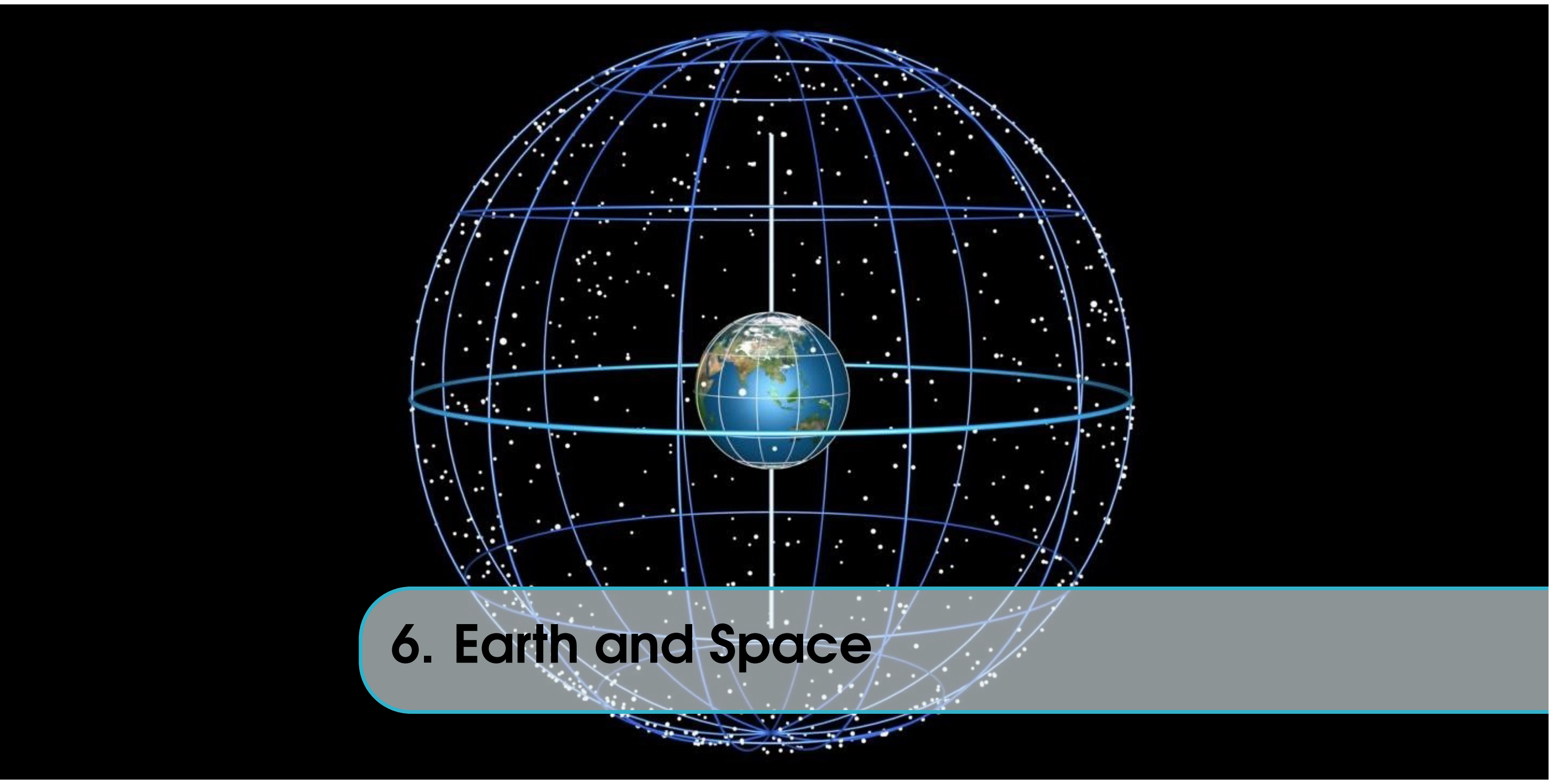



# 6. Earth and Space

## 6.1 Celestial reference frames

### 6.1.1 A unique capability for positioning

The determination of the motion of celestial bodies through repeated measurements of their position using astrometric techniques constitutes the foundation of our present understanding of the Universe. For consistency in time and space, and hence comparisons for different celestial bodies, such determinations must be established in well-defined coordinate (or reference) systems. In practice, coordinate axes for celestial systems are not defined directly but only implicitly through the adoption of a set of fiducial directions, precisely identified and highly stable over long timescales. Specific celestial bodies possessing the required properties are used to materialise such directions.

VLBI is a unique tool that allows astronomers to study the compact radio emission of celestial bodies in extreme details and to pinpoint their direction in the sky with unprecedented accuracy. Thanks to this capability, the technique has been used for the past twenty years to establish fundamental celestial reference frames. The objects targeted for this purpose are black-hole powered AGN. These possess highly compact central emission (of non-thermal synchrotron origin), ensuring well-defined fiducial directions. Additionally, they have no detected proper motions due to their location at cosmological distances. The number of objects measured in this way grew from a few hundreds in the 1990s to several thousands today. On the celestial sphere, they form a grid of points whose two-dimensional coordinates define a reference frame. Such a grid is also the basis for ultra-precise relative VLBI astrometry, e.g. to determine distances and transverse velocities of Galactic objects out to tens of kpc through measurements of proper motions and parallaxes.

The most comprehensive VLBI reference frame to date is the third realisation of the International Celestial Reference Frame, ICRF3 (Charlot et al. 2020), adopted by the IAU in August 2018 to replace the previous realisation, ICRF2 (Fey et al. 2015), built ten years earlier, as the new fundamental celestial reference frame. ICRF3 comprises positions for 4536 extragalactic sources, as measured at 8 GHz (Fig. 6.1), 303 of which, uniformly distributed on the sky, are identified as *defining sources* and as such serve to define the axes of the frame. Positions at 8 GHz are

Chapter image credit: E. Siegel, ScienceBlogs.

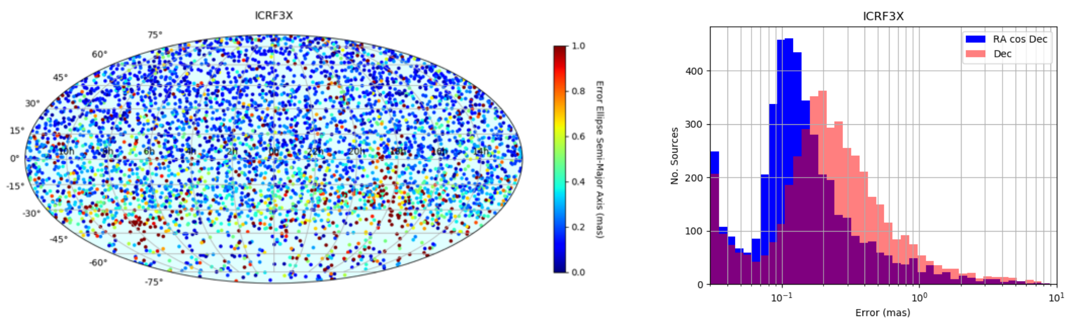



Figure 6.1: (left) Sky distribution of the 4536 extragalactic sources comprised in ICRF3 (8 GHz frequency) with colour coding according to position accuracy. (right) Histogram of errors in right ascension and declination for those sources plotted with a log-scale. Charlot et al. (2020).

supplemented with positions at 24 GHz for 824 sources and at 32 GHz for 678 sources. In all, ICRF3 includes a total of 4588 sources, 600 of which sources have three-frequency positions available. The positions have been estimated independently at each of the frequencies in order to preserve the underlying astrophysical content behind such positions. The frame shows median positional errors of the order of 100 $\mu$as in right ascension and 200 $\mu$as in declination with a noise floor of 30 $\mu$as in the individual coordinates. Among these, a subset of 500 sources is found to have extremely accurate positions, in the range of 30–60 $\mu$as (Fig. 6.1).

### 6.1.2 Fundamental physics and astronomy

The newly-released ICRF3, with its increased positional accuracy and its observing span approaching 40 years (1979–2018), will allow the scientific community to tackle new questions in astronomy and fundamental physics. The long time base now makes mandatory the modelling of Galactocentric acceleration, a secular effect introduced by the rotation of the Solar System barycentre around the Galactic centre. This effect, first detected by Titov et al. (2011), has emerged from the ICRF3 data set with a magnitude of $5.8 \pm 0.3$ $\mu$as/yr and manifests itself through apparent long-term proper motions of the radio sources if not accounted for in the modelling. Continued observing and accumulation of data in the future will further improve that value and determine whether the motion of the Solar System is purely towards the Galactic centre or whether it has an off-plane component. In a similar way, the low-frequency ($< 10^{-9}$ Hz) gravitational wave background, although not detected at present, may be revealed in the future through such quasar proper motions (Gwinn et al. 1997, Titov et al. 2011, Darling et al. 2018). VLBI is also essential for testing General Relativity, e.g. through the determination of the relativistic parameter $\gamma$ (Lambert and Le Poncin-Lafitte 2011) or for trying alternate theories (Le Poncin-Lafitte et al. 2016). Here also, accumulation of data and extending the time base will further improve the level of such tests.

### 6.1.3 Astrophysics of active galactic nuclei

The multi-frequency positional information in ICRF3 together with the optical positions recently derived with the *Gaia* space mission which show similar accuracies (Gaia collaboration et al. 2018) provide new insights into the physics of AGN. At radio frequencies, these objects generally feature a bright compact core and a single-sided relativistic jet with blobs of emission moving away from the

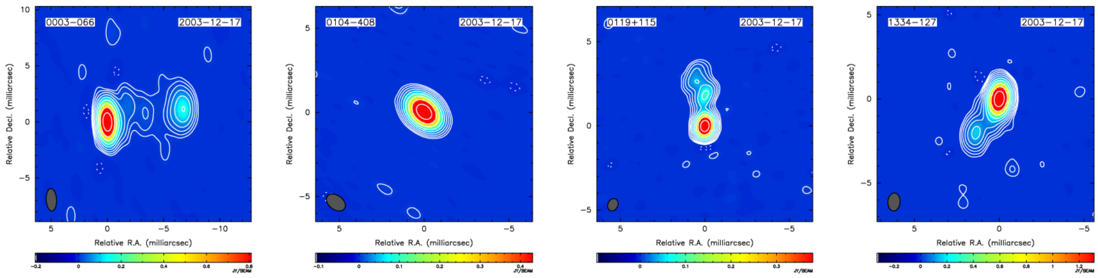



Figure 6.2: A sample of VLBI maps from the Bordeaux VLBI Image Database (Collioud and Charlot 2019) showing the predominantly core-jet structure of the ICRF sources on milliarcsecond scales.

core on time scales of months to years (Fig. 6.2). Future reference frames will have to account for such time-varying extended internal structures for the highest accuracy, a perspective that motivates systematic VLBI imaging programmes to monitor the structure of the ICRF sources. In the light of such extended emission, comparison of the ICRF3 and *Gaia* positions becomes essential to understand whether the radio emission and optical emission are superimposed in these objects. Initial estimates of such radio-optical "core shifts" indicated that they amount to 100 $\mu$as on average (Kovalev et al. 2008), which is significant considering the VLBI and *Gaia* position accuracies. While potentially affecting the alignment between the two frames, the radio-optical positional differences also offer a unique opportunity to directly determine those core-shifts and probe the geometry of quasars in the framework of unified AGN theories. In particular, such measurements may help to locate the optical region relative to the relativistic radio jet and determine whether the dominant optical emission originates from the accretion disk or the inner portion of the jet. Taking advantage of the first and second *Gaia* data releases, it was found that significant VLBI-*Gaia* offsets do exist for 10–20% of the sources (Mignard et al. 2016, Petrov & Kovalev, 2017a, Gaia collaboration et al. 2018, Petrov et al. 2019, Charlot et al. 2020) and that these occur preferably along the jet direction, which was interpreted as a manifestation of the presence of bright optical jets (Kovalev et al. 2017, Petrov & Kovalev 2017b, Plavin et al. 2019). Future *Gaia* data releases may reveal offsets for an increased fraction of objects thanks to further improved positional accuracy, in synergy with VLBI measurements.

### 6.1.4 Rotational motion and dynamics of the Earth

Another unique capability of VLBI is its ability to track the rotational motion of the Earth in the quasi-inertial frame defined by the distant quasars. This motion includes a secular drift and periodic oscillations of the Earth's rotation axis (i.e. precession and nutation, see Fig. 6.3) along with a daily rotation around it. The latter, which may be expressed as the length of day, is irregular and unpredictable at some level since it is closely tied to the atmospheric conditions, thus requiring continuous VLBI observations to be followed. The nutational motion depends on the geophysical properties of the Earth and allows one to learn about the Earth's interior (Mathews et al. 2002, Rosat et al. 2017). Key challenges in this area are the detection of the Earth's solid inner core, independently of seismic data, and the understanding of the origin and variability of the free core nutation. The latter also requires progress in global circulation models and the theory of the Earth's rotation (Ziegler et al. 2019). These challenges necessitate VLBI monitoring over long time scales and with high accuracy. In the future, this should be accomplished with the VLBI Global Observing System, a

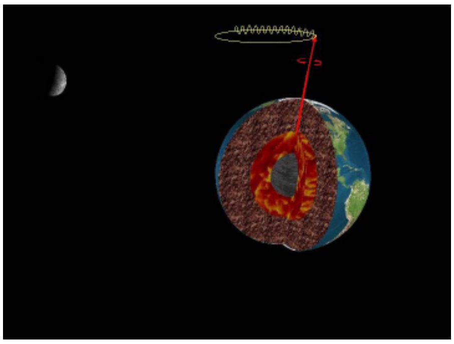


Figure 6.3: Schematic representation of the Earth's precession and nutation motion with the different components of its interior structure depicted (mantle, liquid outer core, solid inner core). Credit: IVS.

new array consisting of fast-moving 12 m antennas that is currently set up by the International VLBI Service for Geodesy and Astrometry and designed to observe 24 hours a day all year long. On the geodesy side, the goal of such an array, permanently observing, is to reach millimeter positional accuracy. Achieving a terrestrial reference frame at that level is essential to understand deformations of the Earth crust (e.g. seasonal signals, seismic and post-seismic effects) and more generally to monitor global changes that affect our planet, among which sea level rise.

### 6.1.5 Contribution of EVN

All scientific topics addressed above should benefit from future improvements of the VLBI celestial reference frame. As shown from Fig. 6.1, there are two obvious areas of improvements: (i) position accuracy in the southern sky, which is typically degraded by a factor of 2 compared to that in the northern sky since the VLBI networks used to build ICRF3 were predominantly East-West, and (ii) lower sky density in the far South (i.e. below $-45^\circ$ declination) due to the sparseness of VLBI radio telescopes in the southern hemisphere. In respect of these improvements, the EVN has a significant role to play. By providing long North-South baselines, from Europe to the Hartebeesthoek antenna in South Africa and in the future to antennas of the developing African VLBI Network (Gaylard et al. 2011), it can help to break the North-South asymmetry in position accuracy. Incorporating SKA1-MID as an element of the array will also largely improve its sensitivity, hence permitting to expand considerably the celestial frame, with the goal of obtaining a more complete radio counterpart of the *Gaia* celestial frame. With its location in the southern hemisphere, SKA1-MID will further help to correct the currently uneven sky distribution, as noted above. Also to be mentioned is the capability of the EVN to observe at higher frequencies, especially at 22 GHz, which is one of the three ICRF3 frequencies, and hence its potential to contribute to the development of the celestial frame at this frequency. Incorporation of observations on long North-South baselines to Hartebeesthoek, here again, would be especially useful to enhance the geometry of the frame.

## 6.2 Near-field VLBI for space and planetary science

### 6.2.1 Spacecraft as a VLBI target: science applications

As outlined above (and also earlier in this document), astrometric and geodetic applications of the VLBI technique are well-established scientific disciplines. They are based on the fundamental assumption of the 'traditional' radio interferometry: the source of the emission is located at an infinitely large distance from the observer, thus the light paths from the source to the elements of the interferometer can be assumed parallel, and the wave front – planar. Such the assumption can be accepted if the distance to the source is (much) greater than the so-called Fraunhofer distance, $B^2/\lambda$, where $B$ is the projected baseline and $\lambda$ the observing wavelength. In astrometry, an ideal source of emission is point-like. Spacecraft, as radio astronomy targets, are indeed point-like sources. In principle, they might be treated as targets of VLBI astrometry and therefore their celestial coordinates could be estimated with the VLBI precision, as is the case for galactic and extragalactic radio sources. However, for typical deep space communication frequencies (e.g. 2.3, 8.4 or 32 GHz) practically the entire Solar system is within the Fraunhofer distance for global VLBI baselines. Thus, implementation of VLBI astrometry for spacecraft requires development of a special technique, the so-called near-field VLBI.

VLBI observations (sometimes called 'VLBI tracking') of spacecraft have been suggested in the early 1970s (e.g. Ondrasik & Rourke 1971) and demonstrated on a number of deep space missions, such as *Apollo 16* and *Apollo 17* (Salzberg 1973), *Pioneer Venus probes* (Councelmann III et al. 1979), *Voyager* (Border et al. 1982), *VEGA* (Preston et al. 1986), *Huygens Titan Probe* (Pogrebenko et al. 2004, Lebreton et al. 2005), *Cassini* (Jones et al. 2011), *SELENE* (Goossens et al. 2011), *IKAROS* (Takeuchi et al. 2011), *Chang'E* (Li 2008 and references therein), *Venus Express* (Duev et al. 2012), *Mars Express* (Duev et al. 2016) and others. In combination with other trajectory measurements techniques, e.g. range and range-rate (Doppler) tracking, VLBI tracking enables estimates of the spacecraft state vector as a function of time – the main task of the orbit determination (OD).

Nominal OD assets of major space agencies, such as the Deep Space Network (DSN) of NASA and European Space Tracking (ESTRACK) of ESA, exploit the Delta-Differential One-Way Ranging, or DeltaDOR technique – an offspring of VLBI (Maddè et al. 2006, Curkendall & Border 2013, and references therein). The latter involves a single baseline configuration of two widely separated (order of thousand kilometres) tracking stations and enables a nanoradian (0.2 mas) precision of lateral positioning of spacecraft. While being the most accurate operational technique for lateral measurements of the spacecraft celestial position, DeltaDOR does not provide as much versatility and robustness as multi-element near-field VLBI tracking. The advantages of the latter technique are in a better instrumental calibratability, redundancy of baseline solutions, ability to exploit larger (more sensitive) radio astronomy antennas, ability to choose the best baselines in terms of local ionosphere turbulence and best target visibility conditions (e.g. a larger elevation at interferometer elements). Besides, flexibility of observing setup, data handling and processing algorithms in VLBI tracking provide for a broad variety of science applications.

Over the period 2005–2018 the methodology of addressing various scientific interests with near-field VLBI observations has grown into the concept of Planetary Radio Interferometry and Doppler Experiment (PRIDE, Gurvits et al. 2013; see Fig. 6.4). The technique of PRIDE has been described by Duev et al. (2012) and Bocanegra-Bahamon et al. (2018); its value for contributing into orbit determination of interplanetary spacecraft and planetary probes is addressed in Dirkx et al. (2016, 2017, 2018).

In addition to the immediate needs of OD, which is required for mission operations (e.g. navigation), near-field VLBI offers a wide range of science applications demonstrated recently in many experiments conducted by EVN and global VLBI networks. These include:

- Ultra-precise tracking of spacecraft during fly-by of a gravitating body (in application to the Mars Express Phobos flyby in December 2013), Duev et al. 2016. Fly-by observations

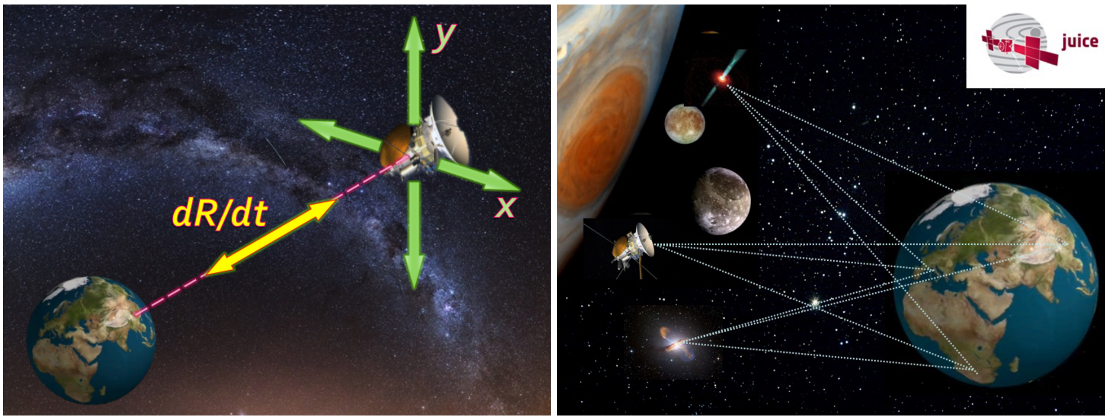



Figure 6.4: (left) Generic configuration of the Planetary Radio Interferometry and Doppler Experiment (PRIDE). Its main measurables are the radial Doppler shift of the spacecraft radio signal (dR/dt) and lateral celestial coordinates x and y. (right) PRIDE configuration for the ESA's Jupiter Icy Satellites Explorer (*JUICE*) mission. From Gurvits et al. (2013).

contribute into estimating parameters of the gravitational field and interior of the gravitating body (e.g. internal structure of planetary bodies).

- Contribution into ultra-precise 'non-standard' OD for scientific missions, e.g. *RadioAstron*, in support of its space-ground VLBI observations (Duev et al. 2015).
- Improvement of ephemerides of planetary satellites (Dirkx et al. 2016, 2017).
- Interplanetary plasma diagnostics (Molera Calvés G. et al. 2014), including serendipitous detection of coronal mass ejections (Molera Calvés G. et al. 2016).
- Deep sounding of (dense) planetary atmospheres by radio occultation measurements (e.g. *Venus Express* occultations, Bocanegra-Bahamon T.M. et al.).
- Contribution into fundamental physics experiments by supplementary Doppler measurements and PRIDE-based data processing (Litvinov et al. 2018).

### 6.2.2 Near-field VLBI in the EVN context

The EVN as a network began operating in the near-field VLBI mode in 2003 in preparation for the Huygens VLBI tracking experiment (Pogrebenko et al. 2004, Witasse et al. 2006). As part of this preparation, the first incarnation of the SFXC correlator has been developed at JIVE, which later has become and remains to date the main operational EVN data processor (Keimpema et al. 2015).

Based on the know-how developed at JIVE with its EVN partners, an implementation of PRIDE for a Jovian mission has been selected by ESA in 2012 as one of eleven experiments of the Jupiter Icy Satellites Explorer, the *JUICE* mission (Hussmann et al. 2014; Fig. 6.4). The mission is scheduled for launch in 2022 and arrival to the Jovian system in the end of 2029 followed by three-year-long science operations in the vicinity of Jupiter and its satellites. PRIDE-*JUICE* will address a number of science topics listed in the previous section.

Several other planetary missions, such as *ExoMars-2020* (Mars), *Chang'E-4* (Moon), *EnVision* (Venus), *Europa Clipper* (Jupiter and Jovian system) are slated to exploit near-field VLBI and PRIDE techniques in order to maximise their science return. PRIDE involvement in planetary science missions addresses most topical issues in the area of origins and evolution of Solar and other planetary systems. As such, the outcome of near-field VLBI tracking addresses the topics of the highest scientific priority in the strategic outlooks of all major world space agencies.

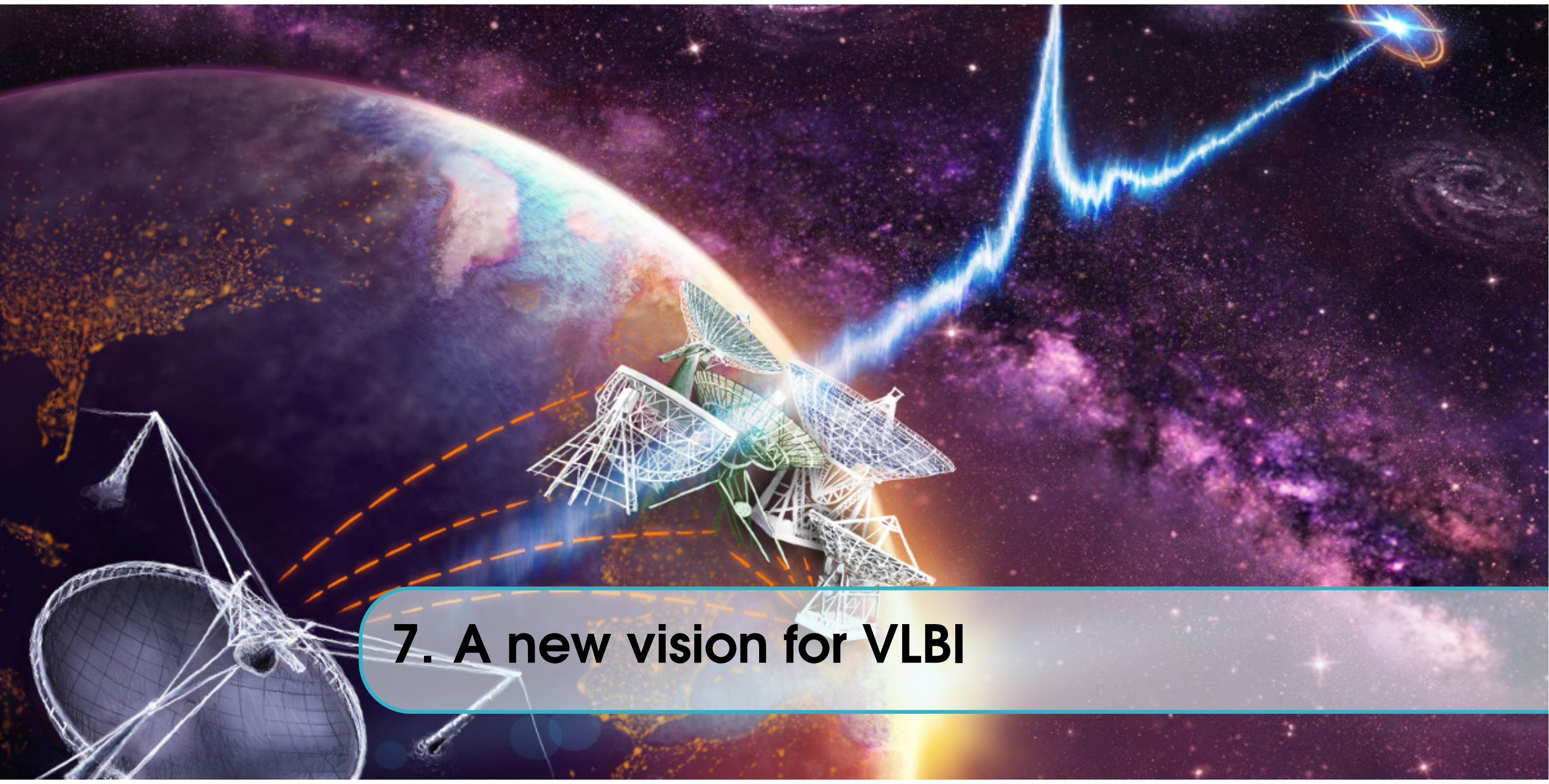
It is important to underline that VLBI tracking experiments with these and other planetary and space science missions require close cooperation with the respective project teams of scientists and engineers for longer than usual in "traditional" VLBI timespans. Typically, a lifetime of a modern planetary science mission is $\sim 20$ years, sometimes longer. This requires a well-balanced foresight of relevant developments of VLBI instrumentation and involved person-power.

EVN is well positioned to address the needs of PRIDE observations in the next one or two decades. Its geographical distribution, frequency coverage and superb sensitivity plus the already demonstrated flexibility of the EVN data processing facilities at JIVE provide a solid basis for multi-disciplinary research in the area of space and planetary science applications.

## REFERENCES


Bocanegra-Bahamon, T.M. et al., 2018, *A&A*, **609**, A59
Bocanegra-Bahamon, T.M. et al., 2019, *A&A*, submitted
Border, J.S. et al., 1982, *AIAA/AAS Astrodynamics Conference*, San Diego, CA, AIAA-82-1471
Charlot, P. et al., 2020, *A&A* (submitted)
Collioud, A. & Charlot, P., 2019, *Proceedings of the* 24$^{th}$ *European VLBI for Geodesy and Astrometry Working Meeting*, Eds. R. Haas, S. Garcia-Espada and J.A. Lopez-Fernandez, p. 219
Counselmann III, C.C. et al., 1979, *Science*, **203**, 805
Curkendall, D.W. & Border, J.S., 2013, *IPN Progress Report*, 42-193, JPL
Darling, J., Truebenbach, A. E. & Paine, J., 2018, *ApJ*, **861**, 113
Dirkx, D. et al., 2016, *PSS*, **134**, 82-95
Dirkx, D. et al., 2017, *PSS*, **147**, 14–27
Dirkx, D. et al., 2019, *Journal of Geodesy*, in press
Duev, D.A. et al., 2012, *A&A* 541, A43
Duev, D.A. et al., 2015, *A&A* 573, A99
Duev, D.A. et al., 2016, *A&A* 593, A34
Fey, A. L. et al., 2015, *AJ*, **150**, 58
Folkner, W.M. et al., 2009, *The Planetary and Lunar Ephemeris*, **DE 421**, Tech. Rep. IPN Progress Report 42-178. JPL
Gaylard, M. J. et al., 2011, *Proceedings of SAIP2011, the 56th Annual Conference of the South African Institute of Physics*, Eds. I. Basson and A. E. Botha, p. 425
Gaia Collaboration, Mignard, F. et al., 2018, *A&A*, **616**, A14
Goossens, S. et al., 2011, *Journal of Geodesy*, **85**, 205
Gurvits, L. I. et al., 2013, *European Planetary Science Congress*, **8**, 357
Gwinn, C. R. et al., 1997, *ApJ*, **485**, 87
Hildebrand, C.E. et al., 1983, *Very Long Baseline Interferometry*, Cepadeus-Editions, France, 55
Hussmann, H. et al., 2014, ESA/SRE(2014)1
Jones, D. et al., 2011, *AJ*, **141**, 29
Keimpema, A. et al., 2015, *Exp. Astr.* **39**, 259
Kovalev, Y. Y. et al., 2008, *A&A*, **483**, 759
Kovalev, Y. Y., Petrov, L. & Plavin, A. V., 2017, *A&A*, **598**, L1
Lambert, S. B. & Le Poncin-Lafitte, C., 2011, *A&A*, **529**, A70
Lebreton, J.-P. et al., 2005, *Nature*, **438**, 758

Le Poncin-Lafitte, C., Hees, A. & Lambert, S. B., 2016, *Phys. Rev. D*, **94**, 125030
Li, J.L., 2008, in: Measuring the Future, eds. Finkelstein A., Behrend D., Nauka:SPb, 193
Litvinov, D. et al., 2018, *Phys. Letters A*, **382**, 2192
Maddè, R. et al., 2006, *ESA Bulletin*, **128**, 68
Mathews, P. M., Herring, T. A. & Buffett, B. A., 2002, *JGR*, **107(B4)**, ETG 3-1
Mignard, F. et al., 2016, *A&A*, **595**, A5
Molera Calvés, G. et al., 2014, *A&A*, **564**, A4
Molera Calvés, G. et al., 2017, *Space Weather*, **15**, 1523
Ondrasik, V.J., & Rourke, K.H., 1971, AAS/AIAA Astrodynamics Specialists Conference, Fort Lauderdale, Fla , paper 71-399
Petrov, L. & Kovalev, Y. Y., 2017a, *MNRAS*, **467**, L71
Petrov, L. & Kovalev, Y. Y., 2017b, *MNRAS*, **471**, 3775
Petrov, L., Kovalev, Y. Y. & Plavin, A. V., 2019, *MNRAS*, **482**, 3023
Plavin, A.V., Kovalev, Y.-Y. & Petrov, L., 2019, *ApJ*, **871**, 143
Pogrebenko, S.V. et al., 2004, *Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science*, **544**, 197
Preston, R.A. et al., 1986, *Science*, **231**, 1414
Rosat, S. et al., 2017, *GJI*, **208**, 211
Salzberg, I.M., 1973, *Proc. IEEE*, **61(9)**, 1233
Takeuchi, H. et al. 2011, `http://www.ursi.org/proceedings/procGA11/ursi/J04-6.pdf`
Titov, O., Lambert, S., & Gontier, A.-M 2011, *A&A*, **529**, A91
Witasse, O. et al., 2006, *Journal Geophys. Research*, **111**, E07S01
Ziegler, Y. et al., 2019, *IVS 2018 General Meeting Proceedings, Global geodesy and the role of VGOS – Fundamental to sustainable development*, Eds. Kyla L. Armstrong, Karen D. Baver & Dirk Behrend, NASA-CP-2019-219039, p. 264



# 7. A new vision for VLBI

The science cases described in previous chapters put forward a range of prerequisites for the EVN to continue its role as the most sensitive cm-wave VLBI array in the world, in all different astrophysical areas. This chapter makes recommendations in terms of needed technical developments to telescopes and correlators, array operations and data archiving, for the EVN to best realise this scientific potential. Since much of the impact of the EVN will be made in tandem with other existing or planned astronomical instruments, we first in Section 7.1 survey the potential synergies between the EVN and those instruments and how those drive future technical, operational and data requirements of the EVN. In Section 7.2 we combine these requirements with the science cases described, to make specific recommendations for EVN development. These recommendations are divided in each case as on-going efforts, to enhance the EVN performance step by step, and long term development goals to be completed by the end of this decade and beyond. Section 7.3 makes some concluding remarks. An overview of the current world radio facilities most relevant to this document, as well as the current technological framework for VLBI in Europe and realistic prospects for its development are reported in Sect. A.1 and A.2 respectively.

## 7.1 The European VLBI Network within the future Astronomical Landscape

### 7.1.1 Synergy with global cm/mm VLBI – Global VLBI Alliance

VLBI is one of the most successful examples of international scientific and technological cooperation. Several independent VLBI networks are operational nowadays (see Sect. A.1): the EVN, VLBA, EAVN, LBA and GMVA offer observing time in the 1-100 GHz frequency range; the International LOFAR Telescope operates at a few hundred MHz; EHT has successfully combined high-frequency telescopes to observe at 230 GHz; the International VLBI Service (IVS) for Geodesy and Astrometry operates in the frequency range 2–14 GHz. All in all, VLBI allows milliarcsecond to $\mu$arcsecond observations in a frequency range which spans 3 orders of magnitude in frequency, from a few

Chapter image credit: The globally distributed dishes of the European VLBI Network are linked with each other and the 305-m William E. Gordon Telescope at the Arecibo Observatory in Puerto Rico. Together they have localised FRB 121102's exact position within it's host galaxy. Artwork: Danielle Futselaar.

hundred MHz to a few hundred GHz; finally SKA will include VLBI modes with outer antennas in phase 1, while long (thousands of km) baselines will be part of the phase 2 development.

Such networks usually operate independently of each other, partly because of the different observing frequencies, and partly because of the different simultaneous sky coverage. At the same time, if we look at the VLBI facilities throughout Earth as a whole, the contribution of VLBI at any given time is amazing. The efficiency and impact of VLBI would further increase with a global coordination effort to facilitate the flow of information among the several VLBI networks.

The concept of a Global VLBI Alliance is under development, formally as a working group within IAU, with the scope to provide such overarching activity. Its main purposes would be sharing strategies, technical developments for compatibility, logistics, operations, and user support. It would further promote, propose and coordinate common observational campaigns with these existing networks, and ensure that adequate information is provided to and from the users.

The VLBI technique is still considered complicated ('black belt') by many, and appropriate user support is essential. This is currently offered by each network independently, with the exception of some training events which involve several networks (e.g. the European Radio Interferometry School, ERIS). A unique common portal would explain the characteristics of the different networks, and the options for users to access them or in combination. Moreover, since the VLBI networks are 'open sky' facilities, the community of VLBI users is global. It would then be beneficial that each network has sufficient knowledge of the characteristics of the other networks in house, so that users can receive support locally.

In practice the Global VLBI Alliance would serve as contact point and framework of collaboration of the VLBI networks, and would encourage and support new VLBI activities, such as the AVN, Iniciativa VLBI IberoAmericana (IVIA), and developments in southeast Asian countries.

With the advent of the SKA and its precursors, and in the light of the next generation Very Large Array (ngVLA), such global coordination of the various networks and their participating telescopes will be a strong requirement.

### 7.1.2 Synergies between EVN and LOFAR

At present LOFAR (see A.1.9) mostly works with very wide field imaging and arcsecond angular resolution while the EVN/JIVE works with small field of view imaging and millarcsecond resolution. The gradual extension of ILT to longer and longer baselines meets the trend of densifying the EVN with short spacings, increasing its brightness temperature sensitivity. Given that LOFAR observes down to few tens of MHz, this offers the possibility to study phenomena over a very broad frequency range at similar angular resolution, which puts strong constraints on emission processes and physical conditions. The ILT imaging capabilities at sub-arcsecond resolutions will be further enchanced by the dramatic advances in software and pipelines that exploit the international baselines, and the future inclusion of Nenufar in France, providing a new large station for the ILT which will significantly increase the signal to noise ratio and image fidelity. In short, the ILT will evolve to have angular resolutions more comparable to EVN+*e*-MERLIN, enabling more joint science projects. As for EVN+*e*-MERLIN, ICT advances leading to increase in correlation capacity, data storage and imaging capacity are expected to dramatically increase the field of view of VLBI observations in the cm-bands. In the future, wide-field EVN images are expected to become the norm as opposed to being special projects as at present. The prospects for wide field VLBI imaging are such that projects to image the whole Northern sky at VLBI resolution are presently being planned. Such wide field imaging will be directly comparable to the LOFAR survey data.

In terms of particular common science areas one exciting prospect is to use international LOFAR wide field images to find large populations of compact objects in galaxies consisting of Radio Supernova/Supernova Remnants and weak AGN - which can then be followed up at higher resolution with the EVN. In the field of AGN, the physics of radio lobes, and the detection of HI absorption at high redshifts on sub-kpc scales have already been considered as example areas where both instruments can make a major impact. Other obvious targets are the local LLAGN population and radio galaxies at very high redshifts. These are two populations of particular interest that LOFAR surveys are sensitive to (for different reasons), and which would be ideal targets for deep EVN follow-up observations as well. In the area of transients, there is synergy in being able to observe and potentially image evolving transient structures (including in polarisations) and their environment over a wide range of radio wavelengths. Identifying short transients at LOFAR frequencies would be particularly interesting, but joint FRB studies would be extremely valuable also for low-frequency characterisation of persistent counterparts, that will help reveal the nature of FRB progenitors. A phenomenon that would hugely benefit from observations in a broad range of frequencies is scintillation and scatter broadening (pulsars, AGN). Simultaneous observations of temporal scattering of signals (LOFAR) and scatter broadening (EVN) would place strong constraints on the location and physical conditions of the scattering medium. Studies of interstellar scattering of AGN would be possible in which the EVN can measure intrinsic sizes of sources that are scatter-broadened at LOFAR frequencies. Likewise EVN+*e*-MERLIN 18 cm observations at matched resolution to international LOFAR will allow the study within galaxies of the distribution of free-free absorption and the spatial distribution spectral index of synchrotron emission. There is also significant overlap between the two instruments in observations of radio emission from radio stars and potentially from extrasolar planets of star-exoplanet interactions. Finally, LOFAR with its large field of view and survey data acting as a baseline can identify and locate new radio sources detected at very low resolution in other wavebands (such as gamma-ray or X-ray) which can then be located even more precisely and potentially have their internal structures imaged by the EVN.

Finally there is potential synergy between LOFAR and EVN in terms of data handling and archiving. Especially given that both instruments have their operational headquarter for user support at ASTRON/JIVE, in the same building, there are obvious advantages in coordinating archive data experience for users of both instruments, so that while remaining separate archives, solutions found for one instrument can be used for the other.

### 7.1.3 Synergy with SKA

The first-phase mid-frequency telescope of the SKA, SKA1-MID will be based in South Africa, with maximum baseline length of about 120 km. Since the science cases have been originally developed for the SKA with 2000-3000 km baselines in mind, there is a strong interest in doing VLBI with SKA1-MID that would cover a broad range of angular scales (Paragi, Chrysostomou & Garcia-Miró 2019; see Fig. 7.1). This will be done by phasing up the SKA1-MID core, just like it was done with the phased-array Westerbork Synthesis Radio Telescope within the EVN. The difference is that SKA1-MID will provide multiple phased-array beams, and the use of local interferometer data (e.g. SKA1-MID data products) will be better streamlined for SKA-VLBI (Paragi et al. 2016).

While SKA-VLBI requires a global collaboration, the EVN (and especially JIVE, as potential SKA-VLBI data centre) would play a major role in this. The Horizon 2020 JUMPING JIVE project work package "VLBI with SKA" (WP10) was established in order to help define the key SKA-VLBI science goals and use cases, the operational model, as well as the VLBI interfaces and specific requirements for the SKA telescopes (Garcia-Miró et al. 2019). The SKA will provide calibrated VLBI beams, but it is up to a future (SKA-)VLBI consortium to deliver VLBI terminals, handle the proposals, schedule and carry out the observations, do the correlation in an external data centre and provide user support.

The science with the SKA-VLBI is naturally aligned with that of the current EVN research. There are a few areas though that receive particular attention, especially those that require ultra-precise astrometric precision: key science projects on pulsar VLBI astrometry and 6D tomography of the Galaxy will support some of the highest ranked science objectives of the SKA. Other areas are very high resolution observations of specific deep fields in support of SKA continuum, spectral line or transient surveys. The latter requires both near real-time e-VLBI correlation and data buffering solutions for SKA-VLBI. The current e-EVN is thus a natural pathfinder not only in a technological sense but also for SKA-VLBI operations.

Besides dedicated VLBI projects, another way of realising SKA-VLBI is commensal VLBI observations, piggybacking on some of the SKA1-MID surveys (for constraints see Garcia-Miró et al. 2019). To fully exploit this option a Southern expansion of the EVN and support for setting up an African VLBI Network would be necessary. It is also essential to make the telescope IF systems compatible with the large bandwidth of SKA1-MID (2.5 GHz IFs), to maximise the sensitivity. The correlator will have to be able to deal with the extra load, also in terms of independent VLBI beams from SKA1-MID[1]. In addition, an SKA-VLBI requirement on the EVN archive will be science ready products derived directly from visibilities rather than just images (e.g. full Bayesian characterisation of source position, size and shape from sparse *uv*-coverage data).

The first phase of SKA will thus bring a lot of new opportunities as well as challenges for doing science with the EVN, primarily at frequencies below 15 GHz. How the landscape will develop on longer timescales is less clear at the moment. But the focus of VLBI technology and research might turn towards employing the very wide bandwidth (>>5 GHz) receivers and going to higher frequencies.

### 7.1.4 Synergy with multi-wavelength/multi-messenger instruments

An ultimate goal for the EVN (and VLBI arrays in general) is to exploit their unique capabilities in a way that it can serve a very broad user community. The proposed improvements in technology (to expand the EVN capability), in the operational model, and in the ways we will approach data processing and archive developments all point in this direction. In particular, it is essential to position VLBI in the multi-messenger landscape. The science chapters in this document have already pointed out important synergies with existing or future facilities. Most of these are related to facilities/missions operating in various parts of the electromagnetic spectrum: radio (ALMA, SKA, CHIME etc.), optical/infrared (*Gaia*, *HST*, LSST, *JWST*, ELT), and the high-energy bands (CTA, *Fermi*, *Swift*, *eROSITA*). To maximise the science output of the EVN it is essential to further strengthen these ties, and look for new opportunities as the multi-messenger landscape evolves. Below we mention four areas of particular interest, where VLBI could make a great impact together with emerging new facilities.

#### Ground- and space-based GW observatories

The role of VLBI observations in Mooley et al. (2018) and Ghirlanda et al. (2019) has already been quite prominent by showing that relativistic jets were produced in the binary neutron star merger

[1]The Science Use Cases deliverable of JJ WP10 lists a number of use cases, with current maximum number of required beams of N=14. This will result in a factor of N times more load on the correlator.

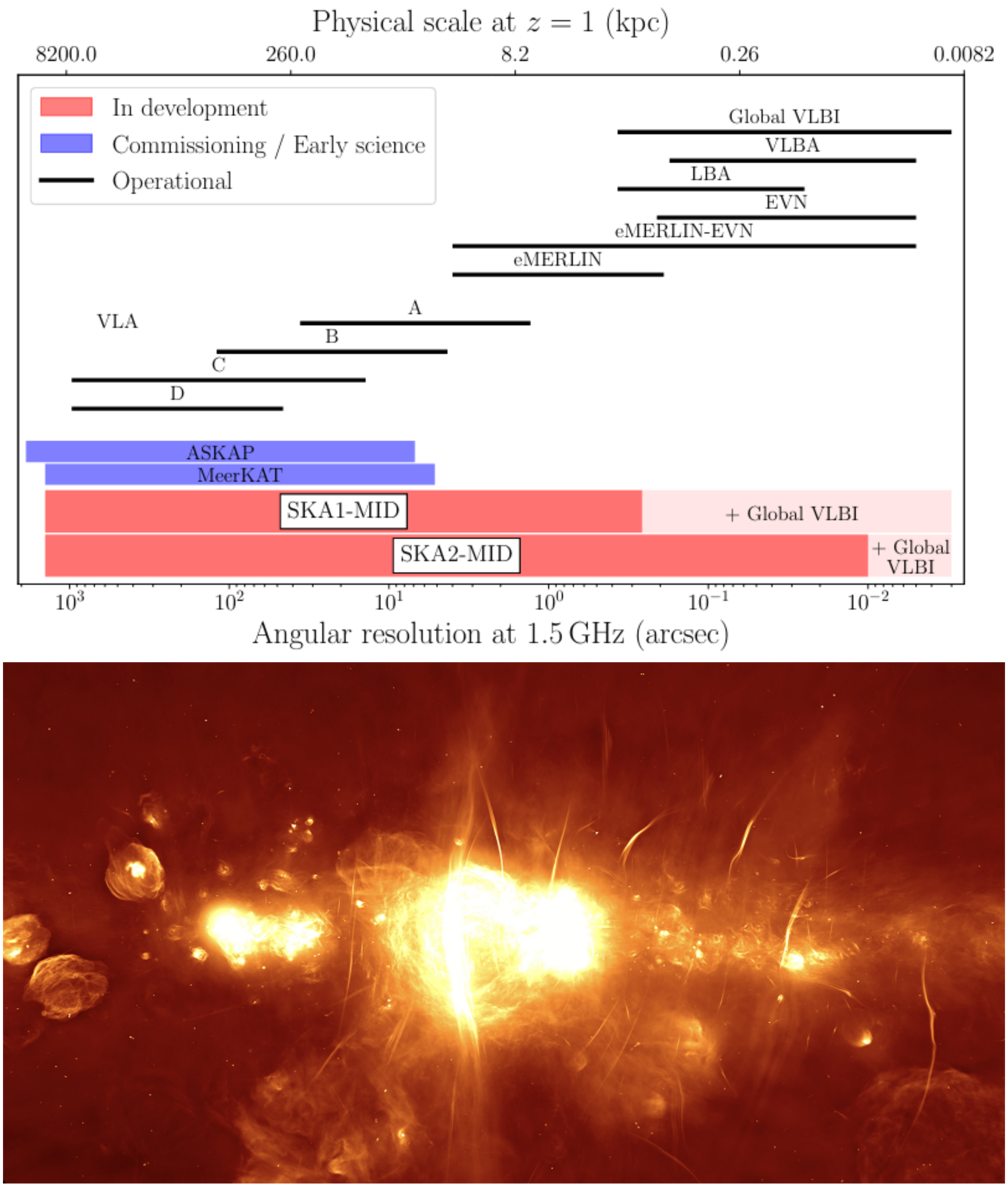



Figure 7.1: (upper panel) A broad range of spatial scales will be probed by a global VLBI array that includes SKA1-MID (courtesy of Jack Radcliffe and Cristina Garcia-Miró). (lower panel) The first public image from the 64-element SKA1-MID precursor MeerKAT, showing the Galactic Centre. (Courtesy of SARAO).

related to the GW 170817 gravitational wave event (see also Sect. 1.2.3, Sect. 4.1.5)[2]. The fact that VLBI imaging may resolve degeneracies between jet viewing angles and GW standard siren distances (Hotokezaka et al. 2019; Sect. 1.2.3) opens new avenues for high angular resolution radio observations; however, these observations are currently challenging, partly due to the (so far) very faint nature of GW counterparts. With SKA-VLBI and/or a broad-band EVN it will be possible in the future to detect a number of GW events, sufficient for constraining $H_0$ below $\sim 1\%$ precision.

The second generation ground based GW observatories (LIGO, Virgo, INDIGO and others) will continue to play an important role in detection of GWs from compact objects of stellar origin. The third generation ground based GW observatories (e.g., the Einstein Telescope) are currently under study. Pulsar Timing Arrays will continue to increase in importance after 2020, as the sensitivity of the arrays increase. The detection of GWs from individual massive BH binaries is expected to happen within the next 10 years. *LISA* should be a game changer in 2030s, when it is expected to detect GWs from galactic stellar binaries, massive BH binaries and extreme mass ratio in spirals with unprecedented precision. Coalescing massive BH binaries will be detected by *LISA* well in advance of the merger, providing a unique opportunity to multi-messenger follow-up (Kocsis, Haiman & Menou 2008; Lang & Hughes 2008). Another area to explore with *LISA*+EVN is IMBH (Sect. 3.2.4). While these are very difficult to find in their quiet state, they may produce spectacular shows of outbursts during a tidal disruption event (TDE, Sect. 4.1.4). Gravitational wave radiation from an IMBH+WD encounter might be detectable in the Local Group (Rosswog et al., 2009; Anninos et al., 2018), which may produce a jet similar to what was observed in Arp 299-B by Mattila et al. (2018) with the EVN.

Space-based GW astronomy will revolutionise our understanding of these fields. There have been a number of new missions proposed for the ESA call for white papers "Voyage 2050"[3]. There are also two suggested EM missions in particular that are relevant to GW science and highly synergistic with the EVN. One is a space-based X-ray interferometer (Uttley et al. 2019), the other is a space mm-VLBI mission concept (THEZA, Gurvits et al. 2019; see Fig. 7.3). In very different wavelength regimes, both of these would achieve hitherto unprecedented angular resolutions down to the (sub-)$\mu$as regime. Several EVN observatories have been involved with developing the THEZA concept.

#### Synergies with ELT

The European Extremely Large Telescope, ELT, is at the frontiers of the investigation of the Universe in the optical and infrared bands, from 0.8 to 13.3 $\mu$m. The telescope, with a 39 m mirror and implemented adaptive optics, is under construction in Chile, on Cerro Amazones, and is expected to provide the first light in 2025. One of the most exciting and novel features of ELT is the diffraction limit mas-scale FWHM which the telescope can provide. Going from 0.88 to 2.20 $\mu$m, the imaging angular resolution will be in the range $\sim$5 to 11 mas, perfectly matching that of the European VLBI Network in the two most sensitive bands, e.g. 1.4 and 5 GHz (as an example, see Fig. 1 in Dravins et al. 2012, and upper panel of Fig. 7.3 in this document). This implies that any radio-optical investigation resulting from ELT observations will hardly be possible with the SKA only, since the high angular resolution of VLBI will be a mandatory requirement.

[2] It is interesting to note that the paper that describes the initial multi-messenger follow-up of GW 170817 by Abott et al. (2017) has become, during a very short time, the most cited paper in which EVN observations are reported. At the time of writing, it has more than 1200 citations.

[3] `https://www.cosmos.esa.int/web/voyage-2050/white-papers`

It is noteworthy that the science case of ELT[4], includes most of the topics in the present document, from exoplanets to transients, from stellar to galaxy evolution, all the way to the very first stars and seeds of galaxies. The scientific potential of the future synergy between ELT and VLBI is thus bound to be transformational. Just to mention some of the several cases, the possibility to resolve binary black holes on $\sim$10–100 parsec scales in the optical and radio bands will revolutionise our understanding of the formation of massive and supermassive black holes, and their observational footprints (de Rosa et al. 2019). The high spectral resolution ELT spectral line observations will map the kinematics and magnetic fields of accretion disk atmospheres around young stars; this combined with VLBI maser astrometry it will strongly constrain models of high-mass star accretion at 10 to 100s of AU scales. VLBI and ELT are both able to directly image nearby exo-planets, the combination of magnetic field measure (from radio) and atmospheric spectral line characterisation (from ELT) will be a great leap forward in the understanding of planetary systems and their formation.

In order to fully exploit such potential, it is crucial to ensure that the portion of sky simultaneously accessible by the ELT, the EVN and the other most sensitive VLBI arrays, such as the VLBA, is as broad as possible. At present it is limited to a stripe of declination $\pm 30°$. This will considerably improve in the SKA era, with the SKA-VLBI mode implemented and more AVN antennas in operation.

#### Synergies with CTA

The Cherenkov Telescope Array (CTA) is the next generation ground-based observatory for gamma-ray astronomy at very high energies (VHE, $E > 100$ GeV). Currently in pre-construction phase, CTA operations are expected to begin in 2022, with the array construction ending in 2025. With more than 100 telescopes located in two sites in the northern and southern hemispheres, CTA will be the world's largest and most sensitive high-energy gamma-ray observatory. It will provide dramatically improved access to the most extreme accelerators in the Universe, whose understanding will necessarily require coordinated complementary efforts in other observing wavelengths.

The vast majority of the VHE sources revealed so far are also detected in radio: at high galactic latitude, blazars, in particular of the BL Lac type, dominate the census of the currently known population; in the Galactic plane, besides supernova remnants and pulsar wind nebulae (PWN), several compact objects (binaries) have been detected, and more could be hidden among the many sources that have remained unidentified. Based on our current understanding of the physical processes responsible for the emission of VHE gamma rays, it seems inevitable that the majority of the sources detected with CTA will also be ideal targets for VLBI observations.

Whereas CTA will be able to discover and characterise the emission from a large number of sources, its angular resolution will remain limited to a few arcminutes. Therefore, the localisation of the gamma-ray emitting region will only be possible through coordinated VLBI campaigns. At present, the only source for which such a coordinated study has been performed is the bright radio galaxy at the centre of the Virgo Cluster, M87 (MAGIC Collaboration, 2020; Hada et al. 2014; Giroletti et al. 2012). Increasing the number of VHE sources and flares, combined with dense monitoring campaigns with VLBI arrays is considered the only way to constrain the location, and thus the physical conditions, required for the production of VHE flares.

Even in the quiescence state, VLBI observations are crucial to characterise the physical parameters of the sources detected in VHE gamma rays, allowing a proper classification, as was the case of HESS J1943+213 (BL Lac object vs. planetary wind nebula: Akiyama et al. 2016; Straal et al.

[4] `https://www.eso.org/sci/facilities/eelt/science/doc/eelt_sciencecase.pdf`
`https://www.eso.org/sci/facilities/eelt/science/doc/`

2016) or IC 310 (blazar vs. head-tail radio galaxy: Aleksić et al. 2014). It is to be expected that the number of VHE sources discovered by CTA with an uncertain nature, if not totally unidentified, will see a huge increase, and thus it will be critical to start a systematic process of high angular resolution imaging of these sources with VLBI.

This new forthcoming synergy is an upgraded extension of projects already undertaken with VLBI, including the EVN, aimed at revealing the parsec scale properties of blazars detected in the highest part of the *Fermi* energy range, such as the 2FHL based on $E > 50$ GeV data (Ackermann et al. 2016). Lico et al. (2017) have shown that the highly significant correlation between radio and MeV/GeV gamma-ray emission breaks down when higher energy gamma rays are considered, possibly as a consequence of the correlation between blazar luminosity and spectral properties. The deep survey carried out with CTA will greatly improve our chances to extend such studies, both going to the actual VHE domain and improving the statistics for the spectral types currently more challenging to reveal.

Finally, at lower $\gamma$-ray energies, there remain opportunities for continued synergies with wide-field facilities such as Fermi-LAT and AGILE. In the longer term, future missions will open a new window at lower gamma-ray energies where many radio sources are expected to emit the majority of their output.

#### Detection of ultra-high energy cosmic rays and neutrinos

One of the unsolved mysteries of today's astrophysics is the origin of ultra-high energy cosmic rays UHECR. Although these are charged particles, UHECR are little affected by the magnetic fields in the Milky Way galaxy and thus their source of origin could be traced back. The Pierre Auger Observatory (Pierre Auger Observatory) found statistical evidence that the sky position of UHECR with energies of $\sim 10^{20}$ eV correlate with nearby ($d < 75$ Mpc) AGN (Pierre Auger Coll. 2007; Abraham et al. 2008).

The same processes that create cosmic rays produce high energy neutrinos as well, and these travel undisturbed through the cosmos. There is evidence that the sources of the highest energy neutrinos are blazars (Kadler et al. 2016, Ros et al. 2020). The IceCube detector recorded a 290 TeV event, IC 170922A, which was followed up by a number of instruments from the gamma rays to the radio regime; the neutrino's position was coincident with the BL Lac object TXS 0506+056, showing gamma-ray flaring activity at the time (Icecube Collaboration 2018). The broad-band electromagnetic observations are explained by a novel one-zone lepto-hadronic model, as co-accelerated electrons and protons interact in a relativistic jet, surrounded by a slow-moving plasma sheath as a source of external photons (Ansoldi et al. 2018). The multi-messenger approach to reveal some of the most extreme environments in the Universe is important because TeV gamma rays are an excellent proxy for photo-hadronic processes in blazar jets, which also produce neutrino counterparts (Ojha et al. 2020). While high energy observations provide important constraints on emission models and can also probe sub-horizon scales by means of variability studies, the EVN will also have a unique role in resolving the blazar inner core-jet region where high energy cosmic rays and neutrinos originate from (Aleksic et al. 2014). Recently, analysis of a complete VLBI-flux-density limited sample revealed AGN that are positionally associated with the highest energy neutrinos (energies above 200 TeV) are typically more core-dominated than the rest of the sample (Plavin et al. 2020). This, and the correlation of $> 10$ GHz radio activity with neutrino detections (Kun et al. 2019) provide additional evidence for AGN with Doppler-boosted jets being an important population of neutrino sources.

Blazars are not the only possible source of extragalactic high energy neutrinos. Kun et al. (2018)

describes a scenario in which a supermassive binary black hole merger could produce neutrinos while a reoriented relativistic jet is generated by the spin-flipping of one of the SMBH. As mentioned above, early EM localisation from *LISA* triggers, in which EVN observations will have a role, will provide a unique opportunity to start broad-band observations of these transient events before they actually happen! Hadronic processes may also occur in cataclysmic events that also produce a fast radio burst (non-recurrent FRBs; e.g. following BH coalescence or during the collapse of a supramassive NS), which raises the intriguing possibility that FRBs may contribute to the high-energy cosmic-ray and neutrino fluxes (The ANTARES Collaboration 2019). This is an opportunity to explore further, in a field where the EVN has already made a breakthrough contribution.

The next generation neutrino telescopes (IceCube-Gen2, Super-Kamiokande-IV and successors) will address cosmic ray physics, the nature and properties of dark matter particles, solar neutrinos, atmospheric neutrinos, supernova explosions, and will search for products of proton decay in order to test the Grand Unified Theory (GUT), which unifies strong, weak and EM interactions.

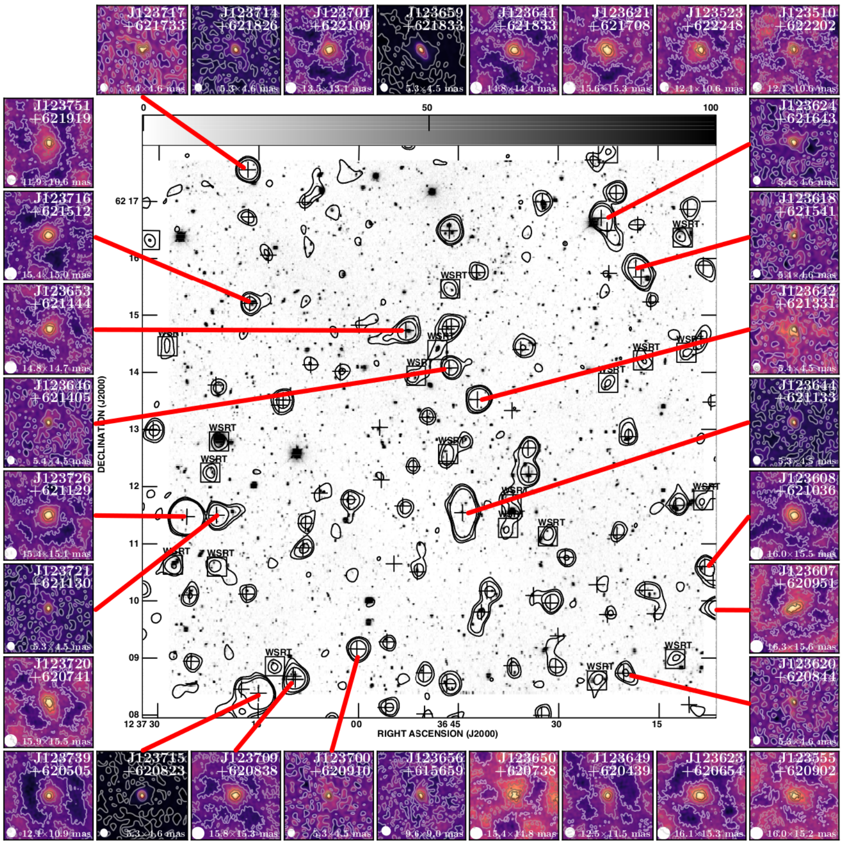



Figure 7.2: Composite image of 1.4 GHz WSRT radio-KPNO optical overlay of the GOODS-N field, centred on the HDF-N (Garrett et al. 2000), surrounded by postage stamp images of the 1.6 GHz 31 VLBI-detected sources. Credit: Radcliffe et al. (2018), reproduced with permission ©ESO.

## 7.2 Recommendations for future EVN Developments

In order to maximise the science synergy with the instruments mentioned in the previous sections, several enhancements in EVN technology, operations, data products and archive need to be explored.

### 7.2.1 Technical enhancements

*On-going efforts*

All the science goals proposed in this document call for improved image sensitivity — at least by one order of magnitude — and image fidelity. These are the first and most urgent needs to to ensure the current high astrophysical impact of the EVN is maintained and expanded. The SFXC correlator at JIVE can already do amazingly flexible operations (e.g. e-VLBI), new solutions might be needed (see A.2) to be able to keep up with the increasing number of telescopes, the increased bandwidth, and the inclusion of telescopes with multiple beams (e.g. SKA-VLBI). The specific science requirements include special fast transient and pulsar processing modes (like a number of simultaneous independent pulsar gates, see Chapter 4.), and the desire to image more steradians on the sky (important for cosmology, galaxy evolution and spectral line VLBI, see Chapters 1., 2. and 5.). The key actions to achieve these requirements are listed below.

- The improvement of image sensitivity requires a continued effort to increase the recording bit-rate. At present the EVN delivers 2 Gbps recording, and this should increase at least by a factor of 4 in the near future. Such a step has obvious implications in terms of data storage at each station and at the correlator. In addition, the connectivity between each station and JIVE needs to be addressed, both for e-VLBI and e-transfer.
- The full integration of *e*-MERLIN in the array is considered very important as it provides users with a much improved *uv*-coverage, from few tens to many hundreds of kilometres. The need for short baselines is particularly relevant for cosmology, galaxy evolution and studies of AGN in continuum and spectral line mode.
- Increasing the image sensitivity and fidelity by adding new and also larger antennas to the array is a continuous effort to increase the EVN capabilities and grow the global VLBI alliance. In particular maser polarimetry requires an increase in antenna surface as higher bit-rates are not the bottleneck for spectral line data. The amazing 500 m FAST and MeerKAT are already operational, and several telescopes are under construction or being refurbished in different countries (some examples are those in the Azores Islands and Thailand, see Sect. A.2.2). It is crucial that the VLBI operations at new observatories are supported adequately to ensure success; this requires a continuous effort.
- The EVN should curate its very sensitive observations in such ways that a larger area of the sky can be imaged (see Fig. 7.2). Not only should it be possible to propose for larger sky coverage, but the EVN should also try to align with 'survey-modes' that are being introduced for many astronomical observatories. Therefore it is necessary to build up an archive that can be used for sensitive, high resolution statistical studies.

Although these are all 'on-going' activities, it should not be underestimated that they require considerable resources, long-term planning, project management and in some cases technical development.

*Goals for new development*

The goals listed below are the core of this document: they are the technological innovations the EVN should focus on. These projects require considerable efforts to design and test, and most of all substantial investments to get the EVN ready for the next decade.

- Broad-band receivers offer extremely important scientific and operational advantages. This development will allow the EVN to make use of digital techniques that cover more bandwidth, providing improved sensitivity, but also instantaneous coverage for wide frequency ranges. It will increase the efficiency of observations as well. Development for a C-X band (covering at least ∼4-8 GHz as a first goal) receiver has started at many stations and it will be important that a system is defined that can be compatible across the EVN and with other VLBI arrays. Caution should be given that polarisation properties and sensitivity are not compromised.
- Extending the frequency coverage is also very important. There is a clearly formulated need to have a better 22 and 43 GHz coverage, both in terms of increased bandwidth and number of telescopes in the array. Improving the capabilities of the EVN at 22 GHz is strongly required both for water maser and cosmological studies. Moreover, AGN and maser (SiO) science would broaden their scope opening up to millimetre wavelength observations. It seems attractive to accommodate in particular the triple band receivers to make progress in high-frequency imaging fidelity. At the same time, follow up of cosmological surveys will require the capability to probe HI at higher redshifts, hence observing well below 1 GHz. A strong requirement in a number of science cases, especially those in need of spectral line observations, is that of homogeneous receivers over as many antennas as possible in the network.
- Improved *uv*-coverage, especially in the Southern direction, is highly desirable. This would increase the prospects of galactic science, as well as improve the accuracy of the terrestrial and celestial reference frames. The EVN should therefore give special attention to initiatives to make antennas available through the AVN (Gaylard et al. 2011, Gurvits et al. 2020) which will include antennas in Namibia, Zambia, Botswana, Mauritius, Kenya, Ghana, Madagascar, Mozambique, but also in the Middle East and in the Canary Islands. Such expansion is a key step forward for the optimisation of the portion of sky common to VLBI arrays and to the SKA.
- Wide-field imaging and survey-mode observing are well established facilities already available to the radio astronomical community, thanks to very large field of view of aperture arrays, such as LOFAR (see Sect. A.1.9), to the large primary beam of small antennas operating at relatively low frequencies, as is the case of MeerKAT, and the use of focal plane array feeds (PAF) as is the case of ASKAP. Increasing the field of view of VLBI imaging with the installation of PAFs on a number of antennas would be an enormous step forward. It would allow fast follow-up of classes of objects over large areas of the sky (a request which is becoming more and more pressing these days), and it would make large VLBI projects (such as gravitational lens surveys for cosmological studies) feasible over limited time scales.

### 7.2.2 Changes in the operations

*On-going efforts*

Since the advent of e-VLBI, the EVN has been adopting new observing modes and proposal types to serve specific scientific goals, such as observing transient events and other time-critical observations. A continued effort to offer observing modes that better match user requirements is needed, which can often happen without requiring upgrades at the telescopes. The most urgent actions are listed below.

- Some science cases – transient and multi-messenger science in particular – call for innovative operational modes, in particular, more observing time and more flexible scheduling (EVN-light). The availability of sub-arrays would allow to accommodate a broader variety of science

cases. Short- and long-term monitoring projects would benefit from this change, too. Maser astrometry requires an array that is available in specific seasons for optimal parallax sensitivity.
- A continuing effort is needed to improve the quality of amplitude calibration and to ensure homogeneous set-up within the array.
- Users' support is essential not only to ensure that VLBI is accessible to a broad fraction of the astronomical community, but also to experienced users whose projects require new and more refined observing modes and data processing. An enduring effort in this area is vital to ensure that VLBI is used at the best of its potentials.

*Goals for new development*

Future observatories and observing facilities will most likely broaden the science and require new approaches to observations. For this reason further changes in the operational modes should be considered, to ensure that the EVN keeps and strengthens its role in the future multi-wavelength and multi-resolution framework. In particular:
- In the next decade, the EVN will need to accommodate search for transients in commensal modes. Collaborations with other observatories will be needed, for projects which require fast response to follow-up observations. New proposal methods and operational modes will be needed to allow observations on (a sub-set of) the array.
- The EVN will need to cater for key programmes, presumably delivering public data products. This will maximise the science return for large field of view observing modes.
- In the SKA era, we can foresee that astronomers accessing the SKA will expect to have access to VLBI data through similar procedures and services.

### 7.2.3 Data products and Archive

*On-going efforts*

The overall accessibility of the array strongly depends on the data analysis support. In particular:
- It is essential that the EVN continues to deliver pipeline products, allowing fast access to the data and initial calibration, as well as support to continue the development of VLBI processing in CASA.
- New observing modes may require other data products (e.g. time series) and it is mandatory that the range of observing modes that are covered by the pipelines continues to increase.
- The EVN archive at JIVE is a key interface between the EVN and its users for all types of data access. It is where the users who proposed observations initially find their data. After a propriety period, which is usually 1 year, the data are publicly available to all users. An essential goal for this archive is to deliver well-calibrated data, and even science-ready data, since the EVN wants to attract users that are experienced in other disciplines. The EVN archive is also an invaluable source to access historical observations for new investigations. Specific examples are variability studies, completion of samples, or even reprocessing of published data. The current interface to the archive is however ten years old, and requires new developments.

*Goals for new development*

Following the developments at other facilities, future data activities will be centred on an archive that eventually implements observatory-side data processing. In the long run, the goal is to reach a homogeneous access model for all astronomy. To note:
- Archiving solutions are under study in the framework of the European Open Science Cloud,