particular spatial projection baselines with high resolution and sensitivity to study the detailed propagation of the nascent dynamic solar wind structure.

Corona radio-sounding observations

The observations were carried out in 2017 and 2021. The projective positions of Mars, participating stations and observation targets are listed in Table 3.1. In 2017, five VLBI radio telescopes observed Mars Express (MEX) when the heliocentric distance were 4.9 and 9.9 Rs on 29 July and 3 August 2017, and the projected Mars position in heliographic latitude were 70° and 40°, respectively. In 2021, Tianwen (TIW) and MEX were observed in the same beam by the EVN telescopes with the heliocentric distance of 2.6 Rs and heliographic latitude of 51°. The observation of TIW continued from 06:50 to 13:00, and MEX ended earlier at 08:30. The observation in 2021 covered the eruption passage typical of one coronal mass ejection (CME).

Time	d_h [R_s]	l_h [°]	Stations	Targets
2017 Jul 29 06:00-13:10	4.9	70	Ht,Ys,Nt,Ur,T6	MEX
2017 Aug 2 06:00-13:00	9.9	40	Hh,Ys,Nt,Ur,T6	MEX
2021 Oct 9 06:50-13:00	2.6	51	Hh,Zc,Bd,Mc,Ys	TIW
2021 Oct 9 06:50-08:30	2.6	51	Hh,Zc,Bd,Mc,Ys,Yg	MEX

Table 3.1: Specifications of the observations in 2017 and 2021: UTC time, the projected Mars heliocentric distance d_h and heliographic latitude l_h, stations and targets.

Detecting the propagation of the nascent dynamic solar wind structure

We obtained the frequency fluctuations (FFs) of the spacecraft from VLBI radio telescopes. In 2021, the effects of the density inhomogeneities caused by CME on the signals could be confirmed from both Tianwen and MEX. With the arrival of the CME front, the most

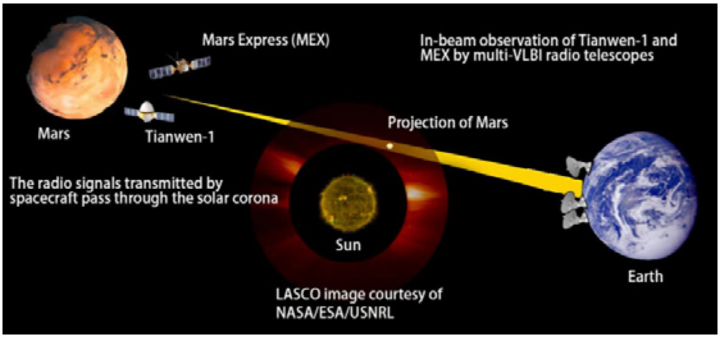

Figure 3.26: Same beam observation of Tianwen and MEX by VLBI radio telescopes when the heliocentric distance was 2.6 Rs in 2021.

intense FFs was up to -30∼30 Hz and the carrier-to-noise ratio decreasing about 5∼8 dBHz. We called the stronger FF as 'spikes', which were distinguished because of the density contrast between the transient inhomogeneities and the ambient flow. By inspection of the spikes at different stations, we found there were time delays between the occurrence times of the spikes with similar structures (Fig. 3.27). It gave us a straightforward understanding about the propagation of the solar wind density structures, and provided the visual evidence for the hypothesis of frozen-in plasma turbulence. By cross-correlation analysis

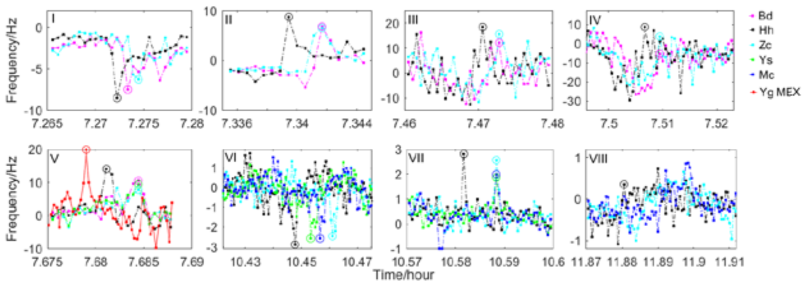

Figure 3.27: The spikes in frequency fluctuations at different moments from individual telescopes. I,II,III,IV. Spikes among Hh, Bd and Zc from TIW. V. Spikes among Yg from MEX, Hh, Bd, Zc from TIW. VI,VII. Spikes among Hh, Zc, Ys and Mc from TIW. VIII. Spikes from Hh, Zc and Mc from TIW.

on the time series of the FFs from different telescopes, we obtained the radial solar wind velocity v_{rad} in both 2017 and 2021. Fast solar wind with v_{rad} larger than 750 km s^{-1} was found in 2017. The CME happened in 2021 brought in more interesting phenomenons (Fig. 3.28). The v_{rad} reflected the variation of the solar wind velocity during the CME passage. We also detected the oscillation of tangential velocity v_{tan} which confirmed the detection of streamer wave. The streamer wave was usually found in bright streamer belts. The high density sensitivity and spatial resolution of our method enabled to find the streamer waves near the north pole of the Sun; a much dimmer area. At the tail end of the CME, we detected the field-aligned fast flow possibly relating to the Alfvén waves. The corona radio-sounding observations by

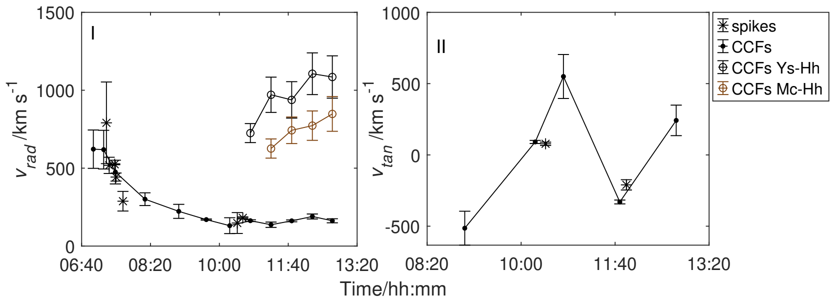

Figure 3.28: The velocity obtained from the visual spikes and the cross-correlation. I. Radial velocity. II. Tangential velocity.

VLBI telescopes provide a unique source to characterise the nascent dynamic solar wind structure. A reasonable distribution of at least 4 telescopes can provide the required spatial resolution along radial and tangential directions. Besides the TIW and MEX, some other deep space spacecraft, e.g., the BepiColombo, the Mars Reconnaissance Orbiter, has a high quality beacon as well. We hope to further connect the radio telescopes and spacecraft to study the challenging inner solar wind in the future.

SagittariusA* revealed

Ilse M. van Bemmel & Huib Jan van Langevelde

Introduction

The Event Horizon Telescope Collaboration (EHTC) made global front page news with the first images of the M87 supermassive black hole in 2019. To image our Galactic black hole, Sagittarius A* (SgrA*), turned out to be a much bigger challenge. At last, on Thursday 12 May 2022 the EHTC presented the first image of SgrA* to peers and the public. This happened at different venues around the globe, with ESO headquarters in Garching, Germany, covering the news for Europe

The data for this image were obtained in the same observing run in 2017, but included a set of new and unique challenges to overcome. The much smaller intrinsic size of SgrA* causes it to vary on much shorter times than the typical length of a VLBI observing track. It was compared to taking a picture of a dog chasing its tail in a dark room. Consequently, it took several years for the EHTC to develop robust techniques for imaging and image validation. Eventually, an entire family of images was produced which is compatible with the data, and 97% of these images are consistent with a ring-like structure with a diameter of 51 micro-arcseconds. The image shown to the press and public is a weighted average across this family (see Figure 3.29).

Although the SgrA* image is second to the M87*, imaging our Galaxy's black hole probably represents a more fundamental result, because mass and distance are so much more accurately determined as stars in orbit around it have been measured with great accuracy.

Vetting and validating: the papers

A scientific result of this calibre requires extensive analysis of all the aspects at hand. From the calibration and imaging of the observations, to extensive GRMHD simulations, to alternative models of gravity, every aspect is presented in detail in six "collaboration" papers by the EHTC. Four additional studies that were not directly connected to the image resulted in "official" papers. These ten papers were made public at the time of the press release. These papers are highly synergetic, by design, together they tell a complete story. Simulations generated to study the physics of accretion flows are essential to test imaging and analysis methods. At the same time, the observations from EHT and other instruments are extremely constraining and set hard limits on the GRMHD simulations.

Paper I describes all the high-level results from the six collaboration papers and the main result: the SgrA* observations are consistent with a ring as expected from lensing magnetised plasma. The diameter of 51 micro-arcseconds matches well with the known size and distance of the Galactic black hole. But the devil is in the details. An essential and unique part of the SgrA* work are the multi-wavelength observations. The complexity of requesting, planning, and processing data from several additional instruments is not apparent from the papers. However, the constraints derived from these observations are crucial in setting constraints on the physical parameters for GRMHD models (Paper II, Paper V).

Imaging was a big challenge. The entire Galaxy blocks our view of SgrA*, causing significant interstellar scattering. In addition, due to its smaller size SgrA* varies both in intensity (amplitude) and in structure (phase) on timescales of minutes to hours. It therefore violates the assumption of aperture synthesis that a source does not change during the observation. To obtain a robust image, the different imaging teams first ran their pipelines on a large library of artificial data, based on seven distinct source models and GRMHD simulations that would fit the visibility data. The parameter combinations that provided the best results were then used to image the actual data. This resulted in many images from each pipeline, with the large majority consistent with a ring-like structure. The diameter of the ring is very stable, but the

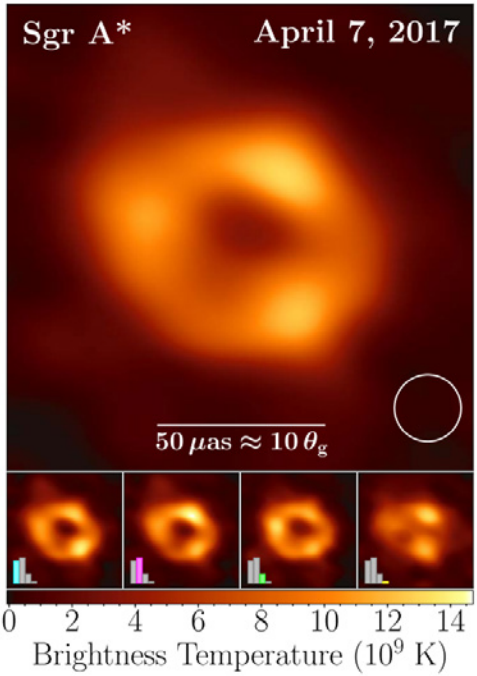

Figure 3.29: EHT image of Sgr A* Paper I, an average obtained across multiple methods. The insets represent different imaging solutions and their associated frequency.

azimuthal structures are less constrained, resulting in three different families of ring-like images. A fourth family consists of non-ring images (Paper III). The final image is a weighted average of all these families, with the relative weights indicated by the bars in the image (see Figure 3.29).

Measuring the ring properties —from images or visibilities directly— also requires a robust approach, and the methods are again tested first with the simulated data before being applied to the actual observations. The data are consistent with the Kerr black hole metric and known mass and distance for SgrA* (Paper IV). Alternative gravity and black hole models are considered, but show no indication that general relativity falls short. SgrA* and M87* look remarkably similar. Spanning over three orders of magnitude in scale, both images are dominated purely by gravity (see Figure 3.30).

Such sharp images of black holes provide a wealth of constraints for our understanding of accretion physics. A large library of GRMHD simulations was made and compared to a set of 12 constraints derived from the observations. The simulations are seriously challenged. The most constraining parameter is the variability, which is very poorly matched by any of the simulations. Nevertheless, the most preferred model is a magnetically arrested disk, with an accretion rate at starvation level. The rotation axis of the gas is likely close to our line of sight, so it would notably be offset from Galactic rotation.

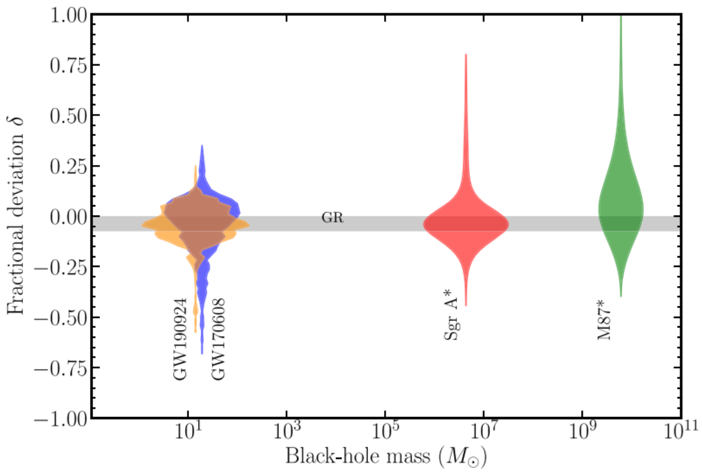

Figure 3.30: Comparison of the posterior distributions for the fractional deviation from the GR prediction, for Sgr A* (red), and two LIGO/Virgo events Paper VI).

In summary, the image of SgrA* was a challenge to make, but the ring feature is quite robust at a diameter of 51 micro-arcseconds. Strong constraints can be derived from the data to challenge our understanding of accretion physics. And finally, Einstein is still not wrong.

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, global VLBI, and correlator 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 JIVE Head of Operations (as 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 2021-2022 is listed in Table 4.1, including the NRAO and GBO representatives, and the e-MERLIN TAG chair who contribute to the EVN PC.

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 2021-2022 are given in Table 4.2.

All standard EVN, EVN+e-MERLIN, global VLBI and e-VLBI proposals are evaluated at the PC meetings, for observations in upcoming standard and real-time correlation e-VLBI 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

Name	Institute	Notes
Observatory members		
Tao An	Shanghai Observatory, CN	
Pikky Atri	ASTRON, NL	from October 2022
Michael Lindqvist	OSO, Göteborg, SE	
Andrei Lobanov	MPIfR, Bonn, DE	
John McKean	ASTRON, NL	until October 2022
Alexey Melnikov	IAA RAS, St. Petersburg, RU	until June 2022
Tom Muxlow	JBCA, UK	
Zsolt Paragi	JIVE, NL	Vice Chair until August 2021; Chair afterwards
Kazi Rygl	INAF-IRA, IT	Chair until August 2021; interim vice-Chair Aug-Nov 2021
At large members		
Carolina Casadio	FORTH, Heraklion, GR	from December 2021
Jan Forbrich	Univ. of Hertfordshire, UK	until February 2023
Krisztina Gabányi	Eötvös Loránd Univ., HU	
Talvikki Hovatta	Univ. of Turku, FI	until December 2020
Iván Martí-Vidal	Univ. Valencia, ES	until November 2021
Mar Mezcua	ISS Barcelona, ES	from December 2021
Alexey Melnikov	IAA RAS, St. Petersburg, RU	from June 2022
Sara Motta	INAF-OAB, Milan, IT	from February 2021; vice-Chair since November 2021
EVN Officers		
Bob Campbell	JIVE, NL	EVN correlator representative
Alastair Gunn	JBCA, UK	EVN scheduler
Other participants		
Mark Claussen	NRAO, US	NRAO VLBA/VLA Scheduler
Toney Minter	GBO, US	GBO Scheduler
Leah Morabito	Univ. of Durham, UK	e-MERLIN TAG chair

Table 4.1: List of members of the EVN PC during 2021-2022 and their roles.

Place	Date	Period
Fully Zoom @ OSO, SE	4 March 2021	Trimester 21A
Fully Zoom @ INAF Bologna, IT	23 June 2021	Trimester 21B
Fully Zoom @ JIVE, NL	3 November 2021	Trimester 21C
Fully Zoom @ JIVE, NL	2 March 2022	Trimester 22A
Fully Zoom @ JIVE, NL	6 July 2022	Trimester 22B
Fully Zoom @ JIVE, NL	2 November 2022	Trimester 22C

Table 4.2: PC Meetings during 2021-2022.

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.

In this period we were still having the EVN PC meetings fully online, as a consequence of the COVID-19 pandemic. It is expected that in the future we will partially come back to in-person meetings, although this will depend on various factors. The EVN PC initiatives affecting EVN operations have been involving Sardinia in Target of Opportunity observations (thanks to the SRT management for making the telescope available for this!), as well as initiating the EVN-lite sub-array pilot program and the EVN/JIVE Support+ Program. The former makes available a limited sub-array of the EVN in between regular sessions - with no strict commitment from any of the stations, on a best-effort basis. The background program for EVN-lite would be projects requiring 100s of hours of observations, of which only a fraction needs correlation (ideal for e.g. transient surveys). Regular trigger projects may also be triggered, overriding some of the background project epochs, should the minimal array requirements in the proposal be met. The EVN/JIVE Support+ Program is intended to provide extended JIVE support for non-expert teams.

EVN proposal statistics

The EVN is an open skies instrument accessible to astronomers all around the world. Regular proposals can be submitted by the deadlines of 1st February, 1st June and 1st October, while Target of Opportunity (ToO) proposals can be submitted at any time. The observations are organised in 3 main sessions of about 6 weeks each, and additional real-time-correlation e-VLBI sessions of 10 days per year.

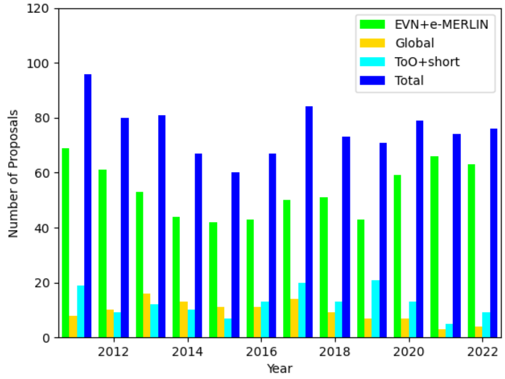

Figure 4.1: Total number of proposals received between 2011 and 2022 (dark blue), subdivided into EVN+e-MERLIN proposals at the regular deadlines (lime), global proposals at the regular deadlines (yellow), and Target of opportunity and short observing proposals (cyan).

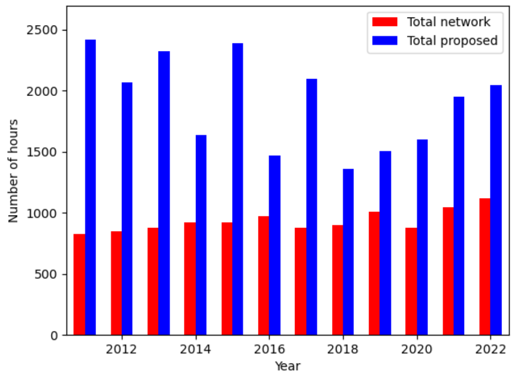

Figure 4.2: Proposed number of EVN Network hours and total proposed hours between 2011 and 2022.

The proposal statistics from 2011 to 2022 are shown in Fig. 4.1. The total number of hours proposed and the EVN network hours (i.e. actually observed hours) are shown in Fig. 4.2. The total demand on EVN time is fluctuating year by year, but it remains stable when we look at the whole period. The network hours show an increasing trend though. The over-subscription rate for 2021-2022, (hours requested)/(EVN network hours), stands at 1.85. The range of science cases proposed for and the requested bands are shown in Fig. 4.3.

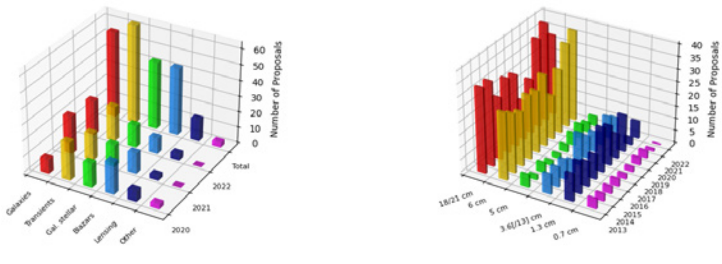

Figure 4.3: Left: The distribution of scientific categories (Cosmology, Galaxy Formation & Evolution, AGN/Jets, Stars/YSOs, Transients, Space and Technology) for proposals submitted from 2018 to 2022. Right: Distribution of requested wavelength bands for regular proposals submitted from 2011 to 2022. In addition, some proposals request 90 and 13 cm.

4.2 EVN Technical and Operations Group Report

Activities during 2021-2022

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.

Since 2019, Uwe Bach from the MPIfR in Bonn chaired the TOG. He finished his term after four years at the end of 2022 and starting from January 2023 Sergio Poppi from the Sardinia Radio Telescope (INAF, Italy) takes over the TOG chair. The TOG vice-chair is Marjolein Verkouter from JIVE, who fills this position since 2020. The TOG met two times during the period of this report. Both meeting were organized as online video conferences, because the ongoing pandemic situation did not allow to reliably organize in person meetings. The first meeting happened on April 29, 2021 and the second meeting on February 8-9, 2022 on two successive days because it was held together with the GMVA technical group meeting. Reports from the meetings are available on the TOG webpage hosted by JIVE[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 implementation of EVN technical road map. 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. In particular this are wider bandwidths to provide larger sensitivity, wider frequency coverage to obtain more precise spectral information and perform multi-frequency synthesis observations, and better uv-coverage by including more antennas to the EVN array. Wider bandwidth and frequency coverage require new receivers and sometimes also new backends (e.g. the DBBC3 VLBI backend), whose development is coordinated and monitored by the TOG. More antennas include the integration and testing of existing antennas that are not yet partners of the EVN and the support for observatories that build new antennas or refurbish decommissioned satellite service antennas.

Some noteworthy activities from the last years include (in no particular order):

- 13 stations are using Flexbuffs for data recording and e-transfer to the correlator, which allows flexible scheduling and fast data availability.
- Many stations have invested in disk and Flexbuff capacity to increased their storage pool to about 1000 TB (split between station and JIVE), allowing to record more and more continuum observations at 4 Gbps.
- Continuum VLBI observations at 4 Gbps are now available in the EVN call for proposals for all frequency bands above L-band and are requested by observers regularly.
- Continuous calibration with a noise diode switched at 80 Hz is used at 12 stations, which allows more precise measurements of system temperatures and therefore better amplitude calibration of VLBI data.
- The implementation of the DBBC3 VLBI backend 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 up to 32 Gbps, corresponding to a sampled bandwidth of 4 GHz at each polarization.
- New wide band receivers covering the range of 4 to 8 GHz are available at some stations or are in development. Together with the DBBC3 this frequency range will provide a very good sensitivity and is not much affected by weather effects.
- Several stations are in progress to install multi-band receivers that

[1] https://www.evlbi.org/TOG/tog-meeting_minutes

[2] https://arxiv.org/abs/2007.02347

cover wide bandwidths at 22, 43, and 86 GHz at the same time, which should allow very precise astrometry and sensitive millimeter wavelengths observations.

The capabilities of modern software correlators like the SFXC correlator at JIVE allow to process multiple phase centers and wide field images without much more effort than a single source processing. If the processed field of view reaches a certain limit the calibration process requires corrections for the primary beam of the receiving antenna to account for the reduced sensitivity at the edges of the beam. The TOG tries to collect the primary beam shapes of the EVN antennas since several years and although some progress has been made unfortunately some stations did not able to provide beam maps to JIVE yet. The TOG continues to provide help to stations were this information is missing.

Figure 4.4: Group picture from the online TOG meeting in April 2021.

Two additional online meetings to focus on the current developments of new receivers have been organized during the last two years. On April 1st, 2021 many EVN technical friends and experts on receiver development met to discuss the options and existing solutions for wide band receivers in the range 4 to 9 GHz (C/X band). The aim is to equip all EVN stations or as many as possible with wide band CX receivers that allow very sensitiv observations with up to 4 GHz of bandwidth per polarization (32 Gbps recording rates) using the DBBC3 VLBI backend. Receivers in this frequency range are relatively easy to build and could be available within a few years. Some stations, like Effelsberg, Tianma, and Yebes already have this kind of receivers available.

The second receiver meeting was held on September 6, 2022 to discuss and coordinate the development and installation of the so called triple-band receivers for simultaneous observations at 22, 43, and 86 GHz. First developed at KASI in South Korea also other EVN observatories became interested in such systems. All three INAF antennas have bought triple-band receivers from KASI, Yebes has build its own receiver, and Effelsberg, Metsahovi, and Onsala are developing individual systems as well. The aim of the meeting was to align concepts to common frequency ranges and to discuss the future requirements for backends, disk storage, scheduling, and data transfer with the expected increase of data rates from this type of multi-band receivers. The presentations from the meetings are available on the TOG wiki pages[3].

[3] https://radiowiki.mpifr-bonn.mpg.de/doku.php?id=na:sustainability:tog#auxilary_meetings

4.3 Scheduling and operations

As in previous years, in each of 2021 and 2022 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 2021 and 2022 respectively.

Observations in each disk-based session utilised between two and six different observing bands. The efficiency (defined as the percentage of available time actually scheduled) in the disk-based sessions ranged from 51.6% to 64.5%. This efficiency is primarily dictated by the time needed to change observing band and the demand on GST range (which is far from uniform).

During 2021 the EVN observed, on average, more hours than were replaced by subsequent proposal rounds. However, in 2022 the EVN operated with a surplus of approved hours, despite very high observing efficiency in all of 2022. This means the EVN pool of approved observations remained quite healthy. By the end of the reporting period, there were about 3 times the average number of hours observed per session waiting in the EVN pool. It should be noted that the large number of recently approved hours will be spread across a few years of EVN sessions. During this reporting period the eVLBI pool of approved observations remained reasonably healthy, although it was, as usual, completely dominated by trigger proposals.

Session	**Dates**	**Length (days)**	**Efficiency (%)**	**Wavelength (cm)**						
				0.7	1.3	3.6	5	6	18/21	92
2021-I	25 Feb - 18 Mar	21.0	51.6			✓	✓		✓	✓
2021-II	25 May - 17 Jun	21.0	60.1			✓			✓	✓
2021-III	21 Oct - 11 Nov	21.0	52.2		✓	✓	✓	✓	✓	✓
2022-I	24 Feb - 17 Mar	21.0	57.1		✓				✓	✓
2022-II	26 May - 16 Jun	21.0	64.5						✓	✓
2022-III	20 Oct - 10 Nov	21.0	62.5			✓	✓		✓	✓

Table 4.3: Summary of regular EVN Sessions 2021-2022.

Figure 4.5 shows the distribution of EVN hours against observing band for 2021 and 2022. 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 observations in both years. K-band and M-band (5cm) have become less popular during this reporting period, while X-band has become more popular.

In 2021 the total number of hours scheduled was 1099.0 and in 2022 it was 1148.5 (total 2247.5 hours). In 2021, 826.0 hours were scheduled within regular sessions, 183.0 hours within eVLBI sessions, and 90.0 hours

	Session 2021-I			Session 2021-II			Session 2021-III		
	No	Hours	TBytes	No	Hours	TBytes	No	Hours	TBytes
Total	26	260.0	2741.6	29	303.0	2885.5	24	263.0	2654.2
EVN-only	25	227.0	2171.6	28	282.0	2638.1	22	209.0	1788.8
Global	1	20.0	419.3	1	12.0	132.7	2	36.0	696.7
Short	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
Tests	5	13.0	150.7	3	9.0	114.7	6	18.0	168.7
CAL	4	16.0	0.0	3	12.0	0.0	6	24.0	0.0
Associated antennas									
e-MERLIN	12			15			9		
VLBA	1			1			2		
VLA	1			0			0		
GBT	1			0			0		
Robledo	1			0			0		
KVN	6			3			2		
Wettzell	1			0			0		
Kunming	6			4			7		
LBA	0			0			0		

Table 4.4: Details of EVN Sessions in 2021, showing the number of observations, hours and TBytes scheduled, and number of observations for associated antennas.

	Session 2022-I			Session 2022-II			Session 2022-III		
	No	Hours	TBytes	No	Hours	TBytes	No	Hours	TBytes
Total	36	288.0	2947.3	39	325.0	2445.5	45	315.0	2952.3
EVN-only	31	270.5	2669.8	31	278.0	2145.5	36	265.5	2423.6
Global	1	7.0	142.4	3	33.0	127.2	3	28.5	280.5
Short	1	1.5	1.1	0	0.0	0.0	1	2.0	33.2
Tests	3	9.0	134.0	5	14.0	172.8	5	19.0	215.0
CAL	3	12.0	0.0	2	8.0	0.0	4	16.0	0.0
Associated antennas									
e-MERLIN	17			27			29		
VLBA	1			3			3		
VLA	0			0			1		
GBT	0			3			2		
Robledo	2			0			2		
KVN	2			0			3		
Wettzell	0			0			0		
Kunming	9			0			0		
LBA	0			0			1		

Table 4.5: Details of EVN Sessions in 2022, showing the number of observations, hours and TBytes scheduled, and number of observations for associated antennas.

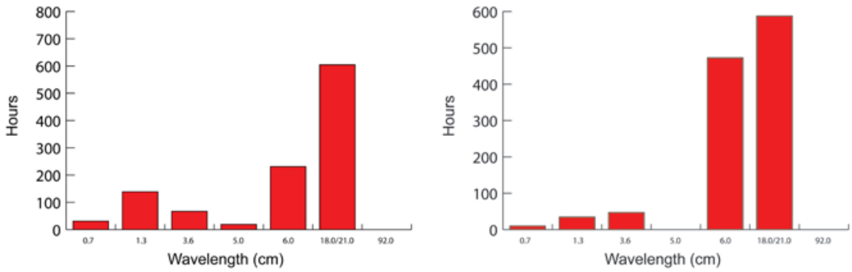

Figure 4.5: Distribution of EVN hours against observing waveband for 2021 (left) and 2022 (right).

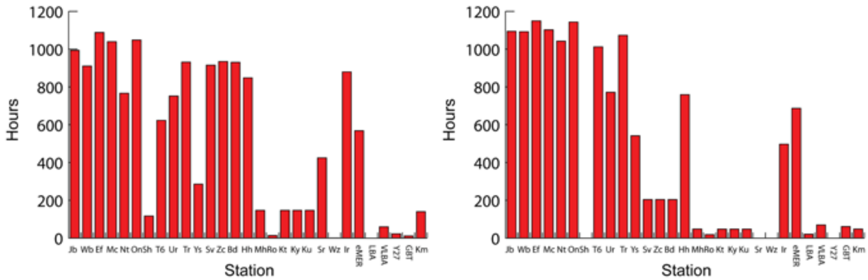

Figure 4.6: Distribution of observing hours for EVN stations and affiliates for 2021 (left) and 2022 (right).

as out-of-session observations. In 2022, 928.0 hours were scheduled within regular sessions, 208.5 hours within eVLBI sessions, and only 12.0 hours as out-of-session observations.

Over this two-year reporting period, 274 separate observations were performed, of which 210 were standard experiments, 12 were global experiments, 27 were network monitoring, fringe-finding or test experiments, 4 were EVN 'short' observations and 21 were target-of-opportunity observations. The 247 science experiments performed in 2021-2022 came from 103 regular proposals, 3 'short' proposals and 9 target-of-opportunity proposals. During the same period there were 3 triggered observations during eVLBI sessions. Details of EVN eVLBI observations in 2021-2022 are shown in Table 4.6 and details of out-of-session (OoS) EVN observations for 2021-2022 are shown in Table 4.7.

Figure 4.6 shows the distribution of observing hours against EVN station and affiliate antennas for 2021 and 2022. The drop in participation of KVN antennas is due to a drop in 1.3cm proposals in this reporting period. Joint EVN/e-MERLIN observations have become more common during the reporting period. The Sardinia Radio Telescope (Sr) was unavailable for all of 2022 due to ongoing engineering works. No observations were requested with the Wettzell (Wz) antenna during this reporting period.

Dynamic Scheduling

During this reporting period a form of dynamic scheduling was considered for the EVN. Essentially the proposal was that EVN antennas observe **2 days out of every week for 40 predetermined weeks of the year**. Several issues were apparent that meant the proposal could not be adopted. Almost all stations complained that operational staff could not be provided to the degree that dynamic scheduling would require. Several stations pointed out that they can't provide frequency agility on a timescale of less than a few weeks. Some would also restrict which set of bands are available for a given predefined period. Standard C- and L-band are usually available, as they are now in eVLBI observations. This means scheduling would only be possible several months in advance, so that ToO or trigger observations would suffer and the 'dynamic' nature of the process would be much reduced. Due to other commitments (which are diverse), some stations would require 'dynamic' scheduling only on week days, while others only on weekends. Some would even restrict observations to only specific days, these to be decided several months in advance. Several stations would require observing days defined at least six months in advance, just as they are now for eVLBI observations. This means that anything approaching a useful array would probably not be dynamically schedulable. Certainly, most stations agreed that availability for 40 weeks of the year is far more than can be reasonably achieved in terms of their other commitments. Several stations said that dynamic scheduling, or anything other than 3×3 weeks per year, would be extremely difficult to coordinate with local engineering requirements. This could mean the number of weeks that telescopes are available would fall far short of the requirement for dynamic scheduling. Furthermore, shifting to weekdays only would mean less days would be available for observations because engineering can only be performed at weekends. Those stations still shipping physical media pointed out that it is not possible to ship more regularly than at present. Indeed, there was concern that disk-based recording would actually become much more inefficient and therefore expensive. There were also concerns about the inefficiency of increasing the 'dead time' of some stations that do not observe complete runs, increasing the amount of telescope time devoted to clock searching, the danger of data back-logs at stations, the requirement for some stations to change observing equipment (other than receivers) on short notice, and the problems of providing stable high-bit-rate data connections almost permanently. The responses from stations indicate that it would be very difficult to implement any form of dynamic scheduling with the EVN.

Run	Date	Band	Hours	eVLBI Proposal Type				
				Queued			Trigger	
				Normal	Short	ToO	Scheduled	Triggered
21e01	19 Jan 2021	18cm	16.0	1	0	0	1	0
21e02	09 Feb 2021	6cm	10.0	0	0	1	4	0
21e03	30 Mar 2021	18cm	9.0	1	0	0	5	0
21e04	13 Apr 2021	18cm	18.0	2	0	0	6	0
21e05	11 May 2021	6cm	10.0	1	0	1	6	0
21e06	22 Jun 2021	18cm	24.0	2	0	1	6	0
21e07	21 Sep 2021	18cm	24.0	4	0	0	2	0
21e08	12 Oct 2021	18cm	24.0	2	0	1	2	0
21e09	16 Nov 2021	18cm	24.0	1	0	0	7	1
21e10	07 Dec 2021	18cm	24.0	1	1	0	7	1
22e01	18 Jan 2022	6cm	24.0	2	0	1	5	0
22e02	15 Feb 2022	6cm	24.0	3	0	0	4	0
22e03	22 Mar 2022	6cm	24.0	2	0	1	4	0
22e04	12 Apr 2022	18cm	24.0	3	1	0	6	0
22e05	10 May 2022	18cm	20.0	2	0	0	1	0
22e06	21 Jun 2022	6cm	16.0	1	0	1	4	1
22e07	20 Sep 2022	6cm	19.0	2	1	0	7	0
22e08	13 Oct 2022	18cm	20.0	2	0	0	2	0
22e09	15 Nov 2022	18cm	21.5	2	0	0	2	0
22e10	06 Dec 2022	6cm	16.0	4	0	0	4	0
	Total		391.5	38	3	7	85	3

Table 4.6: Details of EVN eVLBI runs 2021-2022, showing dates and waveband, number of hours scheduled per run, the type of observation and the number of trigger observations scheduled and actually triggered.

	2021 OoS			**2022 OoS**		
Experiments	No	Hours	TBytes	No	Hours	TBytes
Total	11	90.0	64.5	3	12.0	22.1
Associated antennas						
e-MERLIN	5			0		
VLBA	1			0		
VLA	1			0		
KVN	0			1		

Table 4.7: Details of EVN Sessions in 2022, showing the number of observations, hours and TBytes scheduled, and number of observations for associated antennas.

5. EVN observatory reports, full members

5.1 ASTRON – Westerbork synthesis radio telescope (WSRT)

The Netherlands Institute for Radio Astronomy (ASTRON) has been an integral member of the EVN since its inception. The institute is based in Dwingeloo, the Netherlands, and has been the host of the Joint Institute for VLBI ERIC (JIVE) since 1993. In addition, ASTRON operates the Westerbork Synthesis Radio Telescope (WSRT) as a key element of the EVN, first as a phased array for over 20 years, and now as a single 25 dish. A second 25-m dish is also available for space-based radio astronomy projects. Here, we summarize the status of the observatory at Westerbork and discuss the technical VLBI activities of the staff at ASTRON.

Staff involved in EVN activities

There are a number of ASTRON staff associated with management, operational, technical (hardware and software development) and training activities within the EVN. A brief summary of their roles is given below.

- EVN CBD: Rene Vermeulen attended all meetings of the Board of Directors as representative of ASTRON.
- EVN Technical and Operations Support: The VLBI operations team at ASTRON is led overall by Marco Drost, with technical support from Richard Blaauw. The scheduling and telescope operation is carried out by Jurjen Sluman and Henk Mulder. This team is part of the Astronomy and Operations (A&O) Division within ASTRON,

which is led by Mark Bentum.

- EVN TOG: Richard Blaauw represented ASTRON at the Technical Operations Group of the EVN, attending the 2022 meeting online.
- EVN PC: John McKean represented ASTRON within the EVN Programme Committee until September 2022, and has since been replaced by Pikky Atri from October 2022.
- EVN Post-processing: Shivani Bhandari, Jason Hessels, Franz Kirsten (now at Onsala Space Observatory) and Mark Snelders pioneered methods for the localization of transient events (with Benito Marcote at JIV-ERIC), and Celestin Herbe-George and John McKean developed new methods for wide-field VLBI.
- EVN Training: John McKean led the training work package within the Optical-RadioNet-Pilot project until September 2022, and was responsible for the overall co-ordination of training with RadioNet infrastructures, including the EVN. Roberto Pizzo has taken over this role since October 2022.

EVN Observing Time (in- and out-of-session)

The WSRT participated as a single 25-m dish in all EVN sessions over the reporting period of 2021 to 2022, providing a total of 2173 hours of observing time, with the vast majority being at L-band (see Tables 5.1 and 5.2). Of this time, 776 hours were used for e-VLBI. In addition, the single-dish WSRT was made available for 4868 hours as part of out-of-session observing with other EVN telescopes within the PRECISE (PI: Hessels; ASTRON) collaboration; note that some of this time included using the WSRT (and other small EVN dishes as standalone telescopes) for doing high-cadence monitoring of fast radio bursts at multiple frequencies. The data from PRECISE were correlated onsite at JIV-ERIC, as part of an approved correlator-only EVN project. A total of 104 hours in 2021 were used for operations associated with the *Galileo* satellite navigation system. In general, the VLBI observations made with the single 25-m WSRT dish were successful, with only 221 hours lost due to receiver issues over the reporting period.

Receivers

Due to the commissioning and operation of the Aperture Tile in Focus (Apertif) system at the WSRT since 2015, the phased array observing mode that employed all 14 elements of the array remained unavailable during the reporting period. Therefore, VLBI observations used two 25-m dishes that are equipped with circular Multi Frequency Front Ends (MFFEs). These have cooled receivers at 3.6, 6, 13, and 18+21 cm, and uncooled receivers at 49 cm and 92 cm (although the lowest frequencies are not commonly used due to being superseded by the Low Frequency Array; LOFAR). The MFFEs were placed on the tele-

Observing band	Hours
L	1333
C	902
M	23
X	136
Time lost	221
Total	**2394**

Table 5.1: The total number of WSRT single-dish observing hours used for the EVN from 2021 to 2022, for each frequency band.

Project	2021	2022
VLBI	544	853
e-VLBI	532	244
PRECISE	2360	2508
Galileo	104	–
Total	**3504**	**3605**

Table 5.2: The total number of WSRT single-dish observing hours used for VLBI from 2021 to 2022, for each project.

scopes in 1997, and therefore, the components are sometimes failing, but despite their age they continue to function quite well. Numerous plans to develop new receiver systems for wide-band VLBI at the WSRT are being discussed (e.g. a BRAND-like receiver), but these were not executed during the reporting period.

MASER upgrade at WSRT

During the previous two reporting periods, issues with the MASER at the WSRT became apparent (including going out of lock in April 2018), which was not too surprising considering the MASER was almost 25 years old. This represented a significant risk to on-going VLBI operations at the WSRT, and so, a new MASER was ordered in late 2020. This new MASER arrived in April 2021, and has been used successfully for the EVN sessions since. A picture of the old and new MASERs can be seen in Figure 5.1.

Flexbuff

In December 2022, ASTRON installed a new Flexbuff with 400 TB of storage for VLBI observations. These disks were purchased via a successful NWO-XS project called WesterFlash (PI: Kirsten, now Hessels). This new

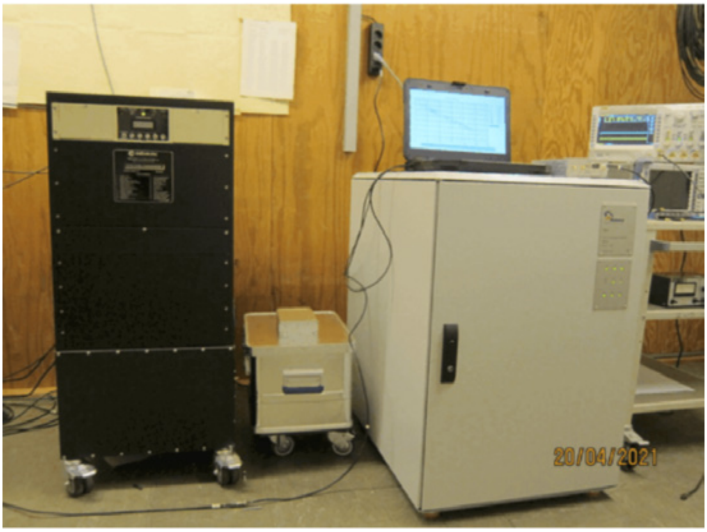

Figure 5.1: The old MASER (left), which was almost 25 years old, next to the new MASER (right) of the WSRT, which was installed in April 2021.

Flexbuff was installed at JIV-ERIC, and was added to the overall EVN storage pool. The old Flexbuff, with 200 TB of storage, was moved to the WSRT site. In the past, VLBI data were recorded at JIV-ERIC via a direct fibre connection from the WSRT. With the new available Flexbuff space, the WSRT VLBI data are now recorded locally at the observatory and then e-shipped to the central Flexbuff pool at JIV-ERIC for storage prior to correlation. This new set-up provides better data transfer reliability between the telescope and the storage facility, and increases the overall data storage capabilities of the EVN.

DBBC

The DBBC at the WSRT has four core2boards. During the reporting period, the DBBC was upgraded from Windows XP to Windows 7 for security reasons. The fila10g interface of the DBBC is now connected to our local Flexbuff at the WSRT and via direct fibre to JIV-ERIC for eVLBI observations.

Training Activities

The constant development of new observing modes and updated calibration processes requires continuous training of the user community in these new techniques. Within the Opticon-RadioNet-Pilot (ORP) programme, there are several EVN and VLBI related training activities that ASTRON staff either led or contributed to. The overall co-ordination of the ORP training for RadioNet facilities is led by John McKean (until September 2022) and Roberto Pizzo (since October 2022).

The main training event for the EVN during the reporting period was the European Radio Interferometric School (ERIS), which was organized by JIV-ERIC with support from ASTRON, in Dwingeloo (September 2022). ASTRON staff contributed to the SOC (John McKean, co-Chair; Marco Iacobelli; Emanuela Orru') and the LOC (Liesbet Elpenhof; Marco Iacobelli; John McKean). Also, ASTRON staff delivered lectures on radio interferometry (John McKean; Harish Vedantham), and polarization (Michiel Brentjens) that were relevant for users of the EVN.

5.2 Istituto Nazionale di Astrofisica, Italy

The Institute of Radioastronomy (IRA) has been an integral member of the EVN since its inception. It is now part of the Italian National Institute for Astrophysics (INAF), together with the Cagliari Astronomical Observatory. Currently, INAF operates the two 32m dishes in Medicina and Noto and the 64m Sardinia Radio Telescope. Here, we summarise the status of the three antennas.

Medicina station

The Medicina 32-m parabolic antenna is operated by the Institute of Radioastronomy of the National Institute for Astrophysics (INAF). The telescope has been active since 1984 in VLBI, Space VLBI and radioscience observations and has regularly participated in EVN and eVLBI activities. Below, we outline the current status and forthcoming upgrades:

Receivers – The antenna operates in the 1.35-26.5 GHz range with L (1.35–1.715 GHz), dual S/X (2.2–2.36/8.18–8.98 GHz), C-low (4.3–5.8 GHz), C-high (5.6–7.3 GHz) and K-band (18–26.5 GHz) receivers. Frequency agility is available. In summer 2022 the simultaneous tri-band receiver (18-26, 34-50, 80-116 GHz) was delivered, which will complement the current suite of receivers (see Fig. 5.2). Installation and operations are expected by the end of 2024. The receiver was funded by the PON (National Operational Program) issued by the Italian Ministry for Research and University. Continuous calibration is available for all receivers except the S/X.

Antenna upgrades – A major upgrade towards active surface is taking place. In particular:

- new panels for primary mirror have been delivered, showing a manufacturing accuracy less than 65 microns;
- the construction of a new subreflector is in progress, its manufacturing accuracy is foreseen to be less than 50 micron and the delivery is expected at the end of 2023;
- all the parts for constructing 244 electromechanical actuators are under delivery and the assembling completion is foreseen for summer 2023;
- a new servo system (drivers, motors, encoders, power lines, firmware and software) both for Medicina and Noto is being designed in Medicina. The plan is to test the prototype by spring 2024. The construction and the the installation is expected in 2024.

VLBI back-end, Field System, and e-VLBI – A DBBC3 back-end has been delivered and tested with the new FS 10.1.0-beta2 version. A new Flexbuff has been installed and configured: the system can record at 4Gbps and the storage capacity is a total of 360TB. An additional Flexbuff with 480 TB capacity has been purchased. Operations are

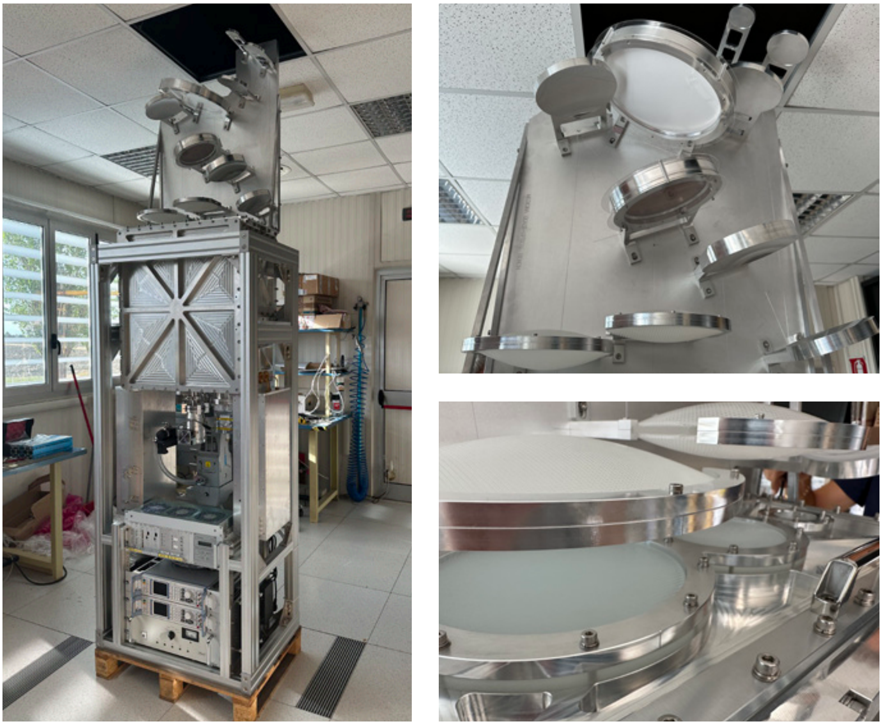

Figure 5.2: Images of the Compact Tri-Band (CTR) receiver at the Medicina radioastronomical station. Left: Complete CTR to be mounted on Medicina and Noto antennas. Right: views of the quasi optic system providing the frequency simultaneity. A similar system was also acquired for installation on the Sardinia radio telescope.

carried out running FS-10.0.0 and Medicina is routinely running e-VLBI experiments.

EVN Sessions – In 2021, no particular problems were reported in any of the three sessions. All NME tests gave fringes. In 2022, no particular problems were reported in sessions 1 and 3, while at the end of session 2 the synthesizer broke and five experiments were lost before we were able to substitute. All NME tests gave fringes.

Staff – The Head of Operations is Alessandro Orfei, the VLBI technical friend is Giuseppe Maccaferri and the VLBI friend is Andrea Orlati. The antenna scheduler is Alessandra Zanichelli.

Noto station

The Noto 32-m parabolic antenna is operated by the Institute of Radioastronomy of the National Institute for Astrophysics (INAF). The telescope has been active since 1989 in VLBI, Space VLBI and radioscience observations and has regularly participated in EVN and e-VLBI activities. Below, we outline the current status and forthcoming upgrades:

Station – At the end of 2022, a full H-maser maintenance has been finalised.

Antenna – The 32-m antenna is fully azimuth and elevation steerable and is equipped with an active surface, allowing it to correct gravitational deformations of the primary mirror. At the end of September 2020 a mechanical component (Z Axis - focusing) failed, preventing the telescope to switch between primary focus receivers (L-, S- and X-band) and secondary focus receivers (C_{low}-, C_{high}- and K-band). Required spare parts were procured and the component repaired in April 2021. The chiller could not be repaired so we were forced to buy a spare and replace it. A complete refurbishment of the telescope infrastructure is planned for the second half of 2023. The intervention will be about three months long and involves a complete replacement of the power lines, the cryogenic pipes, the refurbishment of the vertex room (secondary focus cabin), the main servo system re-cabling and the installation of a new air cooling system. We expect that this will improve the reliability of the antenna.

Receivers – The primary focus receiver is a triband L-(1.316-1.745 GHz)/S-(2.21-2.39 GHz)/X-band (8.21-8.94 GHz) system. Available secondary focus receivers are C_{low}- (4.62-5.02 GHz), C_{high}- (5.1-7.25 GHz), and K-band (21.7-22.2 GHz). All receivers provide double, circular polarisation; C_{low}- and K-band are cryogenics systems. The K-band is planned to be replaced soon, and we are still investigating feasible solutions for the C_{high} receiver. A simultaneous three-band (K,Q,W) receiver (18–26 GHz, 34–50 GHz, and 80–116 GHz, see Fig. 5.2) is now available and ready to be installed in the secondary focus cabin. The receiver was funded by the PON (National Operational Program) issued by the Italian Research Ministry. It can output wide IF bandwidths (K-Band: 8 GHz; Q-Band: 16 GHz; and W-Band: 16 + 16 GHz). The final installation and commissioning of the receiver will be done in late 2023, after the refurbishment of the secondary focus cabin, including the new helium line, is completed.

VLBI back-end – Noto is currently running a DBBC version 2. The firmware version is currently DDC V108 and DFB V16. The recorder is a Flexbuff system (software version 2.8.1). In 2022 we completed the purchase of a new, state-of-the-art Flexbuff with a capacity of 512TB and, under the framework of the PON, we also managed to buy a new DBBC, version 3 (up to 6 IFs). Both systems are available and ready to be tested in order to be operational.

Future plans – In the context of the grant awarded to INAF as part of the Recovery Plan, Noto will go through major maintenance in 2023-2025. The azimuth rail, including the wheels and bearing, the elevation rack and the secondary mirror will be replaced. The telescope structure coating and the primary mirror painting will be completely refurbished, as well as the mechanical components of the active surface system will be replaced. Within the same funds we plan to refurbish the power distribution of the station and to install a photovoltaic system to produce green energy and reduce the carbon footprint of the station. A new main servo system (studied and designed in Medicina) is expected to be in place in Noto by mid-2025.

EVN Sessions – A failure of the chiller dedicated to a cryogenic compressor (serving the secondary focus receivers) just before the beginning of the session compromised the C-band part of 1/2022.

Staff - The head of operations and VLBI friend is Andrea Orlati. The VLBI technical friend is Salvo Buttaccio. The antenna scheduler is Alessandra Zanichelli.

Sardinia radio telescope

The Sardinia 64-m parabolic antenna is operated by the Osservatorio Astronomico di Cagliari (INAF). The radio telescope started its operations in VLBi in 2014.

Antenna – Thanks to the National Operative Programme (Programma Operativo Nazionale, PON) – Research and Innovation 2014-2020, SRT is being upgraded to operate up to 116 GHz. The project includes the procurement of 4 new receivers, upgrade of the plants, a metrology system, new back-ends (including DBBC3) and laboratory instrumentation. 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). Since August 2021, operations have stopped to install sensors for the metrology to allow the upgrade of the cryogenic lines, the mechanical upgrade, and also new optical fibre and radio frequency cabling. Also, the project has included the refactoring of the minor servo system which is responsible for the proper positioning of the telescope optics. The new VLBI backend DBBC3 was delivered at Sr at the beginning of October 2021. SRT was also equipped with a further new flexbuff of 512 TB, delivered at the end of September 2022. A similar new flexbuff was also installed at JIVE. The total disk space of the flexbus at SRT is then equal to 872 TB (512 TB + 360 TB).

Continuous calibration (80Hz), which was installed for observing was regularly used at M- and K-band in 2019 and at L-band during the EVN sessions 01/2021 and 02/2021.

Receivers – P-, L-, M- and K- band receivers were fully operational. The receivers under development/construction by the end of 2022 were:

- a triple-band receiving system (K/Q/W), dual pol, single feed per band (see Fig. 5.2). Delivered in August 2022. Installed in June

2023.

- a millimetre camera (80 – 116 GHz). Installed in May 2023.
- a cryogenic receiver at W Band (75 – 116 GHz), dual pol, 16 feeds. Installed in May 2023.
- a cryogenic receiver at Q Band (33 – 50 GHz), dual pol, 19 feeds. Installed in June 2023.
- a receiver at C band (4.2 - 5.6 GHz), dual pol, single feed. Advanced status. Expected delivery in July 2023.
- a receiver at S band, dual pol, 5 feeds. Advanced status.

VLBI – Firmware and software were by the end of 2022:

- Field System: 10.0.0 at 64 bit
- DBBC: DDC (v107_281019), PFB (16)
- Fila10G: v4.1_231118
- Jive5ab: 3.1.0

EVN sessions – The Sardinia Radio Telescope participated in the PI experiments of session 01/2021, 02/2021 with all the available and scheduled receivers (L- and K-band). Fringes were obtained at all bands during the ftp-fringe tests. SRT did not participate from session 03/2021 to session 03/2022 due to the planned work for its upgrade at higher frequency.

e-VLBI sessions – Sr successfully took part in the e-VLBI sessions on the 19th-20th January 2021 (L-band), on the 30th-31st March 2021 (L-band), and on the 13th-14th April 2021 (L-band). The e-VLBI sessions in February 2021 and May 2021 were missed because they were made at C-band (unavailable at SRT). The SRT also missed the observations of June 2021 (antenna air conditioning problem) and all the observations from September 2021 to December 2022 because of the planned work for its upgrade at higher frequency (see above).

Staff – The Head of Operations is Sergio Poppi. The VLBI friend at the station is Gabriele Surcis and the VLBI Technical friend is Carlo Migoni.

5.3 Instituto Geográfico Nacional, Yebes Observatory, Yebes, Spain

The Yebes Observatory has been involved in the European VLBI Network since the 1990s, but its role became even more important with the addition of the 40-metre radio telescope to the network in 2008. The 40-m RT is a crucial element for the EVN because of its high sensitivity, the quality of its receivers and its geographical position, covering the southern and easternmost part of Europe. For the last four years the telescope has also been open (in single dish mode) to astronomers from all over the world, but the programme committee also accepts VLBI proposals. This report summarises the observations, the status of the radio telescopes, the technical activities and the R&D projects in which we were involved during 2021 and 2022.

Staff involved in EVN activities

The following people are involved in EVN-related activities at the Yebes Observatory:

- EVN CBD: Pablo de Vicente, Director, attends the Board of Directors on behalf of the IGN.
- EVN technical support: Javier González is the technical VLBI representative for Yebes Observatory, and Francisco Beltrán is in charge of software development related to the 40-m radio telescope and VLBI calibration (ANTAB scripting). There is also a team of operators and engineers who support the operations and maintenance activities. Use the following mailing list to contact the whole group: vlbitech@oan.es
- EVN scientific support: Cristina García Miró is the support scientist for the EVN. Other support astronomers help with GMVA activities (Ana Chacón) and IVS/VGOS activities (Victor Pérez and Felipe Paredes). Belén Tercero is the 40-m RT scheduler. Use the following mailing list to contact the whole group: astrovlbi@oan.es

VLBI Observations

Since the last report, the 40-m RT has scheduled a total of 1437 hours for VLBI observations in 2021 and 1753 hours in 2022. In 2021, due to a major antenna failure caused by a severe snow storm that forced us to shut down the antenna for almost half a year, the number of observing hours was dramatically reduced compared to previous years, to only 948.4 hours (66% of the total scheduled), divided into 82 observations. During 2022, the usual observation percentages were recovered, with 1522.5 hours observed (87% of the total scheduled), divided into 119 observations.

The time dedicated to VLBI is used to participate in the observations of several networks: EVN, GMVA, IVS, as well as third-party projects requesting observing time on a per-observation basis, which is granted by the 40-m Programme Committee.

- EVN. We have observed in 5 of the 6 scheduled observing sessions during these two years. We have also participated in several e-VLBI sessions and Target of Opportunity observations. The 40-m telescope contributes to the EVN through its legacy geodetic receivers at simultaneous S/X bands (2.2/8.4 GHz), the broadband CX receiver (4.5-9 GHz) and the K-band (21-25 GHz) and Q-band (31-51 GHz) receivers.
- Global Millimetre VLBA Array (GMVA). We have participated in 3 of the 4 scheduled observing sessions during these two years. Last year, we also started to participate in GMVA out-of-session observations for a more detailed follow-up of the variable targets. These observations are performed at 86 GHz (3 mm) using the same backends as for the EVN. A removable lambda quarter plate allows the receiver to be sensitive to circular polarisation.
- International VLBI Service for Geodesy and Astrometry (IVS) observations. A large fraction of the telescope time is devoted to IVS Legacy 24-hour observations at 2 and 8 GHz, meanly to determine the Earth Orientation Parameters (EOP), and a small fraction of the time to maintain the ICRF and ITRF.
- Others. The observatory receives requests to support other VLBI projects, such as participation in KVN observations to develop the multi-wavelength "Frequency Phase Transfer" technique, EVN radio science observations (PRIDE project), time transfer experiments organised by INAF, or participation in Global Astrometry observations at high frequencies (K-band), etc. All these projects are approved by the 40-m Programme Committee or as Director's Discretionary Time (DDT).

The number of hours and observations per network and project in 2021 and 2022 are summarised in Table 5.3.

Network	N. Obs. 2021	hours 2021	N. Obs. 2022	hours 2022
EVN	36	258.3	68	456
e-EVN	0	0	7	194
EVN ToO	4	44	2	8
GMVA	4	88.6	11	187
GMVA OoS	0	0	3	26.5
IVS	18	432	23	552
Others	20	125.5	5	99
Total	82	948.4	119	1522.5

Table 5.3: Distribution of VLBI observations performed in 2021 and 2022, indicating the number of observations and observed hours per observation type.

VLBI observations with the 13.2 m radio telescope are exclusively part of geodetic programs, mainly VGOS and EU-VGOS programs. The telescope has been part of the VGOS core network since it became operational in 2016. VGOS observations are typically 24 hours long and were scheduled every 7 or 14 days during the reporting period. Since last year, we have also started to participate in weekly Intensive runs with GGAO and RAEGSMAR (second station to come online in the RAEGE project), to determine the DUT1 parameter. From June to December 2021, the Yebes 13.2m telescope was affected by a major problem with the cable wrap which completely stopped operations. During the reported period, the telescope observed 59 24-hour VGOS sessions, 3 EU-VGOS sessions and 18 intensives.

Technical Activities

The technical activities related to the VLBI observations are mainly devoted to the development of new receivers, various upgrades of the radio telescopes, software development for different applications, maintenance and operation of the VLBI backends and servers, Internet connection to the outside world, and the implementation of a software correlator to support geodetic activities.

At the end of 2021, the 40-m radio telescope enhaced its observing capabilities with the installation of a new broadband C/X circular polarisation receiver covering the 4.5-9 GHz band. Comissioning activites included several characterisation sessions and a successful real-time fringe test in C, M and X bands supported by several EVN stations and JIVE. Since then, the receiver has regularly supported EVN and e-EVN observations.

Two new receivers are currently under development at Yebes that will significantly improve our support to the EVN: the ASTROREC K-Ka band linear polarisation receiver covering the range 18-32 GHz (see Figure 5.3) and an extended broadband receiver covering the range 4-18 GHz, compatible with the future SKA1-MID bands. Both receivers are expected to see first light in 2023.

With the development of a dichroic mirror for Q- and K-band transmission and W-band reflection, the Yebes Observatory has acquired the capability for simultaneous K/Q/W-band VLBI observations (Figure 5.4). Our 40-m would be the first radio telescope in Europe to support this capability. Efforts are underway to demonstrate fringes within the KVN and the EVN using the required DBBC3 backend. Additional software development for the 40-m RT has been required to control and monitor 3 receivers simultaneously.

In addition to the receivers for the 40-m RT, an important observatory activity has been the development of geodetic VGOS receivers, covering the 2-14 GHz band, for our own 13.2-m antenna, and for other observatories such as Ny Alesund, Santa María, Matera or HartRAO.

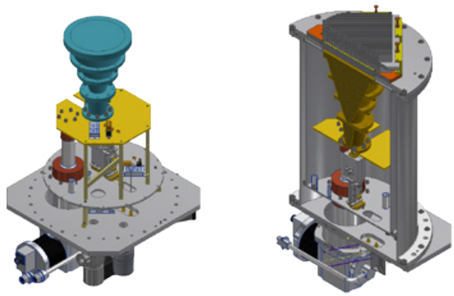

Figure 5.3: New ASTROREC K-band receiver under development.

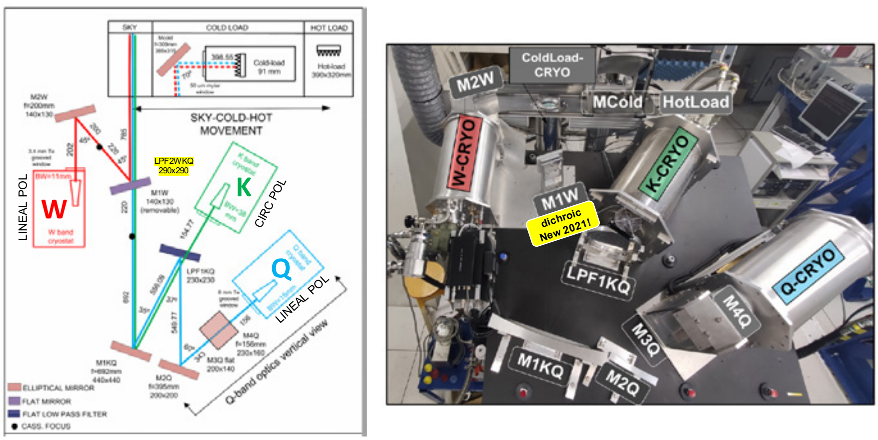

Figure 5.4: Optical components and signal path for VLBI observations in K-Q-W bands simultaneous reception.

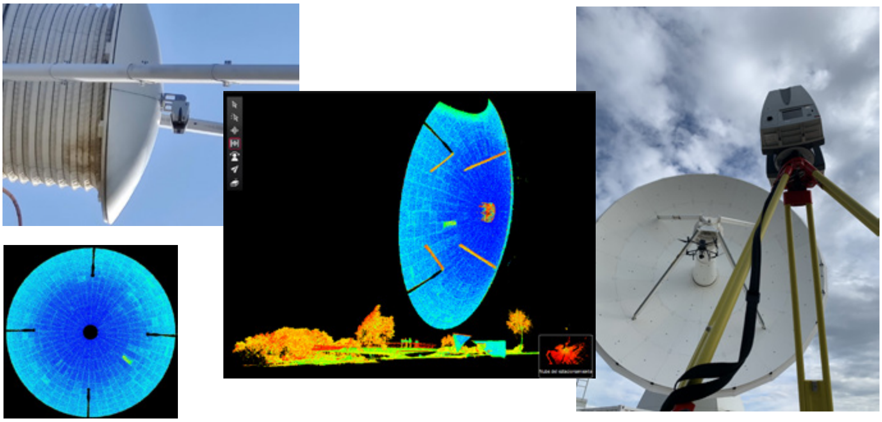

Figure 5.5: Laser scanner and drone surface measurements for RT40 and RT13.

Our own VGOS receiver was replaced in June 2022, incorporating several upgrades that have greatly improved its phase stability.

The 40-m radio telescope is undergoing further upgrades to improve its performance in terms of gain, phase stability and observational efficiency. During this period, the installation of 165 thermal sensors on the back of the paraboloid, tetrapod legs, counterweights, and fork, was completed for modelling studies of structural deformation due to temperature gradients. The Nasmyth receiver cabin was also thermally insulated to minimise daily and annual temperature variations and improve energy efficiency. To study the deformations of the paraboloid due to gravity, several measurements have been made using a laser scanner and a drone for comparison (see Figure 5.5). These measurements are complementary to the holographic technique.

The VLBI equipment used for each Yebes radio telescope is described in Tables 5.4 and 5.5. The 40m RT is currently equipped with a DBBC2 and a flexbuff unit (aka flexastro), which are the nominal backends for observations within the EVN. There is another flexbuff unit (aka flexbuff) which is mainly dedicated to the IVS and GMVA support, but is occasionally used for the EVN. All these units are controlled by a Field System server, running version 9.13.2. In 2022, a DBBC3-2L-2H backend was upgraded to a DBBC3-6L-6H, thus adding four more signal processing chains to support tri-band (dual polarisation) simultaneous observations. This backend is connected to an additional flexbuff (aka flexcosmos), controlled by a Field System server running version 10.1.0. A 10 Gbps switch in the backend room manages traffic between the signal processing backends and the recorders allowing great flexibility without human intervention. This switch also allows us to do e-vlbi observations. Last year, the old 16-port model was replaced with a newer 28-port design, providing the necessary hardware to connect the DBBC3 to the existing equipment.

Regarding the 13m RT, this antenna is equipped with four RDBE-Gs and a Mark6 recorder, allowing a maximum processing rate of 16Gbps, although the recorder is limited to 4 Gbps in single module recording. A spare Mark6 recorder is used as an intermediate buffer to 'vmux' or de-thread the VGOS data recorded by four different backend units. Only after the bits from the different bands have been combined into a multi-channel, single-thread file can they be transferred to the correlator. The maximum sustained transfer rate to the Haystack correlator is 3.5 Gbps. In addition, four R2DBE's are installed in the backend room, but the firmware to perform geodetic observations is still in the final stages of development at Haystack. During the initial setup, several factory problems were discovered. Some components were incorrectly wired and burned out, two of the four synthesiser boards were faulty and one power supply did not work. Replacements were ordered and installed, but the power supply was not delivered until late 2022.

System	Software	Capacity (TB)	Field System
DBBC2	DDC v107	-	9.13.2
DBBC3-6L-6H	DDC v126	-	10.1.0
Flexbuff (aka flexastro)	jive5ab 3.2.0	360	-
Flexbuff (aka flexbuff)	jive5ab 2.9.0	216	-
Flexbuff (aka flexcosmos)	jive5ab 3.1.0-dev	360	-

Table 5.4: RT40m VLBI equipment.

System	Software	Capacity (TB)	Field System
4 x RDBE-G	PFBG_3_0	-	10.1.0
4 x R2DBE	pending	-	-
Mark6	c-plane / d-plane	658	-
Mark6	jive5ab 2.9.0	-	-

Table 5.5: RT13m VLBI equipment.

Connection to the Internet is provided by RedIRIS, the Spanish National Research and Education Network (NREN). On January 2023 the upgrade to a 100 Gbps link was completed, with new network elements installed at the Observatory. However, a revision of the internal LAN is still pending to allow the VLBI equipment to take advantage of the new outside connection.

Since last year, the YNART project has been developing a VLBI correlator for the RAEGE, VGOS and EU-VGOS geodetic networks to be operated at the Yebes Observatory. The project, partly funded by the ERDF 2014-2020, has awarded a 20-month service contract to the Spanish company "Quasar Science Resources S.L." to carry out a technology study, COTS selection and design of the correlator. The next phases of the project will be the installation, commissioning and early operation of the correlator. The design phase has been completed and several public tenders have been launched for the procurement of the hardware. The equipment is expected to be delivered in the first half of 2023. In the meantime, a scaled DifX software correlator has been set up. It is currently limited to a best observation/correlation ratio of 10:1 for VGOS and EU-VGOS experiments, using the standard VGOS observing setup. We have also successfully correlated K-band Global Astrometry observations between Yebes 40m and HartRAO 26m.

Participation in National and International Research and Development Projects

In 2021, the JUMPING JIVE project, funded by the European Union's Horizon 2020 programme, came to an end. The main lines of action of the JUMPING JIVE project included actions to strengthen the sustainability of JIVE ERIC and the EVN by promoting collaborations with radio astronomy and VLBI communities in different countries, and the inclusion of new members for the expansion of the network, a task partly led by the Yebes Observatory (WP 5).

Since March 2021, the observatory has been participating in the Opticon RadioNet Pilot (ORP) project to develop seamless access to radio and optical facilities in an efficient, coordinated and forward-looking programme.

We have also joined the RADIOBLOCKS project, a new European consortium for the development of next-generation technologies for radio astronomy infrastructures, coordinated by JIVE ERIC, which will start on 1 March 2023 and has been awarded 10 Meuros by the European Commission.

Major upgrades and developments at the observatory in recent years have been funded by the European Regional Development Fund (ERDF 2014-2020) through the YNART (2020-2023) and YDALGO (2018-2023) projects, and the future YDEAS project (from June 2023), supported by EU Next Generation Fund. A European Research Council grant funded the Nanocosmos project, which equipped the 40-m RT with next-generation receivers and backends for Q- and W-band astrochemistry studies (Tercero et al. A&A 645, A37, 2021). This project was completed in 2022. The current development of the new ASTROREC K-Ka band receiver is supported by the Spanish National Plan for R&D.

5.4 Institute of Applied Astronomy, Russian Academy of Sciences, St. Petersburg, Russia

The Institute of Applied Astronomy (IAA) of Russian Academy of Sciences is the host institution of the Kvazar 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 fully steerable radio telescope (Bd, Sv and Zc), 13.2 m VGOS radio telescope (Zv, Bv and Sw) and co-located GPS/GLONASS, DORIS, and SLR systems.

In 2018 September the Ussuriysk Astrophysical Observatory on Far East was attached to IAA with all its facilities including 2 m radio telescope leading Sun service from 1954.

In 2019 the IAA in cooperation with the Institute of Geophysics and Astronomy of the Republic of Cuba (IGA) began construction of the Russian-Cuban co-located station in Cuba. The main objective of this project is to improve the accuracy of the Russian network of the co-located stations through a significant improvement in geographical distribution. For the Republic of Cuba, the construction of this station will support the national reference frame at a modern high level of accuracy through joint processing of data from the stations of the Russian and global networks.

VLBI staff

Dmitry Ivanov (director), Alexey Melnikov (PC member), Andrey Mikhailov (technical friend) and Mikhail Kharinov (VLBI friend and Scheduler).

EVN observations

In 2021 IAA observatories fully participated in all 3 EVN sessions and ten e-VLBI EVN runs. In total of 94 experiments, about 37 days of telescope time was scheduled for EVN observations on each of Bd, Sv and Zc antennas.

In 2022 IAA observatories partly participated in first EVN session and one e-VLBI EVN run. This made of 22 experiments or almost 9 days of telescope time. Since March 9, data from IAA stations are not used in joint observations.

Receivers

All RT-32 radio telescopes are fully equipped with the L (1.38-1.72 GHz), S (2.15-2.50 GHz), C (4.60-5.50 GHz), X (8.18-9.08 GHz) and K (22.02-22.52 GHz) bands receivers with LCP/RCP channels. And RT-13 radio telescopes are equipped with three-band receivers on S (2.2-2.6 GHz), X (7.0-9.5 GHz) and Ka (28-34 GHz) with LCP/RCP channels.

Backends

From 2012 February the IAA data acquisition systems R1002M is fully functional on RT-32 radio telescopes and have used on all VLBI observations, including IVS and EVN projects.

The new Multifunctional Digital Backend system (MDBE) has been developed to replace the data acquisition systems currently used on the radio telescopes of the Kvazar VLBI Network. Since September 2020 the Sw with installed MDBE participates in all regular scheduled VLBI observations in the normal mode. Later the MDBE was installed on Zv. Bv is still using previous system - BRAS (Broadband Acquisition System).

The MDBE contains up to 12 channels, or Digital Signal Processing units that capture the signals from receivers in the 2 GHz band, make required processing with them depending on the type of observation being performed, and send the result to the recording system. The MDBE is controlled from the central computer of the radio telescope and is interfaced with any RT-32 and RT-13 radio receiving systems. The total rate of the information data stream produced by the MDBE and transmitted via optical lines can reach 96 Gbit/s. MDBE surpasses the data acquisition systems and the existed backends previously used on the radio telescopes of the Kvazar VLBI Network. MDBE provides signal conversion for both broadband and narrowband registration during VLBI observations, makes it possible to conduct radar observations. The use of MDBE allows in the future abandoning separate recording systems for radiometric and spectral observations. MDBE provides observations in various modes without replacing equipment and allows improving the obtained results.

At present the MDBE is uses in test regime on Sv for domestic VLBI experiments.

Disks and e-VLBI

IAA provides 160 TB (8 TB×20) for the EVN disk pool and 80 TB (10 TB×8) for the Flexbuff for JIVE correlator.

Starting from 2019 April the IAA antennas have participated in regular EVN e-VLBI experiments. The bandwidth of communication channels in the IAA observatories is 1.5-1.7 Gbit/s what allows for e-VLBI with a data rate of 1 Gbit/s.

5.5 Jodrell Bank Observatory, UK

Jodrell Bank Observatory (JBO) performed a total of 189 regular EVN experiments during 2021-2022. Ninety-five experiments at 18/21cm, 72 at 6cm, 3 at 5cm and 19 at 1.3cm were scheduled to use Jodrell Bank's Lovell and Mk2 antennas. During this period, 114 of the EVN experiments were joint e-MERLIN projects (more than three times the previous reporting period), all of which were observed simultaneously rather than contemporaneously.

A total of 1589.0 hours of telescope time was scheduled for regular EVN observations during 2021-2022. This consisted of 480.0 hours on the Lovell telescope and 1109 hours on the Mk2 telescope. In terms of waveband this was 909.5 hours at 18/21cm, 492.5 hours at 6cm, 19.0 hours at 5cm, and 168.0 hours at 1.3cm. The total reported data loss at the telescope for 2021-2022 was 90.0 hours (5.7%), i.e. a success rate of 94.3%.

JBO also contributed 88.0 hours of observing time to out-of-session experiments (targets of opportunity) and a further 391.0 hours of observing time for 20 regular eVLBI observing sessions during 2021-2021. This makes the total contribution of JBO telescopes to the EVN in 2021-2022 equal to 2068.0 hours.

Very little has changed in the VLBI equipment setup during this reporting period. The FiLa10G continued to operate without any problems after work on badly crimped connections on the wires going from the 3.3V PSU to the terminal block. A second VSI cable was added between the DBBC2 and FiLa10G allowing the use of 'wastro' mode at 4Gbps. This was successfully tested in the C-band NME in Session III 2021.

Flexbuff1 (used for home station VLBI) had a problem in Session II 2021 which was believed at the time to be a faulty disk. However, it turned out to be a corruption of the XFS file system. Three disks were replaced as they had non-zero re-allocated sector counts which indicated that failure was imminent. Then, before Session III 2022 all 36 disks of flexbuff1 were replaced with 10TB units. Flexbuff2 (used for e-MERLIN VLBI data) has had the raid cards flashed with new firmware successfully. Thirty new 10TB HDs were purchased and they have replaced the old 2TB drives which were beginning to fail. The storage is now configured as JBOD. Due to problems encountered flashing the firmware on flexbuff3 (used for e-MERLIN VLBI data), the cards were replaced with LSI-9207-8I (the same as flexbuff1) and the storage reconfigured as JBOD. Funding was secured for another 360 TB flexbuff but this is still in construction. Funds were also secured for a petabuf VLBI storage system, to be located at JIVE, to facilitate network transfer of VLBI data from multiple e-MERLIN telescopes.

A DBBC3-2L2H unit, which increases the recording data rate to 32 Gbps and 4 GHz per IF, in line with the rest of the EVN, was ordered in February 2022. In 2022, the FS PC failed due to a graphics card problem but was eventually repaired prior to EVN Session III 2022. A replacement FS PC has been obtained and configured. However the interface to the e-MERLIN control system is being re-written, meaning that the FS interface will also need to be re-written. The new FS machine will be integrated with the DBBC3 unit but is unlikely to be operational until Session III 2023.

4G+ mobile signals were causing significant problems for L-band operations at JBO (compression and intermodulation), particularly with the Lovell Telescope, so we specified and procured band stop filters (Figure 2). These have been fitted to all telescopes and the 4G+ problem has been eliminated. A new C-band cryogenic front-end is complete and has been used for e-MERLIN observations on the Lovell Telescope. Full characterisation has yet to be done because of access restrictions to the telescope focus, but early indications are that performance is good, and we anticipate an improvement in noise and polarisation performance due to an improved OMT. We expect this front-end to be used for future VLBI observations with the Lovell Telescope. Work is nearing completion on a Lovell Telescope L/C band frequency changer. This will allow users to remotely select the operating frequency band with a changeover time of a few minutes. Currently it takes several hours to change frequency.

Remote signal monitoring systems have been installed at the Pickmere and Darnhall sites, using the towers that previously supported the microwave and L-band link dishes. A similar installation at JBO is being monitored continuously to build up a good understanding of the level of non-astronomical signals in L-band. We have successfully identified, and tracked down, illegal transmissions in the 1400 – 1427 MHz protected band.

Figure 5.6: The Lovell telescope at sunset.

Figure 5.7: 4G+ band stop filters.

5.6 Max-Planck Institut für Radioastronomie, Bonn, Germany

General status

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, and Global VLBI etc.).

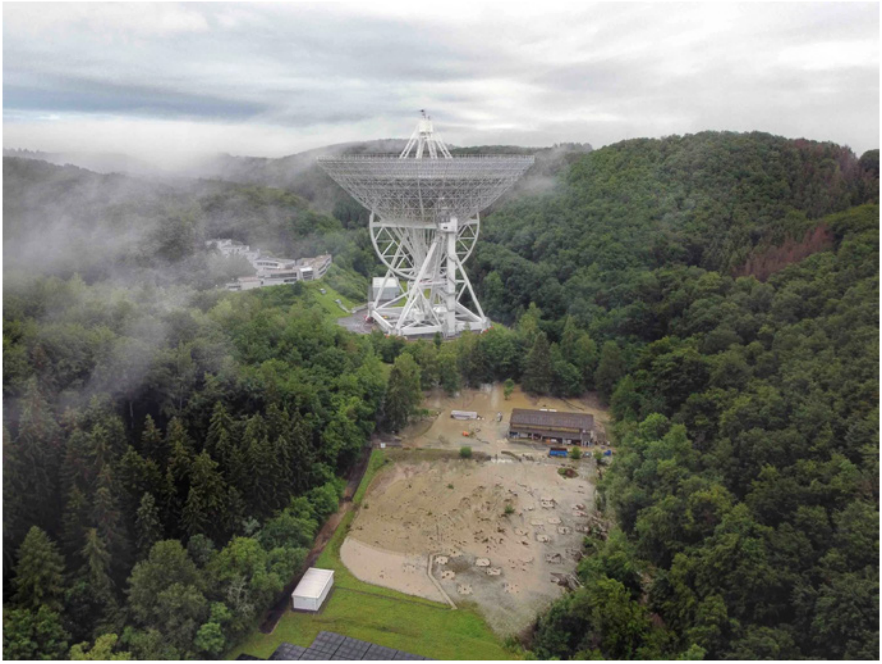

Figure 5.8: Aerial view of the Effelsberg radio observatory on the morning of July 15, 2021. The image shows in the foreground the completely flooded "low-band" part of the Effelsberg station of the European LOFAR telescope network. In the background the 100 m radio telescope and to the left the observatory building with control room (photo N. Tacken, MPIfR).

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), 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 in 2021, the operation of the observtory was not interrupted. A reduced staff ensured the operation and observations were conducted remotely. Since 2022, there have been no general shutdowns and the restrictions have only applied to individual measures, such as quarantine in the event of infection.

In summer 2021 an extreme weather situation with heavy rainfalls on July 13 and 14, 2021 caused serious flooding in the Ahr valley and neighboring regions of the Eifel, with partly devastating destruction. To a relatively small extent – compared to the neighboring valleys – the observatory was also affected. Due to its location in a valley, with the Effelsberger Bach and the Rötzelbach (normally tiny creeks), there was also massive flooding here. Part of the ground was overflowed, including the access road and the storage building south of the telescope. A container with technical equipment was washed away and some low-band antennas of the LOFAR field were destroyed (see also photo in Fig. 5.8). Fortunately, no-one was harmed during this event. The institute, however, was without electricity, water and telephone for a few days. Thanks to the energetic efforts of many colleagues from Effelsberg and Bonn, the situation could soon be eased. Astronomical observations with the 100 m telescope could also be re-started after just five days.

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 390 TB of disk space in a raid configuration and are mounted as flexbuff mount points. One slot is currently kept for modules that can be shipped.

Since the e-transfer of data requires a similar storage capacity at the correlator side as well, the MPIfR has provided a 500 TB raid to JIVE for the storage of Effelsberg EVN data. This is usually enough to cover 1.5 EVN disk recording sessions.

Technical Developments

The DBBC3 is currently being commissioned for the regular use for all Effelsberg VLBI observations. In principle it is fully compatible with both existing systems, the DBBC2 and the RDBEs, and can therefore replace both. However, before this is finalized tests within the EVN, GMVA and together with the VLBA have to be performed to ensure that the correlation and calibration of data is as good as before. Also the operators have to be trained to work with the new backend.

In parallel the direct digitalization of the RF signals from the receivers in Effelsberg is progressing. The same digitizers that are used for Meerkat digitize up to 3 GHz at the receiver and the full band at 10 to 12 bit is streamed over 100 Gbps Ethernet using the SPEAD protocol to the software backend. A software backend on a GPU cluster is being developed that currently supports single dish continuum and spectroscopy observations in full Stokes and pulsar observations. A first implementation of a tunable digital down conversion algorithm that writes out channelized VLBI VDIF data at data rates of up to 2 Gbps is currently being tested. After the verification with local zero-baseline tests, tests with real VLBI observations are planned. There are currently three receivers that provide the digitized signals, the 21cm (1.29 to 1.51 GHz), a prime focus wide band receiver at 1.3 to 6 GHz, and a secondary focus receiver from 4 to 9.3 GHz that cover some of our typical VLBI frequency bands. Once the system is established it is planned to digitize more and more of the Effelsberg receivers over the next years.

A larger project to upgrade the main axis control systems and encoders in azimuth and elevation has started. The contract with a company specialized on radio telescopes has been signed and the detailed design study has started. The actual change of the hardware requires an observational stop of several weeks and is currently foreseen for summer 2024. We will try to minimize the downtimes during the regular EVN sessions and the planned eVLBI dates.

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

Summary of observations in 2021 and 2022

The outline of the VLBI and e-VLBI observations performed with a 32-m Toruń antenna is shown in Table 5.6. The total number of hours of the VLBI and the e-VLBI observations are 1071 and 1233 in 2021 and 2022, respectively. Toruń antenna participated with many hours of observations in the PRECISE-VLBI project.

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Total
2021													
EVN	0	59	171	0	187	80	0	0	0	212	53	0	762
e-EVN	28	28	28	28	28	28	0	9	48	28	28	28	309
2022													
EVN	0	58	229	0	249	249	0	0	0	200	133	0	953
e-EVN	28	28	28	28	28	28	0	0	28	28	28	28	280 309

Table 5.6: Summary of the VLBI and e-VLBI observations with the 32-m Torun antenna in 2021 and 2022. Numbers are given in hours.

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
- The DBBC firmware version in "tunable" mode is 1.07.

Changes/Upgrades Made to Hardware

The station has 10Gbit/s connectivity via PIONIER/GEANT network. Currently, we can use IF bandwidth up to 2GHz on C/M(6-8GHz), X(8-16GHz) and K(20-25GHz) receivers. The X-band receiver was completed in 2021 and successfully passed the first fringe test experiment at 8 GHz. An additional 336 TB of flexbuff disk space was installed in 2021.

Personnel & Personnel Changes

Mr Jarosław Kłuś joined the team in January 2021. The current technical staff team is as follows:

- MSc Roman Feiler - station timing control, digital backend, computer network, telescope control system;
- 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;
- Mr Jarosław Kłuś - software and hardware development and maintenance;
- MSc Rafal Sarniak - software development, telescope operators coordination and scheduling;
- MSc Wojciech Szymański - station timing control, RF signal distribution, hardware development and maintenance;
- dr Pawel Wolak - station timing control, receivers and antenna calibration, observation scheduling.

Financial support

Toruń antenna was financially supported by the infrastructure grants from the Polish Ministry of Education and Science: 50/E-337/SPUB/SP/2019 (2019 – 2021, 900 kEUR) SPUB/SP/526638/2022 (2022 – 2024, 400 kEUR).

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

Operations:

The Onsala Space Observatory (OSO) telescopes continued during 2021 and 2022 to play a full role within the global observing program for astronomical VLBI. In total 9 astronomical VLBI-sessions (6 EVN sessions and 4 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 43 and 39 geodetic VLBI experiments in 2021 and 2022, respectively, as part of the observing program of the International VLBI Service for Geodesy and Astrometry (IVS). The VGOS telescopes have been used for 54 and 44 geodetic VLBI experiments in 2021 and 2022, respectively.

Technical R&D:

During the reporting period, the Onsala station has installed the 3rd generation digital base-band converter (DBBC3) developed by HAT-Lab (https://www.hat-lab.cloud). This new backend enables the Onsala 25 and 20 m telescopes to operate astronomical VLBI observations with a bandwidth up to 4 GHz per polarization in the upcoming years.

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 and other major facilities around the globe. 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, 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 was used for this project on 49 and 40 days in 2021 and 2022, respectively. In addition to that, OSO has been monitoring repeating FRBs and magnetars as potential galactic sources of FRBs. This work is done in collaboration with Westerbork in the Netherlands and Torún in Poland. In total, the 25 m telescope was used for this project on 110 and 58 days in 2021 and 2022, respectively.

5.9 Shanghai Astronomical Observatory, Chinese Academy of Sciences, P.R. China

Operations

The Shanghai Astronomical Observatory (SHAO) telescopes conduct astrophysics, astrometry, geodesy, and space sciences researches with both single dish and VLBI observations during 2021 and 2022. Besides of regular single dish observations on pulsars, spectral line and continuum sources, the Tianma 65 m telescope is a key member of the VLBI tracking system and spends a large amount of time on the Chinese Space Exploration Projects, including the testing before the launch of the Chang'E and Tianwen satellites, and the tracking campaign after the launching. A total of 6 astronomical VLBI-sessions (5 EVN sessions and 1 global mm-VLBI session) were conducted. Tianma 65 m is also regularly involved in e-VLBI sessions (typically ten 24 hour sessions

Figure 5.9: Maintenance of the TianMa 65 m radio telescope: top left, replacing screw spacer; top right, replacing of gear oil; bottom: checking grease status

per year) within the EVN. In addition, the Tianma 65 m telescope has been used for 1 and 3 geodetic VLBI experiments in 2021 and 2022, respectively, as part of the International VLBI Service for Geodesy and Astrometry (IVS). The Sheshan 25 m telescope has been used for 74 and 36 geodetic VLBI experiments in 2021 and 2022, respectively.

Figure 5.10: Maintenance of the Sheshan 25 m radio telescope: (top) structure reinforcement; (bottom) replacement of supporting bars.

East Asia VLBI Network (EAVN) mainly observes at C (6.7GHz), K (22 GHz) and Q (43GHz) bands at a recording rate of 1Gbps, while the 4Gbps recording mode is under testing. In 2021-2022, Tianma 65 m provide about 200 hour machine time per semester. All the observational data are transferred to the correlator in KASI through the high-speed internet.

Sheshan 25 m took part in the EVN observations in 2021 session III due to the Tianma 65 m antenna maintenance. Tianma 65m missed some nighttime observations with L-band when the observations started in 2022 session II due to the impact of COVID-19 then. Unfortunately, we also missed a fraction of some observations due to the Chinese Lunar and Mars missions.

Antenna Maintenance with TIANMA 65m & SHESHAN 25m

In 2022, the maintenance of the TianMa 65 m radio telescope was focused on replacing gear oil, replacing screw spacers and checking grease status of adjusting mechanism of subreflector surface, which provides guarantee for stable operation of telescope (see Fig. 5.9).

Sheshan 25 m radio telescope was built in 1986 and it faces the problems of load-carrying capacity of components weakening and steel corrosion at present. From September to November 2022, we brushed paint and reinforced structure for this telescope, which ensure the safety and stability of the structure and prolong the service life (see Fig. 5.10).

Prospects

For the session of 2023, TianMa 65 will participate in L, C, S/X, K and Q bands observations of EVN.

5.10 South African Radio Astronomy Observatory (Hartebeesthoek site)

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) of South Africa. The Hartebeesthoek site is located 65 km northwest of Johannesburg, just inside the provincial boundary of Gauteng.

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 combined simultaneous 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 single Flexbuff systems, with the latter now being used for most disk-based operations. A second Flexbuff system will be added to the 26-m shortly.

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 COVID-19 pandemic continued to have had little to no impact on VLBI operations thanks to advances in remote operation capabilities and in particular the use of Flexbuffs in place of disk-packs for recording.

However no new receivers have been added over this period, and only routine maintenance has been performed on existing receivers (in part due to budget shortfalls but also due to questions about the ongoing viability of the 26-m). However there has been some progress on implementation of continuous calibration, with the L-band, S-band and C-band receivers now being suitably equipped.

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. Construction of a fully VGOS-capable receiver chain (the associated backend equipment namely DBBC3 terminal and Mark6 recorder baing already in hand) is currently in progress (at Yebes) with delivery expected towards the end of 2023.

5.11 Ventspils International Radio Astronomy Centre, Ventspils, Latvia

Ventspils International Radio Astronomy Centre (VIRAC) of Ventspils University of Applied Sciences (VUAS) was established in 1994 with the aim to develop the research activities in radio astronomy, astrophysics and space sciences. The most important instrumental base for the centre comprised two fully steerable parabolic antennas, RT-16 and RT-32 (i.e. with the mirror diameter of 16 m and 32 m) and LOFAR-LATVIA station. The intensive reconstruction and instrumental refurbishment carried out in 2014 – 2019 made it possible to use radio telescopes for the international scale fundamental and applied research in the field of radio astronomy. During the renovation, radio telescopes were instrumented with dual channel (RCP and LCP) cryogenic broad-band receivers with frequency coverage of 4.5 – 8.8 GHz and instantaneous bandwidth of approx. 1200 MHz. Receivers are cryogenically cooled to 14 Kelvin which nominally achieves system noise temperatures of 30 to 50 Kelvin throughout the whole bandwidth. A secondary receiver is available at RT-32 for observations at 1.40 to 1.72 GHz. It is an uncooled receiver with dual (RCP and LCP) polarization channels and achieves system temperatures of 60 to 100 K. Each telescope has VLBI equipment available, which includes Active Hydrogen masers, DBBC/FlexBuff data registration back-ends and 10 Gbit optical fibre network. Maximum azimuth and elevation tracking velocities are up to 5 degrees/s with RMS tracking accuracies 4 arcsec allowing to track Near Earth satellites. One of the main scientific objectives for the VIRAC radio astronomical observatory is VLBI observations in centimetre and meter wavelengths in collaboration with the global VLBI networks, including EVN, LOFAR, IVS and others. Since October 2015 VIRAC radio telescopes have regularly taken part in international VLBI sessions.

Irbene Ir – RT-32 radio telescope

In March 2022 VIRAC started major improvements of radio telescope RT-32 and the telescope was not available for observations until end of 2022. For the period May 2021 - February 2022 RT-32 took part in all EVN sessions and e-VLBI observations. During some experiments there were minor technical problems due to weather conditions and small faults, but overall participation was successful.

Irbene Ib – RT-16 radio telescope

Since March 2022 RT-16 radio telescope serves as a main instrument for VLBI and e-VLBI observations at C/M/X bands until Summer 2023. Should be noted that only C/M/X receiver is available on this telescope. The L band receiver is not suitable for VLBI observations.

Figure 5.11: Left panel: Irbene Ir - RT-32 radio telescope; middle panel: Irbene Ib - RT-16 radio telescope; right: New vertex cabin mounted at the radio telescope RT-32 secondary focus.

Developments

In March 2022 radio telescope RT-32 was stopped for modernization. Currently, a new vertex room is under development. Enhanced vertex room, located in the secondary focus, will allow simultaneous installation of several cryogenic receivers in offset positions. It is planned to develop a new cryogenic L-S band receiver with horn (design of horn and dewar is completed, we are waiting for funds for CNC works, receiver will be ready approximately 2023 Q4). In the new vertex room, the space for future developments will be allocated, possibly for a 22 GHz cryogenic receiver. During vertex room modernization, it is also planned to equip the secondary mirror with a movable automatic positioning system. In the future, it is planned to align and improve accuracy of the main mirror (Q2 2023).

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, 10 GbE.

If there is no space left on Flexbuffs, older recordings can be transferred to the LOFAR data server (39 TB HDD, up to 2 PB magnetic tapes) and kept there until transfer to JIVE is done.

Problems

Both "Kvarz" active hydrogen masers H-Masers are out of order. Due to war in Ukraine and sanctions to the Russian Federation, currently active hydrogen maser repair is completely not possible. The new "T4Science" active hydrogen maser ordered by VIRAC is delivered in Q1 2023 and currently installed in RT-16 (Ib).

5.12 Xinjiang Astronomical Observatory, Chinese Academy of Sciences, P. R. China NANSHAN STATION (Ur)

Technical Developments

In the past two years, three new wideband receivers working at Q-band, C-band and L-band respectively, were designed and implemented by the engineer team, and have been equipped chronologically in the radio cabin of the Nanshan 26-m Radio Telescope (NSRT). The new Q-band receiver, covering frequency of 30-50 GHz, joined fringe test observations with the EVN and EAVN from late 2021 and got fringes successfully (Fig. 5.12). Meanwhile, the new C-band receiver, covering frequency of 4-8 GHz, also joined fringe test observations with the EAVN and successfully got 6.7 GHz maser fringes. It is expected that the new Q- and C-band receivers could formally service the VLBI community from late 2023. The new L-band receiver, covering frequency of 1-2 GHz, was just equipped on the telescope in late 2022 (Fig. 5.13), and now is conducting single-dish commissioning observations.

In addition, in order to mitigate the RFI mainly generated by on-site digital facilities, a walk-in electromagnetic shielding box was built under the telescope base in the summer of 2022. All the digital facilities originally working in the observation room were dismantled and moved into the new shielding box. Now all the facilities are remounted totally and working normally in the shielding box (Fig. 5.14). The shielding effectiveness of the box is being evaluated in detail.

VLBI terminal Status

Currently, the VLBI terminal system at Nanshan station consists of one DBBC2, one MK5B+, one MK6, one Flexbuff and four CDAS2. Among them, the DBBC2 and MK5B+ are mainly used for 2 Gbps international joint observations of EVN, IVS, EAVN, etc. The CDAS2 is mainly employed to Chinese VLBI observations served for space missions. The MK6 and Flexbuff are now under on-site testing, and newly purchased DBBC3 have arrived at Nanshan station too. In addition, we are planning to purchase another three MK6 in 2023. Based on these new terminal devices, it is expected that Ur will be able to join normally 4 Gbps VLBI observations by the end of 2023.

Scheduled VLBI observations

In 2021, there were 487 VLBI experiments conducted by the Nanshan 26-meter Radio Telescope (NSRT) serving under the EVN, IVS, EAVN networks and domestic joint observations for space missions, with a total effective observing time of about 2578 hours. Among these observations, there were 105 EVN runs with the total time of about 712

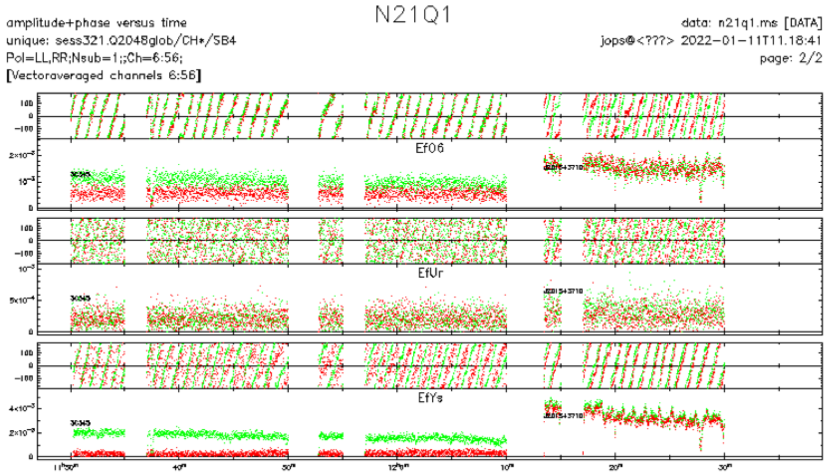

Figure 5.12: The cross correlation amplitude and phase between Ef and Ur at 43 GHz showing in the middle panel.

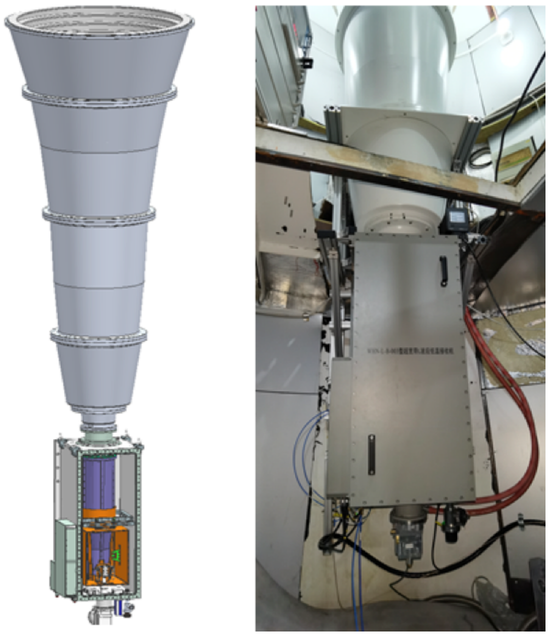

Figure 5.13: The simulated picture (left) and installation status (right) of the new L-band receiver.

Figure 5.14: The digital backend systems for VLBI and single dish operations working in the walk-in electromagnetic shielding box under the telescope base.

Name	Position	Email
Hua Zhang	VLBI friend & terminal engineer	zhangh@xao.ac.cn
Hao Yan	Technical friend & receiver engineer	yanhao@xao.ac.cn
Guanghui Li	VLBI terminal engineer	ligh@xao.ac.cn
Jianping Yuan	Scheduler	yuanjp@xao.ac.cn
Lang Cui	Head of Nanshan station & VLBI chief	cuilang@xao.ac.cn

Table 5.7: The new VLBI operation team at the Nanshan station (Ur).

hours, including 215 hours for the EVN-FRB program.

In 2022, 276 VLBI experiments were conducted for all the VLBI networks mentioned above and the total effective observing time is about 1674 hours. Of which, about one half were spent serving for EVN regular observations and EVN-FRB runs.

Personnel update

The VLBI operation team of the Nanshan station (Ur) was updated in May 2022. The new personnel allocations are listed in Table 5.7.

6. EVN observatory reports, associated members

6.1 Arecibo Observatory

12m Telescope at the Arecibo Observatory

The AO hosts a fully steerable 12m diameter dish antenna. During the time covered by this report, we worked toward the replacement of the existing room temperature receiver of the 12m telescope with a wideband (2.5 to 14 GHz), cryogenic receiver. The development of the cryogenic system was funded by the National Science Foundation (NSF), USA, through the "Restoration of Scientific Capabilities at the Arecibo Observatory after the impact of Hurricane Maria" award (NSF Award Number:1930772). The cryogenic receiver was designed and built using a slightly modified version of the Quadruple-Ridged Flared Horn (QRHF) developed by [0]. The feed and the cryostat were developed by CryoElec, LLC, Arizona, in consultation with AO engineers and Scientists. It was then installed on the telescope along with an upgraded IF system in May 2023. After adjustment of the feed focal position, we obtained a system temperature at zenith of about 40 K at 3.1 and 8.6 GHz and zenith gains of 0.025 K/Jy and 0.018 K/Jy near 3.1 GHz and 8.6 GHz respectively. The telescope was then used for a set of commissioning and shared risk observations between mid June and early August 2023. Fig. 6.1 shows some of the results from the commissioning observations. Further details of the system and its performance are available in Anish Roshi et al. [0].

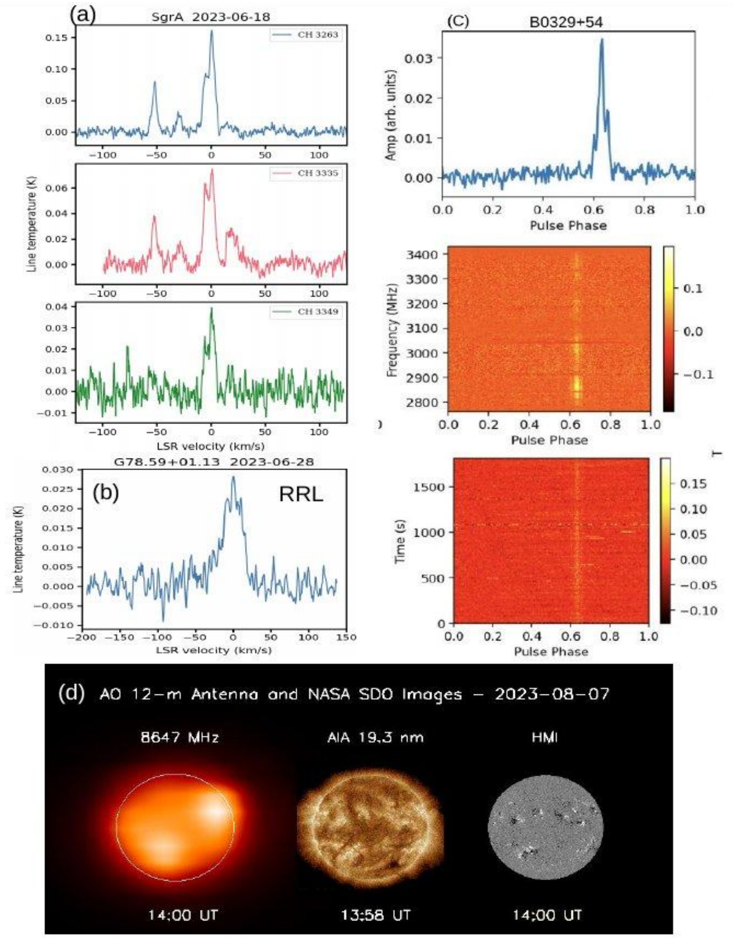

Figure 6.1: (a) The 3.263, 3.335, 3.349 GHz transitions of CH (Methylidyne) radical toward the Galactic center. (b) Hydrogen radio recombination line (RRL) observed toward Cygnus X region (G78.59+1.13) near 8.6 GHz. (c) Pulsar B0329+54 observed near 3.1 GHz. The average pulse profile is shown on the top, frequency vs pulse phase in the middle and pulse amplitudes vs pulse phase in the bottom. (d) Image of the Sun (left) at 8647 MHz made on 07 August 2023 with the cryogenic, wideband receiver of the 12m telescope along with near-simultaneous EUV image of the Sun at 19.3 nm (middle) and the photospheric magnetogram (right). (Figure taken from [0]).

6.2 Geodetic Observatory Wettzell - 20m Radio Telescope and Twin Radio Telescope

The Geodetic Observatory Wettzell, Germany, mainly contributed very successfully to the IVS observing program and to some observations of the EVN in the years 2021 and 2022. Meanwhile, Wettzell supports different fields of the IVS within program coordination, observation and correlation. Technical changes, developments, improvements, and upgrades had been made to extend and increase the reliability of the entire VLBI observing system. All telescopes were regularly in use.

Figure 6.2: Geodetic observatory Wettzell with the 20m radio telescope in the front and the TWIN telescope in the background (reference: BKG web page).

General information

The Geodetic Observatory Wettzell (GOW; see Fig. 6.2) is jointly operated by the Federal Agency for Cartography and Geodesy (Bundesamt für Kartographie und Geodäsie, BKG) and the Research Facility Satellite Geodesy (Forschungseinrichtung Satellitengeodäsie, FESG) of the Technical University of Munich (TUM). Parts of the observatory are now part of the critical infrastructure of Germany for navigation and geodata. The 20m Radio Telescope in Wettzell (RTW) has been an essential component of the IVS since 1983 and produced the longest VLBI-data time series worldwide. The 13.2m Twin radio Telescope Wettzell North (TTW1, Wn) also produced S/X-data as a regular network station and was fitted with a VGOS receiver in late 2022. 13.2m Twin radio Telescope Wettzell South (TTW1, Ws) participates in almost all VGOS and EU-VGOS sessions and is part of the VGOS-Intensive program. Wettzell observatory also became an official correlation site of the IVS. It is also part of the DACH operation center and schedules T2, INT2, INT3, OHIGGINS, and other IVS sessions. Using the Field System extension for remote control and monitoring, all sessions are operated completely unattended. An official on-call service was established in January 2021 to manage appearing issues outside of official business hours. All VLBI data is transferred with e-VLBI techniques to Bonn, Tsukuba, Haystack, Washington, Socorro, and JIVE ERIC, using TSUNAMI or jive5ab on a 5 Gbit/s connection. Bonn and Washington correlators fetch sessions from Flexbuff systems at the Wettzell observatory.

In addition to the VLBI, an ILRS laser ranging system, several IGS GNSS permanent stations, a large laser gyroscope G (ring laser) and the corresponding local techniques, e.g. time and frequency, meteorology and super conducting gravity meters, etc., are operated. Wettzell also runs a DORIS beacon as a complete geodetic core site. A new radio telescope for solar flux observations is almost finally constructed. Activities to monitor atmospheric parameters use a continuously growing number of equipment, including a Nubiscope, and weather balloons. A water vapour radiometer permanently scans the zenith position. A project with the company Menlo Systems as external contractor improves the timing system with compensated fiber-optic transfers and a frequency comb which is under test in parallel to the existing timing distribution. New DFG Research Unit "Clock Metrology: A Novel Approach to TIME in Geodesy" will further investigate and improve time as a geodetic observable. The project is funded for four years.

The GOW is also responsible for the AGGO system in La Plata, Argentina, and the German Antarctic Receiving Station (GARS) O'Higgins on the Antarctic Peninsula (see separate reports).

Staff

The staff of the GOW consists of 42 members in total (plus student operators) mainly on permanent but also on fixed-term contracts to do research, operations, maintenance, and repairs, or to improve and develop all systems of the GOW. The staff operating VLBI is summarized in Table 6.1.

Expansion project for the GOW

German Federal Ministry of the Interior (BMI) and BKG have agreed to a four-year project to expand the infrastructure and operations of the Geodetic Observatory Wettzell in 2018 which is in the final period. The main objective of this project is to contribute to the 17 sustainable development goals of the United Nations (UN), such as promotion of high-tech-facilities in rural areas in terms of employment and education. Furthermore, Germany intends to deepen its role of supporting European's satellite navigation system "Galileo", which will also be a major task of the observatory in Wettzell in the future.

To meet these goals, the expansion-project has the following three topics:

- Further development of the existing geodetic infrastructure (VLBI,

Name	Affiliation	Function	Special tasks
Torben Schüler	BKG	head of the GOW	
Christian Plötz	BKG	BKG head of VLBI ressort, correlator chief	
Alexander Neidhardt	FESG	TUM head of the microwave group, VLBI-operation chief	
Daniel Amberger	BKG	RF-eng., solar flux telescope	
Ewald Bielmeier	FESG	technician	
Martin Brandl	FESG	mechatronic engineer	
Elena Dembianny	FESG	physicist (quitting Feb. 2021)	
Florian Kroner	FESG	RF-engineer (starting Nov. 2021)	
Gerhard Kronschnabl	BKG	electronic engineer (chief engineer TTW)	
Willi Probst	FESG/ BKG	Correlation, quality control	
Walter Schwarz	BKG	electronic engineer	WVR
Michael Seegerer	BKG	IT, correlation, quality control	O'Higgins
Simon Seidl	FESG	IT-/electronic eng. (starting Nov. 2021)	
Robert Wildenauer	BKG	IT-admin, correlation	

Table 6.1: Staff - members of RTW.

SLR, GNSS): VLBI is now "ISO 9000"-certified, a Domestic Coordination Office (DCO) plans and evaluates all observations, an extended quality management is established which offers weekly feedback about performance, and expanded live views show system parameters in real-time.

- Establishment of new systems: The construction phase Solar-Flux telescope is finished and the final testing has started, the Wettzell correlator became an IVS component and is regularly operated, the Internet data rate is extended to two times 5 Gbit/s, and magnetometers etc. are installed to support space weather monitoring.
- Creation of a center of excellence for space geodesy: Contracts with the district administration were signed to offer official school labs, tours are offered, and public relation and outreach is expanded.

Wettzell correlator

Originally planned for domestic sessions and quality control, the new DiFX correlation facility started operation in January 2021. The correlator increases the efficiency and real-time capabilities for VLBI sessions, but can also be used to support Galileo (e.g. EOPs) for time-critical requests. Meanwhile, the facility is an official component of the IVS doing regular operations, especially for the VGOS network. Technically, it is a Dell HPC Cluster with 24 compute nodes having 48 Intel® Xeon® CPUs each with 12 cores, so that 576 cores can be used in total. The storage started with a volume of 834 TB. The extension to 2.8 PB is ongoing and will be done beginning of 2023. The software used is DiFX 2.6.1 and 2.5.4 with HOPS (Haystack Observatory Postprocessing System).

Legacy systems (S/X-bands)

The 20m RTW has been supporting geodetic VLBI activities of the IVS and partly other partners, such as the EVN, for over 40 years now. The RTW did just one session (ed045g) for the EVN in the years 2021/2022 while usually up to 10 sessions are operated. The telescope is still in a very good and stable state supporting legacy S-/X-observations. The main priority was laid to the participation in all daily 1h INTENSIVE-sessions (INT/K/Q) in order to determine UT1-UTC. The antenna supported all main IVS 24h sessions and is still one of the main components of the IVS.

Operation hours in the reporting period compared to the other telescopes are plotted in Fig. 6.3. Sessions operated by RTW in the year 2021 and 2022 are in Fig. 6.4.

All sessions are recorded on local Flexbuff servers with a volume of 281 TB plus 72 TB. It is connected to the correlator head node, so that the complete volume of the correlator storage can be used. It is also the connection point for e-Tranfers. Monthly maintenance days were

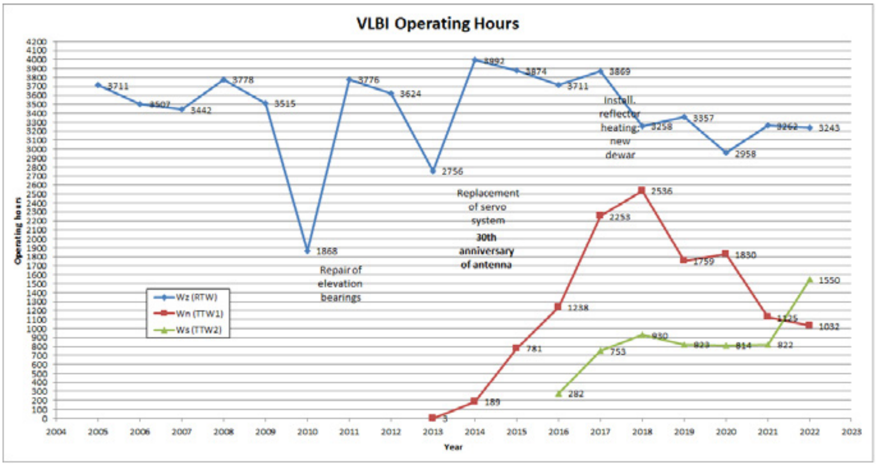

Figure 6.3: Annual operation hours of the Wettzell antennas since 2005.

scheduled to give enough time to maintain the system. The NASA Field System version is 9.13.2, but new FS-PCs are bought where the FSL10 will be installed on a 64-bit operating system. The DBBC2 at the legacy system uses DDC firmware v105 1 for IVS and v107 for EVN sessions and is connected to a FILA10G to stream data over a 10 Gbit/s transfer network directly to a Flexbuff server in the TWIN operation building.

A given oil leakage in two elevation gears was fixed. RF-over-fiber signal transfer were tested and are ready for installation, so that the complete back-end, clock reference connection, and control system can be moved to the main operation room in the TWIN building. Studies were done, to evaluate the use of an L-band antenna in an offset-cassegrain optic. A problem is, that the coldhead model 22 of CTI/Brooks is not supported any more. Therefore, a new cryo-system must be planned. Currently, refurbished models are in use. But the quality is poor, so that longer maintenance time periods or VLBI operations with a warm receiver had to be accepted.

The northern antenna Wn of the TWIN Telescope Wettzell (13.2m Twin Telescope Wettzell North (TTW1, Wn), also see following section) is equipped, with an S/X/Ka receiving system to also support the standard S/X sessions of the IVS. It supported the same or replaced sessions of the 20m antenna. The northern antenna was the first available antenna supporting fast slewing modes in the IVS and uses a DBBC2 (firmware DDC v105 1) in combination with a Mark5B+. Its performance can be found in Fig. 6.3 and 6.4. It suffered from broken bands in the DBBC2 end of 2022. It is controlled with the NASA Field System version 9.13.2.

The performance of Wn suffered from a critical failure of the azimuth encoder of the company BEI Inc., which was not able to offer economical repairs after more than 10 years of use. Because both TWIN antennas showed the same failure in a very tight timespan and because only one replacement set was available on location, the decision was made to first repair the VGOS system Ws. This caused a complete shutdown of the Wn antenna from July 2021 to December 2021.

A complete replacement with Heidenhain encoders and suitable mechanical fitting was done in May 2022. Besides this critical issue, failing UPS in the system and in the control room caused more instabilities than usual. Defective touch panels in the controlling system of the antenna had to be replaced in addition.

VGOS systems

The Twin Telescope Wettzell project is Wettzell's implementation of a complete VGOS conformity. To support a complete VGOS functionality, Wn antenna gets the QRFH feed, a new receiver front-end, and a DBBC3/Flexbuff backend. The rebuilding started end of November 2022 and should be available in the first half of the year 2023.

The southern antenna Ws of the twin telescope (13.2m Twin Tele-

VLBI Session Distribution:
2021

Session	Wz	Wn	Ws	Oh	Ag	Subtotal
GOW	43	28	13	1	32	117
VG2			4			4
VGOS			151			151
IN1	240					240
IN2	93					93
IN3	43	23				66
IVS-R1	42	21			27	90
IVS-R4	47	18			2	67
IVS-T2	7	3		7	2	19
IVS-OHG				6	2	8
IVS-CRD				5	4	9
VLBA	6					6
R&D	10					10
Total	531	93	168	19	69	**880**

EVN sessions:
ed045g (13/03): 1h

VLBI Session Distribution:
2022

Session	Wz	Wn	Ws	Oh	Ag	Subtotal
GOW	15	8	54		7	84
VG2			70			70
VGOS			240			240
IN1	242	25				267
IN2	102					102
IN3	34	23				57
IVS-R1	47	16			30	93
IVS-R4	45	20				65
IVS-T2	7	4		5	2	18
IVS-OHG				6	4	10
IVS-CRD				4	5	9
VLBA	6					6
R&D	10		1			11
UNKNOWN	66		4			70
Total	574	96	369	15	48	**1102**

EVN sessions:
-

Figure 6.4: Session statistics of the year 2021 and 2022 (reference: DCO Levika software).

scope Wettzell South (TTW2, Ws)) is Wettzell's first VGOS compliant antenna using a broadband feed (Elevenfeed). It uses a tunable updown converter, two DBBC2, and a Mark6 to record 4 bands in both polarizations. Ws uses the VGOS branch of the NASA Field System version 9.12.7. Ws is a regular part of the IVS VGOS network doing bi-weekly and partly weekly 24h observations. It is also involved in the regular 1h VGOS intensives. Its performance can be found in Fig. 6.3 and 6.4.

Two weak and later defective LNAs in the Elevenfeed reduced the quality of the antenna in May 2022. A first maintenance in June/July 2022 was not successful. Therefore, there was a complete destruction of the two LNAs in November 2022, so that VGOS operations had to be stopped. The cause of the destruction was a melting isolation of the supporting cryogenic cable inside the dewar. A problem is, that there is no support anymore by Omnisys and that the construction drawings and line plans are not available. Another issue was the failing BEI encoder, already described for the Wn antenna. A complete replacement with Heidenhain encoders and suitable mechanical fitting was done in May 2022. UPS failures also brought instabilities.

The plan is to bring the antenna back in the early months of 2023.

Other VLBI-relevant activities

Several activities supported VLBI. In April 2021, the backbone network of the observatory was renewed with a 10 Gbit/s fiber infrastructure. This allows data streams between different Flexbuffs and correlator facilities of the observatory. The external connection was upgraded to two times 5 GBit/s, where one line is the main connection point and the other is an equivalent backup.

A photogrammetric survey was done at the 20m legacy and at the VGOS antenna using overflights with an UAV. The project was led by the Frankfurt University of Applied Sciences and the Bochum University of Applied Sciences. The goal was to derive a ray tracing based delay model for compensating gravitational deformations of VLBI radio telescopes [0].

In November 2021, the Technical University of Munich did laser scanner observations with an automated scanner system mounted in the quadrupod of the 20m radio telescope. The goal was a 3D deformation analysis [0].

Additionally, local surveys were carried out at the TWIN telescopes in October 2021. A big issue was given due to an almost complete outage of the Internet access from January 28th to April 18th, 2022. It caused manual movements of VLBI modules to dedicated Mark6 systems with a separate Internet connection. Therefore, it was necessary to establish shifts again doing the data management for that time period.

Another issue is the situation with the hydrogen masers. Contracts ended with T4Science which was additionally sold to Orolia. Essential components of the masers are not available anymore, so that spare parts cannot be obtained. Therefore, high efforts were forced to repair EFOS-18 and EFOS-60 in September 2022 to have functional systems again. EFOS-39 was also revised but a failure in the beam stabilizer came up which is not yet repaired, so that it is switched off.

The use of ZABBIX as monitoring and alerting system was extended. Meanwhile, it is an essential part supporting unattended observations. In combination with this local service, the IVS Seamless Auxilliary Data Archive (SADA) was established which collects real-time data of different telescopes. The equivalent EVN monitor is a result of the Jumping JIVE project funded by the Horizon 2020 Framework Programme of the EU. The project ended in the year 2021.

Future plans

Dedicated plans for the next reporting period are:

- Establishing of a complete VGOS TWIN telescope with two VGOS receivers and and additional possibilities for S/X using a hybrid

- Replacement of the frontend at the 20m radio telescope because of missing coldhead support
- Replacing masers by new systems with available components and maintenance
- Installation of an L-band offset system at the 20m radio telescope
- Use of RF-over-Fiber for the 20m radio telescope and centralizing the backends
- Upgrade of the gears at the 20m radio telescope
- Extending routine correlation and post-processing
- Upgrade of the Internet connection to 2x 10 Gbit/s and connection of the HPC storage with same speed
- Completely change to DBBC3s at all telescopes
- Test of time and frequency distribution over compensated fiber
- Regular cleaning of the radio telesopes

6.3 Korea Astronomy and Space Science Institute, Korean VLBI Network, South Korea

The Korean VLBI Network (KVN: http://kvn.kasi.re.kr) consists of three 21 m radio telescopes installed in Seoul, Ulsan, and Jeju Island with a unique characteristics of a simultaneous 4-channel (22/43/86/129 GHz) receiving system. Maximum up to 32 Gbps recording rate is supported in particular for simultaneous multi-frequency VLBI observations. For a general status of KVN, please refer to the KVN status report (https://radio.kasi.re.kr/status_report.php) which has been significantly updated (e.g., gain curve, beam size, efficiency etc).

In general, KVN supports both VLBI and single dish observations with 3000 hours for VLBI and ∼900 hours for single dish observations annually. Among those VLBI time, ∼30% of KVN observing time is allocated to the East Asian VLBI Network (EAVN: http://eavn.kasi.re.kr) and about ∼60% of it is used for KVN only. KVN also participated in the European VLBI Network (EVN) and Global Millimeter VLBI Array (GMVA) sessions regularly with ∼10% of telescope time. We call for observing proposals of KVN and EAVN twice a year (deadline: June 1 and November 1). In 2021-2022, KVN supported a total of 23 EVN observations at K and Q bands.

Three active hydrogen masers (model: CH1-75A) at KVN were introduced from the Russian Kvarz company in 2007. In June 2202, the hydrogen maser (H-maser) at KVN Ulsan station failed due to the hydrogen depletion. A replacement was installed at KVN Ulsan and we are in process to purchase a new H-maser.

In 2021, the existing MOU on scientific and technical collaboration for the EAVN was expanded to include seven organizations (Korea Astronomy and Space Science Institute, National Astronomical Observatory of Japan, Shanghai Astronomical Observatory, Xinjiang Astronomical Observatory, Yunnan Observatory,. National Geographic Information Institute, and National Astronomical Research Institute of

Figure 6.5: The three KVN dishes.

Figure 6.6: Blueprint of KVN SNU Pyeongchang Radio Observatory

Figure 6.7: The frist 230 GHz performance test at KVN Yonsei radio telescope (Left: cartridge type 230 GHz receiver, Middle: installation, Right: 22/43/86/230 GHz configuration)

Thailand) from four countries (S. Korea, Japan, China and Thailand).

Extended KVN Project (E-KVN)

The extended KVN project – building one more KVN telescope – is going smoothly, after signing the MOA between Seoul National University and KASI on the construction and operation of the new telescope in 2020 (see Fig. 6.6). 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. Expected antenna efficiency at 230 GHz is about 30%. Receiver and quasi optical systems are under development to support five radio frequency bands (18-26, 35-50, 86-116, 125-175, 210-275 GHz) observation. The foundation work for the telescope and the observation building construction were completed in 2022 at the Seoul National University's Pyeongchang campus in South Korea. Telescope construction is expected to be completed by the end of 2023. The KVN as a 4-element array with an E-KVN will start normal operation from 2024B season after commissioning in the first half year in 2024.

VLBI Equipment

KVN VLBI backend system consists of one OCTAD (wideband digital BBC), one GPU spectrometer, one Fila 10G and two Mark5, two Mark6 and one Flexbuff recorders. The total capacity of disk storage at each site is about 1 PB. Most of KVN data is transferred to the Daejeon correlation centre where the KASI headquarter is located via the network. This network is called the Korean Research Environment Open NETwork (KREONET) and provides a high performance and stable network connection, with 40G connection to KVN Yonsei telescope and 10G connections to KVN Ulsan and Tamna. Total 100G bandwidth is allocated to the Daejeon correlation center. Both KJCC (Korea-Japan Cross-Correlator) and DiFX correlator are used for KVN and EAVN data correlation, respectively.

R&D Activities and Technical Developments

Receiver development

A new CX and Ka band receiver for geodetic VLBI and space applications is under development funded by the space geodesy group at KASI. A dual-band coaxial horn is designed for CX (6-9 GHz) and Ka (28-43 GHz) bands and two sets of receivers are expected to be installed at KVN Yonsei and Pyeongchang telescopes in 2025.

Receiver development for the new KVN Pyeongchang telescope (E-KVN) is undergoing. The E-KVN receiver consists of three receiver sets: (1) CTR (18-116 GHz), (2) 1-2 mm receiver (125-175 & 210-275 GHz) and (3) CX/Ka receiver (6-9 & 28-34 GHz), which will be installed at the receiver plate similar to the current KVN with optical circuits.

KVN Yonsei 230GHz Performance Test

Together with a new KVN telescope (E-KVN), testing 230 GHz performance with the KVN Yonsei telescope was carried out in February 2022 (see Fig. 6.7). A cartridge-type 230 GHz receiver was developed and installed where the existing 129 GHz receiver cartridge was removed. The receiver noise temperature at 230 GHz was measured $\sim$70K and the half power beam width of KVN Yonsei radio telescope was 12.1 and 14.3 arcseconds in the azimuth and elevation directions, respectively. The OCTAD and GPU spectrometer were used for this test. The measured aperture efficiency of the KVN Yonsei telescope was $\sim$14% at 230 GHz with the Uranus at an elevation of $\sim$50 degrees. The total surface accuracy of the KVN telescope is $\sim$0.13 mm and the system noise temperature was $\sim$200 K with a sky opacity of 0.3 (transmission $\sim$74%, PWD $\sim$3 mm).

6.4 Aalto University Metsähovi Radio Observatory, Finland

Institute news

Metsähovi Radio Observatory (MRO) is located in Kirkkonummi, Southern Finland. The premises underwent major renovations in 2019–2021, including a new wing, and upgrades for the heating and other systems. During this period, also the steering system of the radome-enclosed 14-m radio telescope was upgraded, and also the radome was replaced. In 2021–2022 the observatory network infrastructure was upgraded to 100 Gbps optical Ethernet, to match the upgraded 100 Gbps Internet connection .

In addition to the main 14-m telescope, 2021–2022 saw advance in the "Metsähovi Compact Array" project leading to a small-scale local interferometer for radio astronomy and technology teaching. The first two 5.5-metre parabolic dishes of the "Metsähovi Compact Array", MCA, were installed (in single-dish mode) in 2021–2022, with one or two to be added in the coming years.

Metsähovi Radio Observatory was also included in the Finnish national research infrastructure roadmap in 2021, in a consortium including also the Finnish Geospatial Research Institute carrying out geodetic VLBI and also operating in the Metsähovi observatory area.

Our future development focuses on obtaining a multi-band (K, Q, W bands) receiver for VLBI and single-dish use. In the late 2022 the call for tender was finalised, and soon after that, contract was signed with the Max Planck Institute for Radio Astronomy, with delivery date in late 2025.

From non-scientific activities we would like to mention observing a partial solar eclipse with several radio telescopes in October 2022. Metsähovi Radio Observatory and radio-astronomical observations in general got wide coverage in national media, because rain prevented all other public eclipse viewing opportunities and made our radio solar maps and eclipse website with live feeds the only way for seeing the eclipse in real time in most of Finland.

EVN operations

MRO maintains VLBI receivers for S/X, K, Q, and W bands. During 2021–2022 Metsähovi participated in five EVN sessions (5 sessions at K, 3 at Q, and 1 at X bands), and three ToO sessions (X, K and Q bands).

Personnel participating and enabling the EVN activities were: 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.

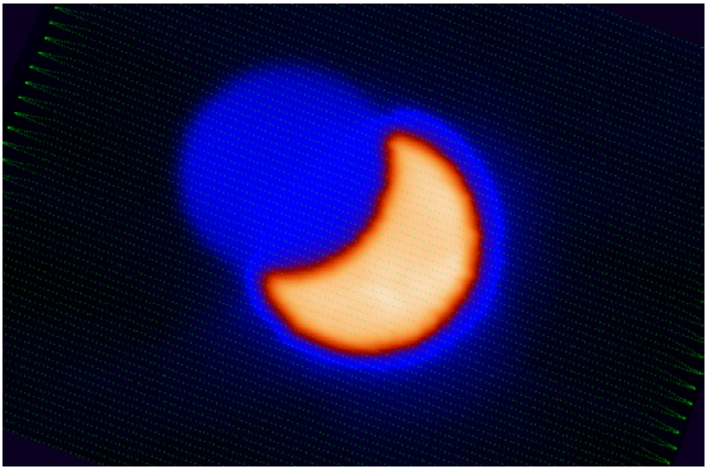

Figure 6.8: Diagnostic map of the October 2022 partial solar eclipse. Green dots mark the MRO 37 GHz total flux measurement points and show the crescent-shaped Sun partially occluded by the Moon.

From the late 2021 we had problems with one of our hydrogen maser, which eventually broke down due to a failed component. The replacement part was to arrive from Russia at the end of February 2022, but sanctions against the country's invasion to Ukraine closed the border for trade three days before the delivery. As a consequence, we have been relying on one hydrogen maser, backed up by two decades' old ones.

The dBBC2 has mainly been working without any problems and it has been used successfully in all VLBI sessions. We obtained a dBBC3 in 2022, but the testing and commission have been delayed due to personnel shortage.

Sessions are stored primarily on the Flexbuff system. In 2021 two new local Flexbuff units were added, with 1368 TB total capacity at the end of 2022. Mark5B+ is available as a back-up system.

As mentioned above, we are waiting for a K/Q/W-multiband receiver to be installed in 2025. Currently, changing between observing frequencies for VLBI require minimum two hours of downtime with 12+ hours or preparatory time, and three people to physically change the receivers, limiting our capability for participating in observing sessions or changing observing modes. We expect these limitations to be relieved with the single receiver capable of observing at different bands. Furthermore, truly simultaneous recording at K, Q and W bands will allow utilising the frequency phase transfer technique to significantly increase the coherence time at mm-wavelengths and thus improve the sensitivity of especially W-band observations.

7. Joint Institute for VLBI ERIC

7.1 Institute news

A notable accomplishment helping to anchor the sustainability of JIVE was the agreement of Italy to become a full member in the ERIC. Italy was one of the founding members of the EVN in the early eighties, and its radio telescopes in Medicina, Noto, and more recently Sardinia, have regularly participated in EVN observations ever since. Through the Institute of Radio Astronomy (IRA-INAF), Italy has supported and been involved with JIVE for several decades. As of 12 March 2021, by joining the JIVE ERIC as a full member, Italy supports the sustainability of our institute for VLBI science, serving as the operational hub of the European VLBI Network and guarding the interests of the global radio-astronomical user community.

But at the beginning of this period, JIVE remained under the shadow of COVID-19 restrictions established in the Netherlands, under which everyone was working from home except for special circumstances. One operator was able to be on-site on average two days per week in order to permit logistics and basic equipment maintenance to stay on track. (Observations at EVN stations were not so affected as they were in 2020 – in fact both 2021 and 2022 each saw new records set for the number of EVN network hours observed!) National COVID-19 restrictions were loosened somewhat in the summer of 2021, only to be re-tightened later in the year, and were finally removed altogether in the spring of 2022. JIVE currently follows the guidance from the Dutch government to allow more flexible working patterns, and discussions continue, both within and outside of JIVE, on optimizing hybrid working practices such that the organisation retains the advantages of spontaneous interactions among staff in Dwingeloo but also that staff retain the flexibility that working from home part of the time can provide.

Maintaining visibility for European VLBI science faced a challenging environment during the first three-quarters of this biennial period owing to the travel restrictions. JIVE was able to jointly organise a Special Session related to VLBI in the 2021 EAS annual conference, which was a fully virtual event: "Extreme astrophysics at extremely high resolution". A Special Session was also organised at the URSI GASS hybrid meeting in Rome, to highlight VLBI applications to astronomy, geodesy, geophysics, and planetary science. JIVE continued to host on-line EVN e-seminars whose recordings are available on the JIVE/EVN YouTube channel – five in 2021 and three in 2022, leading up to the return of an in-person EVN symposium and Users' Meeting in Cork in July 2022. Just prior to that, JIVE and the EVN participated as exhibitors in the 2022 EAS annual conference in Valencia. In mid-October 2022, JIVE and ASTRON co-hosted the 3rd Next Generation Space VLBI workshop (ngSVLBI-3) in Dwingeloo, the Netherlands, as a hybrid meeting. Training new users was also similarly affected. To take the initiative here, JIVE conducted the first ever EVN on-line training event in May 2022. Fortunately, but by early autumn a traditional in-person European Radio Interferometry School (ERIS) was able to be held in Dwingeloo.

Keeping a healthy portfolio of European projects is also vital for JIVE to remain at the forefront of VLBI and data processing/archiving developments.

- H2020 JUMPING JIVE came successfully to an end in 2021. Many of the activities are however continuing, since they have become core activities in JIVE, such as exploring new partnerships to JIVE and the EVN, providing support to training activities in Africa, and SKA-VLBI. Geodetic correlator output has been used by observing teams unrelated to the JUMPING JIVE participants. (Other developments based on accomplishments within JUMPING JIVE are discussed in following sub-sections.)
- H2020 ESCAPE has resulted in a coherent set of tools. A Jupyter-CASA kernel published in the Open Source software and Services Repository enables Jupyter-notebook based radio (VLBI) data reduction using CASA, and makes the data in the EVN Archive findable and downloadable via virtual Observatory queries and protocols. A science platform built on JupyterHub combines all of these to provide easy federated access for users to compute, network, and storage resources at JIVE, significantly lowering the entry barrier for EVN data processing.
- H2020 ERIC FORUM concluded at the end of 2022. In May 2021, the JIVE director became chair of the executive board and spokesperson towards the European Commission and other stakeholders such as the ESFRI. The project aims to strengthen the coordination within the ERIC community and to build the brand identity of ERICs as important stake-holders in consultation of

related policy actions. Participating in the ERIC Forum allowed JIVE to explore a network of research infrastructures that share common challenges, such as long-term sustainability, reporting, VAT exemption practices, and training of governance representatives.

- H2020 Opticon-Radionet Pilot (ORP), which began in March 2021, brings together ground-based optical- and radio-astronomy communities to offer, support and develop access to optical and radio facilities. JIVE is involved in the project through the EVN transnational access (for which JIVE also provides the work package lead), coordinating the communications of the project, and co-leading the Joint Activity 2 subtask 2 "Time-Domain, Multi-Facility & Multi-Frequency access to Research Infrastructures". The latter aims to develop tools to help researchers seamlessly access multiple partner-RI observations and data via a centralised access mechanism.
- Horizon Europe RADIOBLOCKS was approved in July 2022, to begin in March 2023 and run for four years, with JIVE as the coordinator. This project carries out carefully targeted development work to address common aspects in the complete data chain, comprising four phases: novel detectors and components, digital receivers, transport and correlation, and data (post)processing. The building blocks will be new instrument components and advanced digital solutions based on newly available (HPC/AI optimised) hardware.

JIVE prepared a new communication strategy for JIVE and the EVN, which was approved by the EVN CBD in December 2021. It was developed considering the feedback of the outreach officers of all EVN members to ensure that the strategy was as inclusive as possible. Effort went into providing momentum to the EVN Outreach Officers Network (EOON), organising periodic communications between the JIVE Science Communications Officer and the EVN Partners Outreach Officers to streamline the communications within the network and maximise the dissemination reach of the EVN partners individually and as a whole.

JIVE published its Gender Equality Plan (GEP) in 2022, as part of its commitment to promoting gender equality within its workforce and advocating for its importance in the broader context of equality, diversity and inclusion in research infrastructures. It includes an analysis of the current state of actions in place, results of a gender equality survey amongst JIVE employees, and an action plan to address issues highlighted by those assessments. The GEP will be regularly updated based on repeated audits to ensure its continued relevance and effectiveness.

7.2 Personnel

During 2021, Drs. Suma Murthy and Gabor Orosz joined JIVE as support scientists, and Dr. Shivani Bhandari joined JIVE as AstroFlash project postdoc. Dr. Gina Maffey ended her contract as JIVE communications officer, and this role taken by Dr. Jorge Rivero González. Cristina García Miró ended her contract as SKA-VLBI scientist, and moved to Yebes.

In 2022, Prof. Leonid Gurvits retired as the Head of Space Science & Innovative Applications group at JIVE; he continues to share his expertise as "Senior Astronomer Emeritus". Dr. Giuseppe Cimo filled the position of Interim Head of that group. Dr. Junghwan Oh joined JIVE as a support scientist. Support scientists Drs. Olga Bayandina and Dhanya Nair departed, moving to the Osservatorio di Arcetri (Italy) and (the University of Concepcion (Chile), respectively. Dr. Mas Said began a postdoctoral researcher position in the Space Science and Innovative Applications group. Wybren Buis returned to JIVE in a new role as Linux & Network Specialist in the R&D group. Dr Shivani Bhandari, a JIVE postdoc financed by the AstroFlash project, has received a prestigious NWO VENI fellowship. ASTRON became her primary host but she retained her JIVE affiliation.

At the end of the year, the Communications Officer, Dr. Jorge Rivero González, left JIVE to take up a position as Head of Communications and Outreach at the Institute of Space Sciences in Spain. His position will be filled in due course. Notably, 2022 ended with Dr. Francisco Colomer stepping down as JIVE director, to take on the role at the Ministry of Science and Innovation of Spain, as Coordinator for the Spanish Presidency of the Council of the European Union. The JIVE Council appointed Dr. Agnieszka (Aga) Słowikowska as a new director, to start on 1 January 2023.

7.3 Research and Development

Hardware

At then end of this period, JIVE had twenty-three Mark5 units, three Mark6 units used primarily for copying NRAO-recorded data onto local FlexBuffs (so that the NRAO Mark6 packs can be returned on timescales their logistics require), and approximately six PB of FlexBuff space. Among this FlexBuff space is a 90-bay "PetaBuff" (funded by the Medicina, Noto, Sardinia, and Onsala) and a Mark6 unit from Kunming, which was reconfigured as a FlexBuff system.

A total of 31 failed FlexBuff hard disks were replaced, of which only two remained under warranty. This was not surprising given the age that the FlexBuffs units are reaching. Starting from 2022, a more systematic bookkeeping of failing and replaced FlexBuff hard disks was started.

In preparation for being able to accept a doubling of the FlexBuff storage space at JIVE, the raised floor in the correlator room was reinforced in November 2021. (A single FlexBuff loaded with 36 HDDs weighs at least 60 kg.) This involved removing all FlexBuffs, SFXC nodes, the virtual machine cluster, and network switches from the correlator room. A temporary rack with the switches and general purpose servers was set up, so that services such as Mattermost and planobs remained online. The correlator room was completely stripped and the opportunity was seized to optimise the "under-floor" cabling. The installed new floor is rated up to 20 kN per square meter, sufficient to support safely racks filled with FlexBuff servers. When moving the equipment back, the racks were were rotated by 90 degrees, in order to provide room for an extra rack if ever needed and to improve the flow of the cooled air.

A set of fibre optic modules, necessary for the proper functioning of the redundant internal network, were identified as responsible for causing packet loss. In the course of the investigations, a dedicated test framework was built to measures packet loss on all possible host-to-host links and generate a PNG visualisation of the test results using colour-coded packet error rates.

The virtual-machine infrastructure for running most of JIVEs internal and external services was migrated to a pair of new hosts; the existing pair was retired (almost five years after their warranty had expired). The ageing SFXC cluster physical "head" nodes were retired and replaced by virtual machine (VM) instances on the VM cluster. The new VM cluster is powerful enough to allow the "cluster head node" functionality to be run there, and at the same time removes the need for a physical duplicate backup and development environment. The upgrade of the cluster nodes and FlexBuffs to a newer operating system was started. Many configuration and security options were updated or added in the newer version.

The backup software was updated to support archiving onto the new LTO-8 system data from three separate subsystems (the raw correlator output, the EVN Archive, and the backup server). Subsequently the process of re-spooling the older LTO-[345] tapes onto the LTO-8 tapes began. A fire-proof safe of the highest digital-media protection category (S120IS) was installed, which can hold approximately 900 LTO tapes.

New hardware for hosting the EVN Archive was ordered, to support the migration of the Archive to a completely new operating system and newer versions of underlying tools such as web server, website implementation frameworks, and scripting languages. However, in preparation for the transition, archive interface scripts are being rewritten from perl/php into python.

Software correlation

The automated FlexBuff transfer system was modified to change the strategy of when to start transferring data for an experiment. Instead of waiting for an experiment's transfer to finish completely, the system now already starts transferring data from the next finished experiment. This change was necessary to prevent a single station delaying transfers from all stations. However, it does place a greater premium on monitoring available FlexBuff space as a session plays out, so that data from a the data for all observations from a subset of faster stations does not exhaust the available space before data from enough observations from slower stations are received. The means to prioritise (and hold up beginning) specific observations was added, to avoid such situations.

A feature to handle generic per-channel clock offsets was created, in order to handle significant delay differences within a single station's observed channels, for example when multiple digital back-ends are used but aren't perfectly synchronised. Simplified parameterisation for the case when the delay difference is between the two polarisations was encoded to handle the most prevalent of these occurrences.

Two features to help find fringes were implemented. For stations where the physical-channel/logical-datastream layout may differ from the expectation based on the vex file, SFXC can now "broadcast" one channel of a station to all channels of the other stations. This will run the correlation several times; each run broadcasting a different single channel in this manner. SFXC can now sweep through a range of LO offsets, making it easier to test for such a mis-tuning at a station. Before this feature each trial LO offset to test needed to be configured manually and run in a separate correlator job.

SFXC can now provide unnormalised visibilities; the was driven by an EVN user requiring primary beam maps of all stations for wide-field observations. The Polyphase Filter Bank mode algorithm was significantly sped up by using the Intel Integrated Performance Primitives libraries. A modest number of multiple phase centres during (real-time) e-VLBI correlation was enabled by making the output buffer size configurable. The specific performance depends on the number of stations, observing bandwidth, and whether there is any mixed-bandwidth correlation needed (10's to 100's of phase centres would still remain in the realm of disk-based EVN).

Individual databases at JIVE containing information about proposals, experiments, correlation, and resulting user data sets have been linked into a single database instance. The correlator control software (over 30k lines of code in twelve modules) was updated from python2 to python3, resulting in a necessary update from python bindings PyQt4 to PyQt5. The e-VLBI monitoring tool for the JIVE operators was updated to extract FiLa10G configuration parameters to help confirm correct configuration and operation of the hardware.

User software

Maintenance and extension of the NorthStar proposal tool continued. One of the enhancements dealt with the requirement that in proposals requesting e-Merlin stations the principal investigator is required to specifically justify the request for these resources, for which a mandatory dialog box was added if e-Merlin stations are requested.

pySCHED issues improved warning messages for sources observed too close to the sun. The thresholds can be configured on a per-station basis. This required converting another group of functions from FORTRAN to python. Continued incidental maintenance handled changes in the numpy and matplotlib plotting library dependencies of pySCHED. The synchronisation between pySCHED catalogs and new setup files per session was improved, allowing users to rely on pySCHED's "auto-update" capability more robustly.

Linearly polarised receivers are increasingly used for VLBI. The PolConvert program that can be used to change those signals into circular polarisation runs on FITS-IDI files. A program was developed that can take the solutions derived by PolConvert and apply those to a full Measurement Set. PolConvert is normally run on a few short calibrator scans to derive the telescope calibration parameters before being run on the full dataset. Being able to apply the solutions at MeasurementSet level can save significant amounts of disk space and run-time.

The fringefit task in CASA now supports an option to combine polarisations before the fringe search. A prototype for overlapping solution intervals was implemented, and the per-scan interpolation mechanism was validated. Fringe fitting LOFAR HBA long baselines was demonstrated to work, including fitting for dispersive delays. Fringe fitting on a single spectral channel (needed for spectral line VLBI) was likewise implemented. A memo on the fringefit task was accepted in the official CASA memo series as CASA Memo #12. Based on a user request, support for more than 255 antennas in UVFITS files was implemented in casacore, and from there was automatically propagated into importfitsidi.

The table definitions for GAIN_CURVE and PHASE_CAL were improved in casacore. A prototype Earth Orientation Parameter (EOP) correction task was developed and evaluated. The adopted approach, which computes corrections based on the difference between EOPs used in correlation and those that may have been subsequently re-determined, generates a generic calibration table for CASA's applycal task of sufficient accuracy to accommodate EOP corrections for a practical range of date differences.

In collaboration with NRAO, a CASA VLBI companion paper to NRAO's CASA reference paper was published. The CASA VLBI paper describes all VLBI-specific tasks, options, and improvements that JIVE has worked on over the past few years. Of special interest is the most thorough comparison between Classic AIPS VLBI processing and its CASA based equivalent. Another CASA highlight was the publication of the EHT SgrA* image, to which JIVE staff contributed at several levels (algorithm, tooling, writing, review, dissemination).

NRAO's CASA Next Generation Infrastructure (CNGI) project is an attempt to change MeasurementSet access into a more scalable infrastructure, geared towards enabling parallel processing. Investigations into this got under way, since the impact on existing CASA tools would be tremendous.

7.4 Space and Planetary Science

Spacecraft observations in the Solar System

Several major milestones have been achieved in the preparation of JIVE's contribution to ESA's large-class mission Jupiter Icy moons Explorer (JUICE). The VLBI component of the JUICE mission will be implemented as Planetary Radio Interferometry and Doppler Experiment (PRIDE) led by JIVE. The main aim of PRIDE is to support improvement of the Jovian system ephemerides which, in turn, are crucial for maximising scientific return of many in situ measurements and observations of the mission instruments.

In 2021, the international PRIDE team published a detailed description of the data processing algorithms of Doppler tracking component of the experiment. This Spacecraft Doppler tracking (SDtracker) software allows one to obtain topocentric frequency detections with a sub-Hz precision as well as reconstructed and residual phases of the carrier signal of any spacecraft or landing vehicle at any location in the Solar System. This part of the PRIDE data processing will be used for tracking of the JUICE spacecraft during the cruise and science phases of the mission.

Observations of several operational planetary missions, such as ESA's Mars Express and China's Tianwen have been conducted in collaboration with the University of Tasmania and the Chinese Academy of Science. The correlation of the spacecraft signal provided a novel approach to studying the solar wind structure and the inhomogeneities in the interplanetary plasma.

Another fundamental novel application of VLBI has been the observations of the space VLBI radio telescope, the Russian-led mission RadioAstron, to test Einstein's equivalence principle by measurements of the gravitational redshift of RadioAstron.

Towards space-borne mm/sub-mm VLBI

The next major leap in VLBI aims to reach microarcsecond angular resolution. This is the main driver behind THEZA (TeraHertz Exploration and Zooming-in for Astrophysics), a concept for a multi-element space-borne mm/sub-mm interferometric system. proposed in response to the ESA Call for ideas Voyage 2050. The THEZA collaboration published a paper on the science case and challenges of space-borne sub-millimetre interferometry.

The THEZA rationale is focused on the physics of space-time in the vicinity of super-massive black holes as the leading science drive. However, it will also open up a sizable new range of hitherto unreachable parameters of observational radio astrophysics and create a multi-disciplinary scientific facility and offer a high degree of synergy with prospective "single dish" space-borne sub-mm astronomy and infrared interferometry. As an amalgam of several major trends of modern observational astrophysics, THEZA aims at facilitating a breakthrough in high-resolution high image quality astronomical studies.

An important step forward in building a multi-disciplinary collaboration in the field of space VLBI was the organisation of the next-generation space VLBI workshop in Dwingeloo on 17-19 October 2022. The event, a hybrid workshop attended by almost one hundred people, focused on the future of high-resolution radio interferometry in space as a natural space-borne extension of advanced existing and prospective Earth-based facilities and space VLBI. The workshop programme spread across all spectral domains and covered a wide range of science cases from the detection of cosmological inhomogeneities of the atomic hydrogen distribution in the early Universe to enigmatic processes near super-massive black holes.

7.5 EVN Operations

Correlation

The core of JIVE's service is the correlation of astronomers' observations conducted with the EVN and global VLBI arrays; tables 7.1 and 7.2 below summarize experiments that were correlated at JIVE during 2021 and 2022.

	User Experiments			Test & Network Monitoring		
	N	Ntwk_hr	Corr_hr	N	Ntwk_hr	Corr_hr
Correlated	114	1093	1224.5	16	45	51
Distributed	109	1058	1183	15	41	44
e-EVN experiments	25	207.5	207.5			
e-EVN ToO/triggers	8	74	74			

Table 7.1: Experiments correlated at JIVE during 2021. "Network hours" sum the duration of experiments and "Correlator hours" are the network hours multiplied by any multiple correlation passes required – the actual time to correlate can be several times larger for the more complex correlations.

Despite the lingering effects of COVID-19 during this period, the number of EVN network hours observed set new records in each year

	User Experiments			Test & Network Monitoring		
	N	Ntwk_hr	Corr_hr	N	Ntwk_hr	Corr_hr
Correlated	114	988.5	1111	15	66.5	68.5
Distributed	90	772.5	869	9	48	51
e-EVN experiments	29	209.5	209.5			
e-EVN ToO/triggers	6	44	44			

Table 7.2: Experiments correlated at JIVE during 2022.

(2021, 1044.5; 2022, 1121), including over 200 e-EVN network hours for the first time in consecutive years since 2016-17. The number of correlator hours completed were the second and third most since shifting to SFXC. The year 2022 also set new records for the number of user observations (152; was 127 from 2019) and disk-based user observations (123; was 94 also from 2019). All observations in this biennial period correlated at JIVE. There was a vacancy in the support-scientist ranks for the first ten months of 2021 and from March to September in 2022. Together with extra demands on support-scientist time in mid-2022 for EVN Symposium LOC responsibilities and tutorial preparation and further LOC work for the ERIS, the increased correlation output helps explain the unusual situation in which the distribution of correlated observations has fallen behind the correlation itself (the reduced observing in 2020 as a consequence of the initial wave of COVID-19 on the stations helped keep this disparity low in 2021 despite also being short one support scientist for several months).

In this biennial period, there were 21 EVN target of opportunity observations and four e-EVN trigger observations, together arising from 11 proposals. Scientific topics covered include the persistent source associated with an FRB, the afterglow of an extreme short GRB and a different newly discovered long GRB, the progenitor of a new type Ia supernova, shocks generated by outbursts of two different novae, two different AGN undergoing a state transition, the evolution of the jet in a TDE, a possibly merging binary AGN, and associations between jets in blazars and IceCube-detected neutrinos (two different AGN covered in a total of three observations).

Highlights from the 2021-22 period included:

- The program PolConvert (to transform a station's observed linear polarisations to circular, after correlation) now needs to be applied to all 18-/21-cm and 5cm observations (owing to Tianma and Effelsberg, respectively). This currently occurs at the IDI-FITS file stage, prior to archiving. Use of PolConvert requires correlation with both parallel- and cross-hands.
- GM077 was a large (24 hour, 25 station) global Galactic water maser phase- referencing observation, resulting in the largest set of output FITS files for a single phase-centre observation, at 4.1 TB. Spectral zooming was used for the high-resolution line correlator

pass – otherwise the size would have been almost double.

- Correlation and distribution of the final epochs of ER047, a 72-hour project investigating the contributions of AGN and star formation in a faint (few uJy) population of radio sources, were completed. This project holds the current record for the highest number of output phase centres at 761, and in the end the total time to correlate its six 12-hour epochs occupied 660.5 hours, and the total size of its output FITS files amounted to 66 TB.
- The second 4 Gbps user experiment, which was the first one with a PI from a non-EVN institute, was observed in session 3/2021. Fourteen further 4 Gbps user observations followed in 2022, spread evenly across the sessions (5,5,4), including a project from a first-time PI who was also from a non-EVN institute. The first 4 Gbps user observations at 1.3 and 3.6 cm took place in session 3/2022.
- EM160 was a correlator-only experiment to recorrelate one of the proposer's earlier observations with a large number of multiple phase centres (127 around the target, 130 around the phase-reference source). The 21.9 hours contained in the scans took 218.5 actual correlator hours to complete. The post-correlation processing required multiple iterations, as bugs in recently introduced steps were ironed out. In the end, this correlation resulted in 17.9 TB of FITS files, a record for a single observation.
- There were twenty-two FRB triggers from the on-going correlation-only projects based on VLBI observations shadowing the CHIME radio telescope and other facilities (EK048A-G, EK050A-G, EK051A-H). The triggers cover eight different FRB targets. Correlation of the shadowing VLBI observations is triggered if a burst is detected by the tracking facilities. Depending on the accuracy of the a priori position of the FRB, one or two correlation passes over the whole range of the phase- referencing data (ranging from 2-10 hours) would ensue, with the ultimate goal of deep- imaging to detect any associated persistent radio source. There is also a special off-line high time-resolution correlation of the burst itself (i.e., no more than a few milliseconds of data), which would be required before beginning the second, full pass, if the target's a priori position was not good enough.

EVN Support

JIVE coordinated tests of new receivers at EVN stations, including 3.6 cm at Torun (Tr), 7 mm at Urumqi (Ur), the Yebes 4.5-9.0 GHz wide-band receiver, and the Effelsberg 4.0-9.3 GHz wide-band/linear-pol receiver. The frequency capabilities for Tr and Ur were added to the EVN Proposal Tool. Initial tests within EVN observations of the DBBC3 back-end at Onsala were made during the session 3/2022 6 cm NME. Robledo included the new DSN VRA back-end in some session 3/2022 user observations. Both these last two back-ends required use of VEX2 for correlation to handle the multiple VLBI Data Interchange Format (VDIF) streams, each of which could contain multiple channels. At present, VEX2 files cannot yet be used to drive observations, so in such cases both versions of the same schedule need to be made – which pySCHED can do (any manual fixes of cable-(un)wraps must be done to both output schedules). JIVE also developed in consultation with the stations a local oscillator (LO) tuning scheme for the 4 Gbps user observation at 3.6 cm in session 3/2022.

JIVE also coordinated test observations for telescopes that potentially could join in future EVN observations. The Arecibo 12m telescope participated for the first time in an EVN context during the session 3/2021 3.6 cm NME. Good fringes were seen in RCP channels (which come from one of their two RDBE back-ends; the LCP channels come from the other RDBE, auto-correlations there suggested a problem configuring it). The 500m FAST telescope in China also participated in 18 cm NMEs during sessions 3/2021 and 1/2022 (portions of which were conducted at 21 cm to accommodate their upper-limit in frequency, and in a stand-alone observation in session 2/2022, the latter two including phase-referencing. Internal policies at FAST prevented data being sent to JIVE for correlation. Therefore data from other stations were e-shipped to Shanghai Astronomical Observatory, where fringes were reported. uGMRT participated in two test EVN observations in February 2022, including simultaneous data from both a single-dish and a tied-array configuration. Data must be re-sampled (in some cases) and translated into VDIF before being sent to JIVE. Fringes were seen to both single-dish and tied-array "stations". Another test observation was conducted during session 3/2022, whose data are still being investigated.

The Technical Operations and R&D group completed a pilot project to demonstrate that a Mattermost plug-in can be developed which could become a replacement to the existing EVN feedback facility running on significantly more modern/secure webservices. This new system will be presented to the EVN TOG in the first meeting in 2023. The central EVN Monitoring system, resulting from previous work in the JUMPING JIVE project, was improved by editing and adding scripts to make it easier for EVN stations to upload data in general and multiple sample point values at the same time. A user guide was compiled for the EVN stations to document usage and integration of the EVN monitoring system within their own systems.

The 2021 IVS Technical Operations Workshop was entirely virtual, where JIVE staff contributed a live-streamed "Recorder, Media Handling, and e-Transfers" seminar, as well as a pre-recorded seminar on "Pointing and Amplitude Calibration".

User Support

JIVE provided support in all stages of a user's EVN observation, from proposal definition to data analysis, including experiment-specific set-up templates when needed to track the evolving configurations of equipment at EVN stations, and making corresponding updates to the pySCHED catalogues. There were twenty-seven first-time PIs in projects observed in 2021-22; nine of these were students and nine were female (there was one female student).

JIVE offers a "Support+" pilot programme to teams that are particularly unsure about the VLBI-specific part of observe file preparation and processing. Two teams applied for this in 2022. Support scientists offered additional help for scheduling and data post-processing, as required. Whether this is a sustainable mode of operation will depend on the user demand and the available resources at JIVE.

The limitations arising from COVID-19 continued to have drastic effects on data-reduction visits to JIVE – being able to receive visitors was possible again only in mid-2022. To combat the isolation early in this biennial period, a series of topical on-line seminars continued (five in 2021, three in 2022), there was a virtual EVN mini-symposium in June 2021, and the first on-line EVN Users' training event was conducted in May 2022. Here, the EVN Support Scientists guided participants through the different steps to allow them to propose and conduct EVN observations. A total of forty-eight people from all over the world and from a variety of backgrounds mostly outside the VLBI radio community, took advantage of this training event. Participants could join through Zoom, YouTube, and Mattermost (chat only). The morning session briefly introduced the EVN, provided background information on the Call for Proposals, and demonstrated the use of the EVN Observation Planner and the NorthStar proposal tool. The afternoon session focused on observing schedule preparation.

By the summer and early autumn of 2022, the EVN symposium (Cork) and ERIS (Dwingeloo) were able to be conducted in-person. The ERIS provided training via lectures and tutorials on calibration and imaging of continuum, spectral, line and polarisation data in all the radio interferometry domains (LOFAR, e-MERLIN, VLA, ALMA/IRAM, EVN). This time VLBI was actually one of the most popular topics, thanks to the increasing interest of using very long baselines at low (ILT) and high (EHT) frequencies. The school was attended by seventy-two students from all over the world. The public lecture was given by the VLBI legend Jim Moran.

Existing users who asked for help still largely used AIPS for processing, but new users often only work in CASA. JIVE supported both worlds and promotes CASA use, but it is clear that the bulk of the core users will require keeping AIPS support for quite a few years to come. While the missing functionalities in CASA VLBI processing are being continuously addressed, some limitations of the package have surfaced as well.

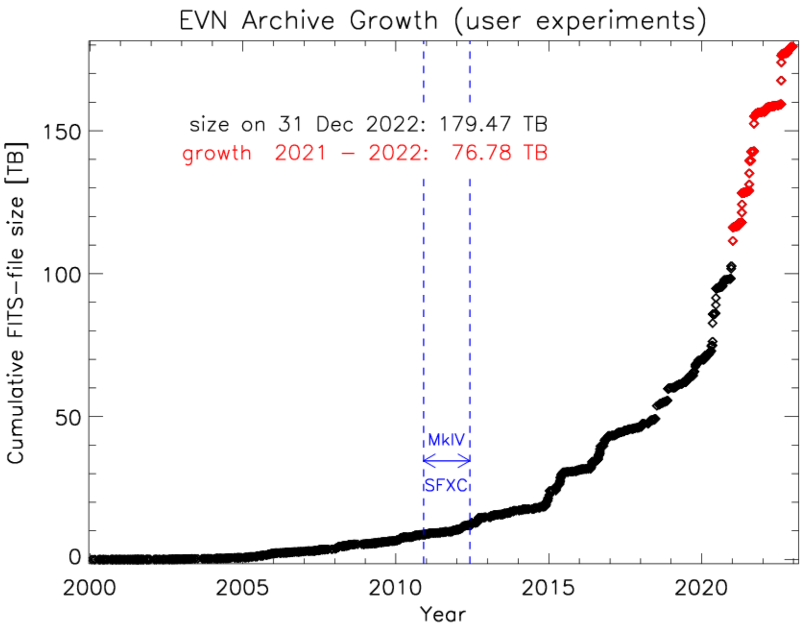

Figure 7.1: Growth of user experiments in the EVN Archive. Experiments archived in 2021-22 are plotted in red. Vertical dashed lines show the transition period between the MkIV and SFXC correlators.

CASA has known performance issues, especially when visualising data, which makes classical, iterative processing more difficult – although it does have clear advantages for automated processing. The VLBI tutorials within the ERIS were conducted entirely within CASA.

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 months for ToO projects, and a new policy of zero proprietary period enacted at the end of 2020). The total size of user-experiment FITS files in the Archive reached almost 180 TB by the end of 2022, increasing by 74% over the two-year period.

8. VLBI related events and seminars organized by the EVN

8.1 VLBI related meetings with significant participation by EVN institutes

Following is a description of the most notable VLBI related meetings organised during the years 2021 and 2022, with a significant participation of the different EVN institutes. Throughout 2021, most of the events were still affected by the COVID-19 pandemic and were held online. This includes the virtual mini-symposium that was organised in place of the traditional in-person EVN Symposium and Users Meeting that was cancelled in 2020. A full EVN Symposium and Users Meeting was then held in person in 2022 in Cork, Ireland.

- **Science at the Horizon: the Next-Generation EHT**
  22-26 February, 2021
  Online
  https://www.ngeht.org/ngeht-meeting-2021
- **East-Asian VLBI Workshop**
  2-5 March, 2021
  Online
  https://indico.narit.or.th/event/152/
- **6th workshop on CSS and GPS sources**
  10-14 May, 2021
  Online
  http://cssgps2020.umk.pl/index.html
- **European Astronomical Society (EAS) General Assembly**
  28 June-2 July, 2021
  Online
  https://eas.unige.ch/EAS2021/

Figure 8.1: The conference picture from the 2022 EVN Symposium showing participants attending in person (main panel) and remotely (top row).

- **European VLBI Network Symposium and Users' meeting**
  12–16 July 2021
  Online
  https://www.ucc.ie/en/evn2020/
- **URSI General Assembly and Scientific Symposium**, including J04 session on "Very Long Baseline interferometry"
  28 August–4 September 2021
  Rome, Italy
  https://www.ursi2021.org/
- **9th Microquasar workshop: celebrating over 50 years of discovery**
  20-24 September 2021
  Cagliari/online, Italy
  https://sites.google.com/inaf.it/microquasar-2020
- **50th Young European Radio Astronomers Conference (YERAC)**
  24-27 August 2021
  Online
  https://www.iram-institute.org/EN/content-page-422-7-67-422-0-0.html
- **VLBI in the SKA Era**
  14-18 February 2022
  Online

https://whova.com/web/vlbis_202111/

- **RFI 2022**
  Reading, United Kingdom
  14-18 February 2022
  https://events.ecmwf.int/event/258/
- **International VLBI Service for Geodesy and Astrometry (IVS) 2022 General Meeting**
  27 March - 1 April 2022
  Helsinki, Finland
  https://www.maanmittauslaitos.fi/en/12th-ivs-general-meeting-gm2022/
- **18th NRAO Synthesis Imaging Workshop**
  18-25 May 2022
  Online
  https://web.cvent.com/event/b7f82cf3-7126-4a71-a88b-7a93c66a4dc7/summa
- **3rd URSI Atlantic Radio Science Meeting**
  30 May - 4 June 2022
  Gran Canaria, Spain & Online
  https://www.atrasc.com/
- **LOFAR Famility Meeting 2022**
  13-17 June 2022
  Cologne, Germany
  https://www.glowconsortium.de/index.php/en/lofar-family-meeting-2022
- **Assembling the ngEHT: Community-Driven Science to a Global Instrument**
  22-25 June, 2022
  Granada, Spain
  https://www.ngeht.org/ngeht-meeting-june-2022
- **European Astronomical Society Meeting 2022 (EAS 2022)**
  27 June - 2 July 2022
  Valencia, Spain
  https://eas.unige.ch/EAS2022/
- **2022 European VLBI Network Symposium and Users' meeting**
  11-15 July 2022
  Cork, Ireland
  https://www.ucc.ie/en/evn2022/
- **PARI 2022**
  18-20 July 2022
  Manchester, UK & Online
  https://skao.eventsair.com/pari2022/
- **European Radio Interferometry School (ERIS 2022)**
  19-23 September 2022
  Dwingeloo, The Netherlands
  https://www.jive.eu/ERIS2022/
- **XXXI IAU General Assembly**
  2-11 August 2022

Busan, Republic of Korea & Online
https://www.iauga2022.org/

- **51st Young European Radio Astronomers Conference (YERAC)**
24-26 August 2022
Aalto University campus, Finland
https://wiki.aalto.fi/display/YERAC2022/YERAC2022+Home
- **2nd Malaysian VLBI Workshop**
5-8 September 2022
Kuala Lumpur, Malaysia
https://sites.google.com/view/2myvlbiworkshop/home
- **VLA Sky Survey in the Multiwavelength Spotlight**
7-9 September 2022
Socorro, USA
https://web.cvent.com/event/e705a49c-1886-48a4-bbc2-365f5c35e419/summar
- **ALMA Archive School 2022**
5-7 October 2022
Bologna, Italy
http://www.eso.org/sci/facilities/alma/arc/alma-archive-school2022.html
- **Science Enabled with Multi-Band Receivers at High Radio Frequency**
12-14 October 2022
Bonn, Germany
https://events.mpifr-bonn.mpg.de/indico/event/283/
- **Next Generation Space VLBI (ngSVLBI) Workshop**
17-19 October 2022
Dwingeloo, The Netherlands
https://indico.astron.nl/event/297/
- **11th IRAM Interferometry School**
21-25 November 2022
Grenoble, France
https://www.iram-institute.org/EN/content-page-452-7-67-452-0-0.html

8.2 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 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. Six seminars were organised during 2021 and three in 2022, leading up to the organisation of the 2022

Figure 8.2: Poster for the EVN virtual seminars "The sharpest view of the radio Universe".

EVN Symposium and Users' meeting. The seminars were followed by a large number of participants that held very interesting discussions. The seminars were recorded and are accessible at the EVN/JIVE Youtube channel.

Distance of optically-obscured evolved stars

Seminar by Sandra Etoka, Jodrell Bank Centre for Astrophysics & University of Manchester. Friday 5 February 2021.

As intermediate-mass stars head towards their final fate, they pass through the red-giant stage where they experience an increase of mass loss. This induces the creation of a circumstellar envelope of dust and gas. By the very end of this evolutionary stage, the amount of

dust in the circumstellar envelope of a good fraction of these evolved stars is such that it blocks optical radiation, turning them into so-called OH/IR stars. These precursors of planetary nebulae are commonly observed throughout the Galaxy and are also observed in the Magellanic Clouds. Since optically thick, measurements of their distances using optical parallaxes as e.g. delivered by GAIA, is not possible. This issue can be circumvented thanks to maser emission. As their name gives it away, the physical conditions turn out to be ideal for a strong (1612-MHz) OH maser emission to be produced in the outer layers of the radially-expanding spherical circumstellar envelope of OH/IR stars. I will present how, combining single-dish monitoring and interferometric mapping of this OH maser emission, the "phase-lag method" allows us to measure their distance.
This seminar is available at the EVN/JIVE Youtube channel.

Shadows and Photon Rings: Imaging Supermassive Black Holes with the Event Horizon Telescope

Seminar by Michael Johnson, Harvard-Smithsonian Center for Astrophysics. Monday 29 March 2021.

The Event Horizon Telescope (EHT) uses very long baseline interferometry (VLBI) at 1.3-mm wavelength to produce images of supermassive black holes with horizon-scale resolution. I will discuss the breakthroughs that made these images possible and their implications for our understanding of supermassive black holes. I will also describe the emerging capabilities of the EHT to study relativistic dynamics of accretion flows and to elucidate the role of magnetic fields in jet launching. Finally, I will discuss the complex, fractal structure that is predicted to appear in higher resolution images of black holes, which enables a new type of radio interferometer capable of precision tests of General Relativity.
This seminar is available at the EVN/JIVE Youtube channel.

Re-solving multi-messenger puzzles with Very Long Baseline Interferometry

Seminar by Marcello Giroletti, INAF Istituto di Radioastronomia. Wednesday 19 May 2021.

The detection of information carried by means other than electromagnetic waves has opened a new era in the study of the Universe. Very Long Baseline Interferometry, thanks to its exquisite angular resolution, remains the only technique allowing astronomers to directly image the most compact structures associated with the emission of energetic photons or other carriers of information, as well as their evolution. An outstanding example was the observation of the formation of a jet following the first - and so far unique - concurrent detection of gravitational and electromagnetic waves in GW 170817. In this talk,

I will review the observational and astrophysical novelty of the VLBI campaign following this event, and the prospects for future synergies between VLBI and multi-messenger observations in the field of transient astrophysical sources.
This seminar is available at the EVN/JIVE Youtube channel.

X-ray binaries unveiled by very high resolution radio imaging

Seminar by Pikky Atri, ASTRON. Wednesday 9 June 2021.

Accreting X-ray binaries are excellent laboratories to study extreme physics in our universe and provide unique opportunities to understand exotic neutron stars and black holes. It is thought that black hole X-ray binaries are small-scale Active Galactic Nuclei whose radio jets vary on human timescales. High-resolution radio imaging and astrometry are powerful tools that allow us to directly probe into the evolution of these jets. In this talk, I will review the study of compact X-ray binaries and how Very Long Baseline Interferometry is enabling exciting breakthroughs in understanding their birth, evolution and advancing the search for new X-ray binary systems.
This seminar is available at the EVN/JIVE Youtube channel.

Tying the Sky to the Ground

Seminar by Iván Martí-Vidal, University of Valencia. Friday 9 July 2021.

The technique of Astronomical Interferometry allows us achieve the highest spatial resolutions in the observation of the Universe, thanks to the perfect coordination of different radiotelescopes spread across the Earth's surface. Besides the unbeatable spatial resolution, interferometry can also be used to estimate the locations of the sources on the sky, as well as the relative positions of the radiotelescopes, with precisions of a few tens of micro-arcseconds in the former and a few millimeters in the latter. In this talk, we will discuss about the use of interferometry techniques for high-precision Astrometry and Geodesy. We will review some key results and talk about on-going and future projects.
This seminar is available at the EVN/JIVE Youtube channel.

Observing interplanetary spacecraft with radio telescopes: connecting astronomers and space scientists

Seminar by Giuseppe Cimò; Joint Institute for VLBI ERIC. Monday 29 November 2021.

Observations of human-made satellites using arrays of radio telescopes can provide the ultra-precise determination of their speed and their position on the celestial sphere. The Planetary Radio Interferometry and Doppler Experiment (PRIDE) is a technique that con-

nects ground-based radio astronomy and space science to deliver the sharpest view of spacecraft in our solar system. PRIDE's precise determination of the lateral position of spacecraft can be used for a variety of scientific applications, including improvement of ephemerides, ultra-precise celestial mechanics of planetary systems, gravimetry, spacecraft orbit determination, and fundamental physics. Furthermore, observations of the radio signal transmitted by a spacecraft are an important source of information on interplanetary plasma and solar wind. In this talk, I will present novel results of observing ESA and NASA spacecraft with ground-based radio telescopes and demonstrate the capabilities of such a technique.
This seminar is available at the EVN/JIVE Youtube channel.

High resolution observations of magnetic fields in the Central Molecular Zone of the Galactic Center

Seminar by Cornelia C. Lang; University of Iowa. Friday 28 January 2022.

In addition to harbouring a supermassive black hole at its very core, the Galactic centre is one of the most physically extreme environments in the Galaxy. Dense and massive molecular clouds on non-circular orbits are abundant in this region, yet star formation is not as active and frequent as expected. In addition, radio observations have revealed a population of synchrotron-emitting filaments that provide insight on the magnetic field strength and configuration in this unique region of the Galaxy. I will review observational results from several recent studies undertaken by my research group: we have examined the properties and kinematics of a group of unusual molecular clouds that appear to be part of an orbital "stream" of material around the Galactic centre. In addition, we have been studying the detailed structure of the synchrotron-emitting radio filaments and their connection to larger-scale energetic outflows from the Galactic centre. Our relative proximity to the Galactic centre provides an unprecedented view of a galactic core and studies of this region can be used as an astrophysical analogue to understanding the nuclei of more distant galaxies.
This seminar is available at the EVN/JIVE Youtube channel.

Exploring the lowest mass objects at the highest angular resolution: low-mass stars, ultracool dwarfs and exoplanets

Seminar by Juan B. Climent; University of Valencia. Monday 14 March 2022.

At the very low mass regime of stellar and substellar objects, ultracool dwarfs (UCDs) cover the boundary between stars and exoplanets where radio observations have already proved the existence of powerful magnetic fields. Such observations are crucial not only to directly measure the strength and topology of the UCDs' magnetic fields but

also for opening a new route for the detection of exoplanetary radio emission, and hence, establishing a novel tool to discover new worlds. The great utility of radio observations is amplified in the case of binary systems as sub-mas astrometry can determine the dynamical masses. Despite this great potential, only a handful of VLBI observations of UCDs have been successful. In this talk, we will discuss the current state of the scientific knowledge regarding these topics while sharing our contributions: (i) multi-epoch multi-wavelength observations of a sub-stellar triple system; (ii) new radio detections in several UCDs, including three binary low-mass systems, and, remarkably, a T6-object; and (iii) the sub-mas morphology of UCDs displaying auroral radio emission.
This seminar is available at the EVN/JIVE Youtube channel.

Intermediate-mass black holes in the era of radio astronomy

Seminar by Mar Mezcua; Institute of Space Sciences (*ICE-CSIC*). *Thursday 5 May 2022.*

Black holes of 100–100,000 solar masses formed at redshifts of $z <$ 20 are currently the best candidates to being the seeds of the first supermassive black holes that power the quasars detected at z 6–7. Studying this population of high-redshift seeds has so far only been possible by investigating the possible local relics of those that did not become supermassive, which can be found in the local Universe as intermediate-mass black holes (IMBHs) in dwarf galaxies. I will show how radio interferometric observations have been key to identify and characterize actively accreting IMBHs in the local Universe and out to z 3. The next generation of radio telescopes such as the SKA will open a new window on detecting seed black holes at birth, probing the formation pathways of the first quasars in the Universe.
This seminar is available at the EVN/JIVE Youtube channel.

9. EVN publications

9.1 EVN related referred publications (in alphabetical order) 2021

Journal Articles

1. Aberfelds, A., Steinbergs, J., Shmeld, I. , ., & Bartkiewicz, A. *A preview look at the maser cloudlet evolution in the HMSFR IRAS 20126+4104*, 2021, Astronomical and Astrophysical Transactions, 32, 383
2. Baldi, R. D., Giovannini, G., & Capetti, A. *The eMERLIN and EVN View of FR 0 Radio Galaxies*, 2021, Galaxies, 9, 106
3. Bietenholz, M. F., Bartel, N., Kamble, A., Margutti, R., Matthews, D. J., & Milisavljevic, D. *SN 2014C: VLBI image shows a shell structure and decelerated expansion*, 2021, Monthly Notices of the Royal Astronomical Society, 502, 1694
4. Biggs, A. D. *The time delay of CLASS B1600+434 from VLA multi-frequency and polarization monitoring*, 2021, Monthly Notices of the Royal Astronomical Society, 505, 2610
5. Boccardi, B., Perucho, M., Casadio, C., Grandi, P., Macconi, D., Torresi, E., Pellegrini, S., Krichbaum, T. P., Kadler, M., Giovannini, G., Karamanavis, V., Ricci, L., Madika, E., Bach, U., Ros, E., Giroletti, M., & Zensus, J. A. *Jet collimation in NGC 315 and other nearby AGN*, 2021, Astronomy and Astrophysics, 647, A67
6. Bruni, G., Savolainen, T., Lobanov, A., Gomez, J. L., Kovalev, Y., Fuentes, A., & Vega-Garcia, L. *RadioAstron reveals a spine/sheath jet structure in 3C273*, 2021, 43rd COSPAR Scientific Assembly. Held 28 January - 4 February, 43, 1436
7. Casadio, C., Blinov, D., Readhead, A. C. S., Browne, I. W. A.,

Wilkinson, P. N., Hovatta, T., Mandarakas, N., Pavlidou, V., Tassis, K., Vedantham, H. K., Zensus, J. A., Diamantopoulos, V., Dolapsaki, K. E., Gkimisi, K., Kalaitzidakis, G., Mastorakis, M., Nikolaou, K., Ntormousi, E., Pelgrims, V., & Psarras, K. *SMILE: Search for MIlli-LEnses*, 2021, Monthly Notices of the Royal Astronomical Society, 507, L6

8. Cheng, X., An, T., Sohn, B. W., Hong, X., & Wang, A. *Parsec-scale properties of eight Fanaroff-Riley type 0 radio galaxies*, 2021, Monthly Notices of the Royal Astronomical Society, 506, 1609
9. Dallacasa, D., Orienti, M., Fanti, C., & Fanti, R. *VLBI images at 327 MHz of compact steep spectrum and GHz-peaked spectrum sources from the 3C and PW samples*, 2021, Monthly Notices of the Royal Astronomical Society, 504, 2312
10. EHT MWL Science Working Group, Algaba, J. C., Anczarski, J., Asada, K., Baloković, M., Chandra, S., Cui, Y.-Z., Falcone, A. D., Giroletti, M., Goddi, C., Hada, K., Haggard, D., Jorstad, S., Kaur, A., Kawashima, T., Keating, G., Kim, J.-Y., Kino, M., Komossa, S., Kravchenko, E. V., Krichbaum, T. P., Lee, S.-S., Lu, R.-S., Lucchini, M., Markoff, S., Neilsen, J., Nowak, M. A., Park, J., Principe, G., Ramakrishnan, V., Reynolds, M. T., Sasada, M., Savchenko, S. S., Williamson, K. E., Event Horizon Telescope Collaboration, Fermi Large Area Telescope Collaboration, H. E. S. S. Collaboration, MAGIC Collaboration, VERITAS Collaboration, EAVN Collaboration *Broadband Multi-wavelength Properties of M87 during the 2017 Event Horizon Telescope Campaign*, 2021, The Astrophysical Journal, 911, L11
11. Liu, L., Xu, Z., Yan, Z., Zheng, W., Huang, Y., & Chen, Z. *VOLKS2: A Transient Search and Localization Pipeline for VLBI Observations*, 2021, The Astronomical Journal, 162, 159
12. Ma, M., Molera Calvés, G., Cimò, G., Zhang, P., Xiong, M., Li, P., Kummamuru, P., Chu, Z., Jiang, T., Xia, B., Tetsuro, K., Tong, F., de Vicente, P., Quick, J., Zhang, H., & Chen, Z. *VLBI Data Processing on Coronal Radio-sounding Experiments of Mars Express*, 2021, The Astronomical Journal, 162, 141
13. Malkin, Z. *Towards a robust estimation of orientation parameters between ICRF and Gaia celestial reference frames*, 2021, Monthly Notices of the Royal Astronomical Society, 506, 5540
14. Mandarakas, N., Blinov, D., Casadio, C., Pelgrims, V., Kiehlmann, S., Pavlidou, V., & Tassis, K. *Local alignments of parsec-scale AGN radiojets*, 2021, Astronomy and Astrophysics, 653, A123
15. Nesci, R., Cutini, S., Stanghellini, C., Martinelli, F., Maselli, A., Lipunov, V. M., Kornilov, V., Lopez, R. R., Siviero, A., Giroletti, M., & Orienti, M. *Multiwavelength flare observations of the blazar S5 1803+784*, 2021, Monthly Notices of the Royal Astronomical Society, 502, 6177

16. Nimmo, K., Hessels, J. W. T., Keimpema, A., Archibald, A. M., Cordes, J. M., Karuppusamy, R., Kirsten, F., Li, D. Z., Marcote, B., & Paragi, Z. *Highly polarized microstructure from the repeating FRB 20180916B*, 2021, Nature Astronomy, 5, 594
17. Perger, K., Frey, S., Schwartz, D. A., Gabányi, K. É., Gurvits, L. I., & Paragi, Z. *Multi-scale Radio and X-Ray Structure of the High-redshift Quasar PMN J0909+0354*, 2021, The Astrophysical Journal, 915, 98
18. Piro, L., Bruni, G., Troja, E., O'Connor, B., Panessa, F., Ricci, R., Zhang, B., Burgay, M., Dichiara, S., Lee, K. J., Lotti, S., Niu, J. R., Pilia, M., Possenti, A., Trudu, M., Xu, H., Zhu, W. W., Kutyrev, A. S., & Veilleux, S. *The fast radio burst FRB 20201124A in a star-forming region: Constraints to the progenitor and multiwavelength counterparts*, 2021, Astronomy and Astrophysics, 656, L15
19. Plavin, A. V., Kovalev, Y. Y., Kovalev, Y. A., & Troitsky, S. V. *Directional Association of TeV to PeV Astrophysical Neutrinos with Radio Blazars*, 2021, The Astrophysical Journal, 908, 157
20. Powell, D., Vegetti, S., McKean, J. P., Spingola, C., Rizzo, F., & Stacey, H. R. *A novel approach to visibility-space modelling of interferometric gravitational lens observations at high angular resolution*, 2021, Monthly Notices of the Royal Astronomical Society, 501, 515
21. Pérez-Torres, M., Mattila, S., Alonso-Herrero, A., Aalto, S., & Efstathiou, A. *Star formation and nuclear activity in luminous infrared galaxies: an infrared through radio review*, 2021, Astronomy and Astrophysics Review, 29, 2
22. Pötzl, F. M., Lobanov, A. P., Ros, E., Gómez, J. L., Bruni, G., Bach, U., Fuentes, A., Gurvits, L. I., Jauncey, D. L., Kovalev, Y. Y., Kravchenko, E. V., Lisakov, M. M., Savolainen, T., Sokolovsky, K. V., & Zensus, J. A. *Probing the innermost regions of AGN jets and their magnetic fields with RadioAstron. IV. The quasar 3C 345 at 18 cm: Magnetic field structure and brightness temperature*, 2021, Astronomy and Astrophysics, 648, A82
23. Radcliffe, J. F., Barthel, P. D., Thomson, A. P., Garrett, M. A., Beswick, R. J., & Muxlow, T. W. B. *Nowhere to hide: Radio-faint AGN in the GOODS-N field. II. Multi-wavelength AGN selection techniques and host galaxy properties*, 2021, Astronomy and Astrophysics, 649, A27
24. Schulz, R., Morganti, R., Nyland, K., Paragi, Z., Mahony, E. K., & Oosterloo, T. *Parsec-scale HI outflows in powerful radio galaxies*, 2021, Astronomy and Astrophysics, 647, A63
25. Veres, P. M., Gabányi, K. É., Frey, S., Paragi, Z., Kun, E., & An, T. *European VLBI Network Observations of the Proposed Dual AGN SDSS J101022.95+141300.9*, 2021, The Astrophysical Journal, 922, 99
26. Yang, J., van Bemmel, I., Paragi, Z., Komossa, S., Yuan, F., Yang, X.,

An, T., Koay, J. Y., Reynolds, C., Oonk, J. B. R., Liu, X., & Wu, Q. *A parsec-scale faint jet in the nearby changing-look Seyfert galaxy Mrk 590*, 2021, Monthly Notices of the Royal Astronomical Society, 502, L61

27. Yang, J., Paragi, Z., Nardini, E., Baan, W. A., Fan, L., Mohan, P., Varenius, E., & An, T. *The nearby extreme accretion and feedback system PDS 456: finding a complex radio-emitting nucleus*, 2021, Monthly Notices of the Royal Astronomical Society, 500, 2620
28. Yang, J., Paragi, Z., Beswick, R. J., Chen, W., van Bemmel, I. M., Wu, Q., An, T., Wu, X., Fan, L., Oonk, J. B. R., Liu, X., & Wang, W. *A compact core-jet structure in the changing-look Seyfert NGC 2617*, 2021, Monthly Notices of the Royal Astronomical Society, 503, 3886

9.2 EVN related referred publications (in alphabetical order) 2022

Journal Articles

1. An, T., Zhang, Y., Wang, A., Shu, X., Yang, H., Jiang, N., Dou, L., Pan, Z., Wang, T., & Zheng, Z. *VLBI imaging of the pre-coalescence SMBHB candidate SDSS J143016.05+230344.4*, 2022, Astronomy and Astrophysics, 663, A139
2. Baczko, A.-K., Ros, E., Kadler, M., Fromm, C. M., Boccardi, B., Perucho, M., Krichbaum, T. P., Burd, P. R., & Zensus, J. A. *Ambilateral collimation study of the twin-jets in NGC 1052*, 2022, Astronomy and Astrophysics, 658, A119
3. Bobylev, V. V., & Bajkova, A. T. *Study of the structure and kinematics of the Galaxy according to VLBI astrometry of masers and radio stars*, 2022, arXiv e-prints, arXiv:2212.03045
4. Breiding, P., Burke-Spolaor, S., An, T., Bansal, K., Mohan, P., Taylor, G. B., & Zhang, Y. *Deep Very Long Baseline Interferometry Observations Challenge Previous Evidence of a Binary Supermassive Black Hole Residing in Seyfert Galaxy NGC 7674*, 2022, The Astrophysical Journal, 933, 143
5. Cao, H.-M., Migliori, G., Giroletti, M., Frey, S., Yang, J., Gabányi, K. É., Cui, L., An, T., Hong, X.-Y., & Zhang, W.-D. *A long-lived compact jet in the black hole X-ray binary candidate AT2019wey*, 2022, Astronomy and Astrophysics, 657, A104
6. Climent, J. B., Guirado, J. C., Zapatero Osorio, M. R., Zakhozhay, O. V., Pérez-Torres, M., Azulay, R., Gauza, B., Rebolo, R., Béjar, V. J. S., Martín-Pintado, J., & Lefèvre, C. *Radio emission in a nearby, ultra-cool dwarf binary: A multifrequency study*, 2022, Astronomy and Astrophysics, 660, A65
7. Durjasz, M., Szymczak, M., Olech, M., & Bartkiewicz, A. *Discovery of recurrent flares of 6.7 GHz methanol maser emission in Cepheus*

A HW2, 2022, Astronomy and Astrophysics, 663, A123

8. Giarratana, S., Rhodes, L., Marcote, B., Fender, R., Ghirlanda, G., Giroletti, M., Nava, L., Paredes, J. M., Ravasio, M. E., Ribó, M., Patel, M., Rastinejad, J., Schroeder, G., Fong, W., Gompertz, B. P., Levan, A. J., & O'Brien, P. *VLBI observations of GRB 201015A, a relatively faint GRB with a hint of very high-energy gamma-ray emission*, 2022, Astronomy and Astrophysics, 664, A36
9. Gómez, J. L., Traianou, E., Krichbaum, T. P., Lobanov, A. P., Fuentes, A., Lico, R., Zhao, G.-Y., Bruni, G., Kovalev, Y. Y., Lähteenmäki, A., Voitsik, P. A., Lisakov, M. M., Angelakis, E., Bach, U., Casadio, C., Cho, I., Dey, L., Gopakumar, A., Gurvits, L. I., Jorstad, S., Kovalev, Y. A., Lister, M. L., Marscher, A. P., Myserlis, I., Pushkarev, A. B., Ros, E., Savolainen, T., Tornikoski, M., Valtonen, M. J., & Zensus, A. *Probing the Innermost Regions of AGN Jets and Their Magnetic Fields with RadioAstron. V. Space and Ground Millimeter-VLBI Imaging of OJ 287*, 2022, The Astrophysical Journal, 924, 122
10. Holoien, T. W.-S., Neustadt, J. M. M., Vallely, P. J., Auchettl, K., Hinkle, J. T., Romero-Cañizales, C., Shappee, B. J., Kochanek, C. S., Stanek, K. Z., Chen, P., Dong, S., Prieto, J. L., Thompson, T. A., Brink, T. G., Filippenko, A. V., Zheng, W., Bersier, D., Bose, S., Burgasser, A. J., Channa, S., de Jaeger, T., Hestenes, J., Im, M., Jeffers, B., Jun, H. D., Lansbury, G., Post, R. S., Ross, T. W., Stern, D., Tang, K., Tucker, M. A., Valenti, S., Yunus, S., & Zhang, K. D. *Investigating the Nature of the Luminous Ambiguous Nuclear Transient ASASSN-17jz*, 2022, The Astrophysical Journal, 933, 196
11. Kirsten, F., Marcote, B., Nimmo, K., Hessels, J. W. T., Bhardwaj, M., Tendulkar, S. P., Keimpema, A., Yang, J., Snelders, M. P., Scholz, P., Pearlman, A. B., Law, C. J., Peters, W. M., Giroletti, M., Paragi, Z., Bassa, C., Hewitt, D. M., Bach, U., Bezrukovs, V., Burgay, M., Buttaccio, S. T., Conway, J. E., Corongiu, A., Feiler, R., Forssén, O., Gawroński, M. P., Karuppusamy, R., Kharinov, M. A., Lindqvist, M., Maccaferri, G., Melnikov, A., Ould-Boukattine, O. S., Possenti, A., Surcis, G., Wang, N., Yuan, J., Aggarwal, K., Anna-Thomas, R., Bower, G. C., Blaauw, R., Burke-Spolaor, S., Cassanelli, T., Clarke, T. E., Fonseca, E., Gaensler, B. M., Gopinath, A., Kaspi, V. M., Kassim, N., Lazio, T. J. W., Leung, C., Li, D. Z., Lin, H. H., Masui, K. W., Mckinven, R., Michilli, D., Mikhailov, A. G., Ng, C., Orbidans, A., Pen, U. L., Petroff, E., Rahman, M., Ransom, S. M., Shin, K., Smith, K. M., Stairs, I. H., & Vlemmings, W. *A repeating fast radio burst source in a globular cluster*, 2022, Nature, 602, 585
12. Koryukova, T. A., Pushkarev, A. B., Plavin, A. V., & Kovalev, Y. Y. *Tracing Milky Way scattering by compact extragalactic radio sources*, 2022, Monthly Notices of the Royal Astronomical Society, 515, 1736
13. Krezinger, M., Perger, K., Gabányi, K. É., Frey, S., Gurvits, L. I., Paragi, Z., An, T., Zhang, Y., Cao, H., & Sbarrato, T. *Radio-loud*

Quasars above Redshift 4: Very Long Baseline Interferometry (VLBI) Imaging of an Extended Sample, 2022, The Astrophysical Journal Supplement Series, 260, 49

14. Kun, E., Jaroschewski, I., Ghorbanietemad, A., Frey, S., Becker Tjus, J., Britzen, S., Gabányi, K. É., Kiselev, V., Schlegel, L., Schroller, M., Reichherzer, P., Cui, L., Wang, X., & Shen, Y. *Multimessenger Picture of J1048+7143*, 2022, The Astrophysical Journal, 940, 163
15. Laha, S., Meyer, E., Roychowdhury, A., Becerra Gonzalez, J., Acosta-Pulido, J. A., Thapa, A., Ghosh, R., Behar, E., Gallo, L. C., Kriss, G. A., Panessa, F., Bianchi, S., La Franca, F., Scepi, N., Begelman, M. C., Longinotti, A. L., Lusso, E., Oates, S., Nicholl, M., & Cenko, S. B. *A Radio, Optical, UV, and X-Ray View of the Enigmatic Changing-look Active Galactic Nucleus 1ES 1927+654 from Its Pre- to Postflare States*, 2022, The Astrophysical Journal, 931, 5
16. Liu, N., Lambert, S. B., Arias, E. F., Liu, J.-C., & Zhu, Z. *Evaluation of the ICRF stability from a position time series analysis*, 2022, Astronomy and Astrophysics, 659, A75
17. Ma, M., Molera Calvés, G., Cimò, G., Xiong, M., Li, P., Kong, J., Zhang, P., He, J., Liu, L., Kummamuru, P., Hou, C., Edwards, J., Liu, Q., Chen, Z., Chu, Z., Wu, D., Zhao, X., Wang, Z., Han, S., Zhi, Q., Liu, Y., Quick, J., González, J., García Miró, C., Kharinov, M., Mikhailov, A., Neidhardt, A., Venturi, T., Morsiani, M., Maccaferri, G., Xia, B., Zhang, H., & Hao, L. *Detecting the Oscillation and Propagation of the Nascent Dynamic Solar Wind Structure at 2.6 Solar Radii Using Very Long Baseline Interferometry Radio Telescopes*, 2022, The Astrophysical Journal, 940, L32
18. Mohan, P., An, T., Zhang, Y., Yang, J., Yang, X., & Wang, A. *High-resolution VLBI Observations of and Modeling the Radio Emission from the Tidal Disruption Event AT2019dsg*, 2022, The Astrophysical Journal, 927, 74
19. Moscadelli, L., Sanna, A., Beuther, H., Oliva, A., & Kuiper, R. *Snapshot of a magnetohydrodynamic disk wind traced by water maser observations*, 2022, Nature Astronomy, 6, 1068
20. Munari, U., Giroletti, M., Marcote, B., O'Brien, T. J., Veres, P., Yang, J., Williams, D. R. A., & Woudt, P. *Radio interferometric imaging of RS Oph bipolar ejecta for the 2021 nova outburst*, 2022, Astronomy and Astrophysics, 666, L6
21. Nanci, C., Giroletti, M., Orienti, M., Migliori, G., Moldón, J., Garrappa, S., Kadler, M., Ros, E., Buson, S., An, T., Pérez-Torres, M. A., D'Ammando, F., Mohan, P., Agudo, I., Sohn, B. W., Castro-Tirado, A. J., & Zhang, Y. *Observing the inner parsec-scale region of candidate neutrino-emitting blazars*, 2022, Astronomy and Astrophysics, 663, A129
22. Nimmo, K., Hessels, J. W. T., Kirsten, F., Keimpema, A., Cordes, J. M., Snelders, M. P., Hewitt, D. M., Karuppusamy, R., Archibald, A. M., Bezrukovs, V., Bhardwaj, M., Blaauw, R., Buttaccio, S. T.,

Cassanelli, T., Conway, J. E., Corongiu, A., Feiler, R., Fonseca, E., Forssén, O., Gawroński, M., Giroletti, M., Kharinov, M. A., Leung, C., Lindqvist, M., Maccaferri, G., Marcote, B., Masui, K. W., Mckinven, R., Melnikov, A., Michilli, D., Mikhailov, A. G., Ng, C., Orbidans, A., Ould-Boukattine, O. S., Paragi, Z., Pearlman, A. B., Petroff, E., Rahman, M., Scholz, P., Shin, K., Smith, K. M., Stairs, I. H., Surcis, G., Tendulkar, S. P., Vlemmings, W., Wang, N., Yang, J., & Yuan, J. P. *Burst timescales and luminosities as links between young pulsars and fast radio bursts*, 2022, Nature Astronomy, 6, 393

23. Nimmo, K., Hewitt, D. M., Hessels, J. W. T., Kirsten, F., Marcote, B., Bach, U., Blaauw, R., Burgay, M., Corongiu, A., Feiler, R., Gawroński, M. P., Giroletti, M., Karuppusamy, R., Keimpema, A., Kharinov, M. A., Lindqvist, M., Maccaferri, G., Melnikov, A., Mikhailov, A., Ould-Boukattine, O. S., Paragi, Z., Pilia, M., Possenti, A., Snelders, M. P., Surcis, G., Trudu, M., Venturi, T., Vlemmings, W., Wang, N., Yang, J., & Yuan, J. *Milliarcsecond Localization of the Repeating FRB 20201124A*, 2022, The Astrophysical Journal, 927, L3
24. Plavin, A., Paragi, Z., Marcote, B., Keimpema, A., Hessels, J. W. T., Nimmo, K., Vedantham, H. K., & Spitler, L. G. *FRB 121102: Drastic changes in the burst polarization contrasts with the stability of the persistent emission*, 2022, Monthly Notices of the Royal Astronomical Society, 511, 6033
25. Powell, D. M., Vegetti, S., McKean, J. P., Spingola, C., Stacey, H. R., & Fassnacht, C. D. *A lensed radio jet at milliarcsecond resolution I: Bayesian comparison of parametric lens models*, 2022, Monthly Notices of the Royal Astronomical Society, 516, 1808
26. Ricci, L., Boccardi, B., Nokhrina, E., Perucho, M., MacDonald, N., Mattia, G., Grandi, P., Madika, E., Krichbaum, T. P., & Zensus, J. A. *Exploring the disk-jet connection in NGC 315*, 2022, Astronomy and Astrophysics, 664, A166
27. Salafia, O. S., Ravasio, M. E., Yang, J., An, T., Orienti, M., Ghirlanda, G., Nava, L., Giroletti, M., Mohan, P., Spinelli, R., Zhang, Y., Marcote, B., Cimò, G., Wu, X., & Li, Z. *Multiwavelength View of the Close-by GRB 190829A Sheds Light on Gamma-Ray Burst Physics*, 2022, The Astrophysical Journal, 931, L19
28. Surcis, G., Vlemmings, W. H. T., van Langevelde, H. J., Hutawarakorn Kramer, B., & Bartkiewicz, A. *EVN observations of 6.7 GHz methanol maser polarization in massive star-forming regions. V. Completion of the flux-limited sample*, 2022, Astronomy and Astrophysics, 658, A78
29. van Bemmel, I. M., Kettenis, M., Small, D., Janssen, M., Moellenbrock, G. A., Petry, D., Goddi, C., Linford, J. D., Rygl, K. L. J., Liuzzo, E., Marcote, B., Bayandina, O. S., Schweighart, N., Verkouter, M., Keimpema, A., Szomoru, A., & van Langevelde, H. J. *CASA on the Fringe-Development of VLBI Processing Capabilities for CASA*, 2022, Publications of the Astronomical Society of the Pacific, 134,

114502

30. Wu, H., Wu, Z., Sotnikova, Y., Chen, Y., Zhang, B., Mufakharov, T., Shen, Z., Chen, X., Mikhailov, A., Mingaliev, M., Han, X. L., & Misra, P. *Radio properties of the OH megamaser galaxy IIZw 096*, 2022, Astronomy and Astrophysics, 661, A125
31. Yang, J., Yang, X., Wrobel, J. M., Paragi, Z., Gurvits, L. I., Ho, L. C., Nyland, K., Fan, L., & Tafoya, D. *Is there a sub-parsec-scale jet base in the nearby dwarf galaxy NGC 4395?*, 2022, Monthly Notices of the Royal Astronomical Society, 514, 6215
32. Yang, J., Chen, Y., Gurvits, L. I., Paragi, Z., Yang, A., Yang, X., & Shen, Z. *Structural and spectral properties of Galactic plane variable radio sources*, 2022, Monthly Notices of the Royal Astronomical Society, 511, 280
33. Yang, X., Ji, J., Joshi, R., Yang, J., An, T., Wang, R., Ho, L. C., Roberts, D. H., & Saripalli, L. *The X-shaped Radio Galaxy J0725+5835 is Associated with an AGN Pair*, 2022, The Astrophysical Journal, 933, 98
34. Zhang, M., Yuan, Q., Liu, J.-Y., & Zhang, L. *Role of the companion lensing galaxy in the CLASS gravitational lens B1152+199*, 2022, Monthly Notices of the Royal Astronomical Society, 511, 1085

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

The European VLBI Network (EVN) is a network of radio telescopes located primarily in Europe and Asia, with additional antennas in South Africa and Puerto Rico, which performs very high angular resolution observations of cosmic radio sources. This report comprises information on the EVN science, operations, observatory reports, activities, meetings, and publications over the biennium 2021-2022.

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