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European VLBI Network: Present and Future

J. Anton Zensus[*a] **and Eduardo Ros**[abc†]
[a] *Max-Planck-Institut für Radioastronomie*
Auf dem Hügel 69, D-53121 Bonn, Germany
[b] *Observatori Astronòmic, Universitat de València*
C. Catedrático José Beltrán 2, E-46980 Paterna, València, Spain
[c] *Departament d'Astronomia i Astrofísica, Universitat de València*
C. Dr. Moliner 50, E-46100 Burjassot, València, Spain
E-mail: azensus@mpifr-bonn.mpg.de, ros@mpifr-bonn.mpg.de

The European VLBI Network[‡]is a collaboration of the major radio astronomical institutes in Europe, Asia, South Africa and Puerto Rico. Established four decades ago, since then it has constantly improved its performance in terms made using resolution, data bit-rate and image fidelity with improvements in performance, and the addition of new stations and observing capabilities. The EVN provides open skies access and has over time become a common-user facility. In this contribution we discuss the present status and perspectives for the array in a continuously changing environment, especially in the era of ALMA and with the Square Kilometre Array *ante portas.*

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*Speaker.

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1. A very short history of the EVN

After successful VLBI observations using European telescopes in the late 1960s and intra-European observations in the early 1970s, discussions about a European array date back to 1975. After several meetings the European VLBI Network was formally established in 1980 with five founding radio astronomy institutes (MPIfR, IRA, ASTRON, OSO, and Jodrell Bank). A detailed description of the early times of the network has been published in recent conferences [1, 2]. Initially it was a 4-station network (Dwingeloo/Westerbork, Effelsberg, Jodrell and Onsala). From the very beginning a program committee (the EVNPC) was established and reviewed observing proposals submitted 3 times per year. A scheduler to coordinate observations was appointed in 1982, and this task was performed by different individuals at the MPIfR until Alastair Gunn (Jodrell) took this over in 2014.

Since 1980 many stations have been added to the network: Medicina (1984), Wettzell (1995), Noto (1989), Shanghai, Metsähovi and Cambridge-32m (1990), Yebes-14m and Urumqi (1994), Torun-32m (1996), Arecibo and Hartebeesthoek (2001), Yebes-40m (2008), the KVAZAR network: Svetloe, Zelenchukskaya and Badary (2009), and recently the KVN: Yonsei, Ulsan and Tamna (2014). The Sardinia-64m and Tianma-65m will start regular participation in 2015.

Data were initially correlated at the MPIfR processing centre in Bonn. The Joint Institute for VLBI in Europe, established in 1993, is currently tasked with data correlation and postprocessing and EVN user support. A new correlator was dedicated in 1998, and in recent years this has now been replaced by a software correlator, SFXC. The EVN has constantly improved its capabilities since foundation, both in terms of antenna performance and data bit-rate, from the 4 Mbps provided by the Mk II system in 1980 to the plans for 2 Gbps in 2015 using the Mk V system with digital backends.

The science addressed by EVN observations has covered a broad range of topics with a high scientific impact. Several hundred refereed papers make use of observations from the network; the most cited works include:

- the properties of compact steep-spectrum sources using radio observations at different scales [3]
- a study of a sample of radio galaxies [4]
- examining the dynamics of the compact symmetric objects 0710+439 and 0108+388 [5, 6]
- investigation of methanol masers (a unique EVN capability for many years) [7, 8]
- imaging of gravitational lenses such as B0218+35.7 [9]
- imaging of radio jets in galactic objects such as LS I +61°303 [10].

Recent publications with the largest number of citations per month report astrometric studies of the Milky Way [11, 12], and feedback in the jet of the radio loud galaxy 4C +12.50 [13].

2. Present EVN

At present the EVN comprises 14 major institutes[1] including JIVE. Overall EVN policy is set by the Consortium Board of Directors. EVN science topics cover a broad range; they include investigations of high brightness-temperature objects emitting non-thermal radiation, atomic and

[1] See http://www.evlbi.org/contact/.

molecular processes, synchrotron radiation and pulsar emission. The high sensitivity provided by the large collecting area of many of its elements makes the EVN especially suitable for the study of faint objects such as young radio supernovae.

EVN in context In its early days VLBI was confined to centimetre wavelengths where observing systems made it feasible; shorter wavelengths suffered from short coherence times and relatively low performance of receivers, and longer wavelengths were affected by the ionosphere and plagued by steadily increasing radio frequency interference. Recent technical developments have expanded the parameter space in radio astronomy. Progress in processing data from thousands of dipoles and "software telescopes" have pushed towards longer wavelengths, with pathfinders and precursors of the Square Kilometre Array (SKA), such as LOFAR. At the same time, improvements in detector techniques and increasing bandwidths have triggered the advent of new-generation, short-wavelength telescopes, the recently dedicated Atacama Large Millimetre/sub-millimetre Array (ALMA) being the most important. It is planned that ALMA, as a phased array, will observe as an element in millimetre VLBI arrays, notably with the aim of investigating the morphology of the immediate neighbourhood of the super-massive black holes at the Galactic Centre and in the nearby galaxy M 87 – the so-called Event Horizon Telescope [14]. Additionally, the desire for longer baselines has pushed VLBI to have elements in Earth orbit, first with the VSOP project in the late 1990s [15] and currently RadioAstron [16]. EVN as a ground array is a key element supporting RadioAstron observations. The use of a large dish such as Effelsberg together with the small dish onboard *Spektr-R* has the same collecting area as two 30-m dishes. The first results reported are spectacular (see e.g., [17] in this conference).

Observing The EVN performs observations with disk recording (standard EVN, three sessions of three weeks each per year) or in real time (e-VLBI, 10 sessions per year, each of 24h). Out-of-session scheduling has been introduced recently in blocks of up to 12 hours of duration (up to a maximum of 144 hours per year), for specific purposes which justify observations outside of regular sessions. Observations are possible at 92, 49, 30, 21, 18, 13, 6, 5, 3.6, 1.3, and 0.7 cm wavelength. Joint observations with the Very Long Baseline Array (VLBA), ('Global' proposals) can also include the Green Bank Telescope and the phased Jansky Very Large Array. Global proposals can currently use up to 1 Gbps data bit rate. Joint observationswith the RadioAstron project are possible as well. Following the Korean VLBI Network joining the EVN as an associate member in 2014, it is planned that some joint time with the Australian Long Baseline Array will be available, starting in 2015, creating a real global array. The details and updates of the EVN performance are announced in every call for proposals[2]. The status of the telescopes, receiver availability, observing modes, etc., is maintained by JIVE in the EVN status tables[3]. For observations at 3.5 mm, astronomers can use the Global Millimetre VLBI Array (GMVA), operated jointly by the MPIfR, IRAM, Onsala and NRAO[4].

2.1 Recent highlights

Technical As mentioned above the KVN recently joined the EVN. Its 3 antennas (with separa-

[2]See `http://www.evlbi.org/proposals/call.txt`.

[3]See `http://www.evlbi.org/user_guide/EVNstatus.txt`.

[4]See `http://www3.mpifr-bonn.mpg.de/div/vlbi/globalmm/`.

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tions up to 480 km) at the easternmost edge of the network enhance remarkably the (u,v) coverage. An interesting feature of these telescopes is their novel high-frequency capabilities, since *simultaneous* observations are possible at 13, 7, 3.5, and 2 mm wavelength; 13 and 7 mm are offered by the EVN for joint observations.

RadioAstron has performed joint observations with the EVN since early 2012, combining the high resolution provided by space VLBI with the high sensitivity of the EVN (see above).

Recently a new correlator developed at JIVE (UniBoard project, supported by RadioNet3, see [18]) has successfully demonstrated 4 Gbps operation. When brought into operation the correlator will support 32 stations with 64 MHz bandwidth, integration times of 0.022 s to 1 s, and a frequency resolution up to 15.625 kHz.

In September 2014 the radome of the 20m-Onsala telescope was renewed. The top cap of 50 panels was replaced in one piece, and the remaining 570 elements were changed one by one[5].

As mentioned above the Tianma 65-m telescope will be available for EVN observations in 2015. It will operate with adaptive optics in all the bands offered by the EVN from 21 cm to 7 mm. First fringes with the EVN were obtained in March 2014 [19]. It can also provide a very short baseline together with the Seshan 25-m telescope.

EU Support The EVN is an excellent example of international cooperation in science. This collaborative aspect has been boosted over the last twenty years by the support of the European Commission via different funding instruments. Following from support inder the 3rd Framework Program (FP3) with *The European VLBI network of radio telescopes*[6], it continued in FP4 with *Enhancing the European VLBI Network of Radio Telescopes*[7] and *Access to the EVN of radio telescopes*[8], in FP5 with the projects *EVN-ACCESS*[9] and *FARADAY*[10], in FP6 with *RadioNet*[11] and *EXPReS*[12], and in FP7 with *NEXPReS*[13], *RadioNet-FP7*[14] and currently *RadioNet3*[15].

Additional funding for EVN research activities was provided by programs such as the cooperation with the former Soviet Union by *The nature and origin of the most compact cosmic radio*

[5] See `http://goo.gl/Ca0dJH`.

[6] Ref. CHGE920011, programme FP3-HCM.

[7] Code FMGE980101, programme FP4-TMR.

[8] Code FMGE950012, programme FP4-TMR, subprogramme 0201 - Access for researchers, funding scheme 0201 - Access for researchers.

[9] *European vlbi network via the joint institute for vlbi in europe*, Ref. HPRI-CT-1999-00045, programme FP5-HUMAN POTENTIAL.

[10] *Focal-plane arrays for radio astronomy; design, access and yield*, Ref. HPRI-CT-2001-50031, programme FP5-HUMAN POTENTIAL.

[11] *RadioNet: Advanced Radio Astronomy in Europe*, Ref. 505818, programme FP6-INFRASTRUCTURES, subprogramme INFRASTR-2.1 - Integrating activities combining cooperation networks with transnational access and research projects.

[12] *EXPReS: a production astronomy e-VLBI infrastructure*, Ref. 026642, programme FP6-IST, funding scheme I3 - Research Infrastructure-Integrated Infrastructure Initiative.

[13] *NEXPReS- Novel EXplorations Pushing Robust e-VLBI Services*, Ref. 261525, programme FP7-INFRASTRUCTURES, subprogramme INFRA-2010-1.2.3 - Virtual Research Communities.

[14] *Advanced Radio Astronomy in Europe*, Ref. 227290, programme FP7-INFRASTRUCTURES, subprogramme INFRA-2008-1.1.1 - Bottom-up approach: Integrating Activities in all scientific and technological fields.

[15] *Advanced Radio Astronomy in Europe*, Ref. 283393, programme FP7-INFRASTRUCTURES, subprogramme INFRA-2011-1.1.21. - Research Infrastructures for advanced radio astronomy.

sources known in the Universe[16], geodesy-related projects such as *RADIO-INTERFEROMETRY*[17], and research training networks such as *CERES*[18], *ANGLES*[19] and *ESTRELA*[20].

The present I3 project *RadioNet3* includes a transnational access programme (which supports EVN observations and data analysis), networking activities (which, amongst other things, support this conference), and joint reseach activities to support research and development at the radio astronomical facilities in Europe, including JIVE and several EVN radio telescopes. A complete description of the project and its goals is provided in its webpage[21]. *RadioNet3* also contributes to the implementation of the strategic plan for European radio astronomy (*AstroNet*[22]) by building a sustainable radio astronomical research community.

Scientific As reported above, the EVN has produced hundreds of scientific publications in several areas; highlights are shown regularly on the EVN webpages. Its high fidelity imaging is especially useful for global experiments and for observations of complex jet structures, e.g., in the study of helical features in 0836+710 [20]. Methanol masers can be probed at 5 cm wavelength, and these astrometric results complement astrometric studies performed at 1 cm with water masers, see [21]. The high sensitivity shows its full power in the study of ultraluminous X-ray sources [22], in setting upper limits to the emission from radio supernovae, e.g., SN 2014 [23], or in the imaging of the Crab nebula [24]. Synergies with observations from telescopes at the very highest frequencies are possible, as in the case of the blazar IC 310 in the Perseus cluster, studied jointly by MAGIC and the EVN [25].

3. The future

JIV-ERIC The future has now become the present, since the European Commission decided in the course of writing this contribution to allow JIVE to become a European Research Infrastructure Consortium, initially with four member countries (The Netherlands, United Kingdom, Sweden and France). In addition, research councils and institutes in other countries – Italy, Spain, South Africa, Germany and China – will contribute to JIVE as well. The official dedication of the JIV-ERIC is planned for April 2015.

Expanding the network Six dishes were recently added to the network (KVAZAR with 3×32 m in 2009 and KVN with 3×21 m in 2014). The telescopes in Sardinia (64-m) and Tianma (65-m) are a reality and will increasingly participate in EVN observations in 2015. Further in the future

[16] Ref. INTAS-94-4010.

[17] *Measurement of vertical crustal motion in Europe by VLBI*, Ref. FMRX960071, programme FP4-TMR, subprogramme 1.4.1.-3.1S4 - Environment and Geosciences.

[18] *The universe at high redshift and the physics of active galaxies from multi-wave length studies of compact radio sources - consortium for European research on extragalactic surveys*, Ref. FMRX960034, programme FP4-TMR, subprogramme 1.4.1.-3.1S7 - Physics.

[19] *Astrophysics Network for Galaxy Lensing Studies*, Ref. 505183, programme FP6-MOBILITY, subprogramme MOBILITY-1.1 - Marie Curie Research Training Networks (RTN).

[20] *Early stage training site for European long-wavelength Astronomy*, Ref. 19669, programme FP6-MOBILITY, subprogramme MOBILITY-1.2 - Marie Curie Host Fellowships - Early stage research training (EST).

[21] See `http://www.radionet-eu.org/`.

[22] See `http://www.astronet-eu.org/`.

are the planned 110-m telescope in Qitai, near Urumqi, and the FAST 500-m telescope in China, which could join EVN observations, and also a 70-m class telescope in Poland (RT90) to the north of Toruń. Furthermore, a beam-formed MeerKAT telescope would be an excellent addition to the network to the South, with a short baseline to Hartebeesthoek and with high sensitivity. Plans for an African VLBI array are also being developed, and this would yield an unprecendented coverage at centimetre wavelengths, to boost radio astronomy in the next years, complementing the Square Kilometre Array.

New frontiers In the future the EVN will continue being a key instrument in radio astronomy, complementing multi-messenger campaigns, in the study of transients, enhancing its image fidelity and astrometric precision, complementing millimetre- and space-VLBI, and as a match in the radio for astrometric measurements in the era of *GAIA*. Even when other facilities are threatened with funding cuts, one of the strengths of the EVN is its international nature, making a sustainable and flexible facility for many years in the future.

References

[1] Porcas, R.W., PoS(10th EVN Symposium)011 (2010)
[2] Booth, R.S., PoS(RTS2012)005 (2012)
[3] Fanti, R., et al., A&A 231, 333-346 (1990)
[4] Giovannini, G., et al., ApJ 552, 508–526 (2001)
[5] Owsianki, I. & Conway, J.E., A&A 337, 69–79 (1998)
[6] Owsianik, I., Conway, J.E., & Polatidis, A.G., A&A 336, L37 (1998b)
[7] Minier, V., Booth, R.S., & Conway, J.E., A&A 362, 1093–1108 (2000)
[8] Beuther, H., et al., A&A 390, 289–298 (2002)
[9] Patnaik, A.R., et al., MNRAS 261, 435–444 (1993)
[10] Massi, M., et al., A&A 414, L1-L4 (2004)
[11] Reid, M.J., et al., ApJ 738, 130 (2014)
[12] Xu, Y., et al., ApJ 769, 15 (2013)
[13] Morganti, R., et al., Science 341, 1082 (2013)
[14] Doeleman, S.D., PoS(10th EVN Symposium)053 (2010)
[15] Hirabayashi, H., et al., Science 281, 1825 (1998)
[16] Kardashev, N.S., et al., Astron. Rep. 57, 153–194 (2013)
[17] Kovalev, Y.Y., et al., PoS(EVN 2014)020 (2014)
[18] Szomoru, A., PoS(10th EVN Symposium)098 (2010)
[19] Shen, Z.Q., in 3rd China-U.S. Workshop on Radio Astronomy Science and Technology, see http://goo.gl/5N7M6u (2014)
[20] Perucho, M., et al., ApJ 749, 55 (2012)
[21] Rygl, K.L.J., et al., A&A 539, A79 (2012)
[22] Mezcua, M., et al., MNRAS 436, 1546–1554 (2013)
[23] Pérez-Torres, M.A., et al., ApJ 792, 38 (2014)
[24] Lobanov, A.P., et al., A&A 533, A10 (2011)
[25] Aleksic, J., et al., Science 346, 1080–1084 (2014)