EVN Biennial Report
2015- 2016

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Foreword from the EVN Consortium Board of Directors chairperson

This Biennial Report bears abundant witness to the flourishing of the European VLBI Network during the period 2015 – 2016. It demonstrates, from cover to cover, that the EVN is a major and vibrant research infrastructure, producing frontline science, and constantly upgrading, expanding and innovating so as to remain at the cutting edge. The importance of the EVN was underlined by the 2015 report of the European Radio Telescope Review Committee (ERTRC, established by ASTRONET, then the EU-FP7 ERANet for astronomy); it states: "Due to its high angular resolution, high sensitivity and superb astrometric precision, the EVN had become a unique astronomical facility. These unique capabilities allowed the EVN to cover a vast range of astrophysical phenomena, establishing itself as a general-purpose observatory." The ERTRC report shows the EVN to be a research facility with the very highest impact on the topics in the ASTRONET Science Vision.

This Biennial Report contains diagrams showing the wide range of science areas covered by EVN projects, in the EVN Programme Committee section. There is also an extensive list included of the Refereed Publications in 2015 – 2016 based on EVN data. There is furthermore a chapter on Selected EVN Scientific Results, which is indeed just that: an inevitably arbitrary and limited selection, highlighting the broad variety of observations through which the EVN is making important and unique contributions to present-day astronomical research. Another highlight was of course the first localization of a Fast Radio Burst (FRB), in which the EVN played a prominent role; it attracted much press attention in late 2016.

The capabilities of the EVN have also been showcased at several broadly attended meetings in 2015 – 2016, including the workshop on "Nanoradians on the sky: VLBI across the Mediterranean and beyond" at the 2016 European Week of Astronomy and Space Science (EWASS); these and further specialized conferences and workshops are listed in this Biennial Report. The most extensive and impressive forum and showcase for the science output power of the EVN in the period 2015 – 2016 was undoubtedly the 13th EVN Symposium. This full week of excellent presentations and discussions was held at a splendid palace in St. Petersburg in September 2016. It was particularly satisfying that this event attracted many early-career scientists, engaged in a great variety of scientific projects. During the EVN Users Meeting at the EVN Symposium, attendees were engaged in verbal and electronic dialogue, concerning their wishes and priorities for further improvements of the capabilities of the EVN, related to their scientific ambitions.

The EVN capabilities did indeed continue to improve steadily in 2015 – 2016. An increased recording bandwidth of 2 Gbps (Gigabits per second) saw first operational use in the autumn of 2015 for observations recorded to disk and in June 2016 for e-VLBI observations, with consequently increased sensitivity. This was enabled in part by firmware upgrades to the DBBC backends jointly financed by several EVN members. Further software development of the controlling Field System, financed by several EVN members, has ensured more efficient utilization of the new generation of DBBC2 backends. While 2 Gbps is rapidly becoming the default for EVN continuum observations, development to even higher recording rates is continuing.

Recent advances in electronic data storage and transport technology have been important in enabling this continued evolution to higher bandwidth observing. Specifically, during 2015 – 2016 several EVN observatories took the lead in installing FlexBuff recorders. These systems are flexibly expandable with time, as higher disk capacity becomes affordable. They are dimensioned to offer enough instantaneous storage capacity for an entire observing session of three weeks, with data gradually transferred by fibre connections to the correlator – JIVE hosts further FlexBuff systems to receive that data. During 2015 – 2016 the EVN Technical Operations Group (TOG) further enhanced the flexibility of observing and processing, and successfully tackled many other issues.

In their work to keep network performance high and to promote further development, the observatory members of the TOG collaborate closely with JIVE staff. JIVE, originally the abbreviation for the Joint Institute for VLBI in Europe, was, as always. a crucial EVN member. It not only furnishes the correlator capacity for EVN telescope data, but also participates in many other operational as well as development activities and carries out user support. The establishment of JIVE as an ERIC, completed as of 1 January 2015, was therefore an important change for the EVN. The ERIC status aptly recognizes the stature of JIVE within the European research infrastructure landscape. In order to formalise the respective roles of the JIVE ERIC and the EVN, the EVN CBD chair and the JIVE Director have signed a Service Level Agreement in 2016.

A number of the EVN observatories also participate in geodetic VLBI observations, and are members of the International VLBI Service for Geodesy and Astrometry (IVS). Realizing that significant synergy exists between the EVN and the IVS, and that there is potential for further collaboration, the chairs of the two organisations were charged in 2016 with preparing a Letter of Intent to cooperate.

The backbone of the EVN is the network of its member observatories, which make available joint telescope time. The Observatories section of this Biennial Report records the impressive range of activities and advances that have occurred all across the EVN in 2015 – 2016. The network, furthermore, has continued to expand. Following joint technical explorations, the KunMing 40m radio telescope is now affiliated to the EVN and made available to users on a best-efforts basis. A highlight was the entry, in October 2016, of the Ventspils International Radio Astronomy Centre (VIRAC) with its Irbene observatory as a new full member of the EVN! Many colleagues in the EVN have provided support in one way or another to make possible this addition to our family, which is furthermore a tribute to the dedication and competence of the VIRAC staff in accomplishing a truly major overhaul of their 16-meter and 32-meter Soviet-vintage radio telescopes.

Figure 1: Participants of the October 25-26, 2016 EVN CBD meeting, in front of the Irbene 32m telescope

Finally and fundamentally responsible for enabling the consortium to function and deliver top-notch science data, are the many highly skilled and deeply dedicated staff at all of the institutes within the EVN family. It has been my privilege to serve as the EVN CBD chair, and in that capacity I wish to express my gratitude to all of these individuals, who each play their part, and who jointly propel the EVN forward on its remarkably successful path.

René Vermeulen
Chair, EVN Consortium Board of Directors
(July 2015 – June 2017)

The EVN

The European Consortium for VLBI

The European VLBI Network is a joint facility of independent European, African, Asian, and North American radio astronomy institutes, which conduct high angular resolution radio astronomical observations of cosmic radio sources.

The EVN is a Consortium, founded in 1984, following 4 years of EVN observing made under less formal arrangements. It is governed by an MoU, most recently updated in 2004. The Directors of EVN Member Institutes form the Consortium Board of Directors (CBD). A list of EVN and EVN Board membership during 2015–2016 is given below.

Table 1: The EVN membership, 2015-2016

Institute	CBD Member	Comment
Full Members		
ASTRON	René Vermeulen	Chair since July 2015
Hartebeesthoek Radio Astronomy Observatory	Ludwig Combrinck	
INAF – Institute of Radio Astronomy	Luigina Feretti	CBD member until 2015
	Steven Tingay	CBD member since 2016
Institute of Applied Astronomy, St. Petersburg	Alexander Ipatov	
JIVE ERIC	Huib van Langevelde	
Jodrell Bank Observatory	Simon Garrington	
Max-Planck Institut für Radioastronomie	Anton Zensus	Chair until June 2015
Observatorio Astronómico Nacional , Instituto Geográfico Nacional	Rafael Bachiller	
Onsala Space Observatory	John Conway	
Shanghai Astronomical Observatory	Hong Xiaoyu	
Torun Centre for Astronomy	Andrzej Marecki	
Ventspils International Radio Astronomy Centre	Valdis Avotins	EVN Member since 27 Oct. 2016
Xinjiang Astronomical Observatory	Wang Na	

Associate Members

Arecibo Observatory	J. Schmelz
Geodetic Observatory Wettzell, Bundesamt für Kartographie und Geodäsie (BKG)/Forschungseinrichtung Satellitengeodäsie (FESG)	Torben Schueler
Korean VLBI Network, Korea Astronomy & Space Science Institute	Do-Young Byun
Metsähovi Radio Observatory, Aalto University	Joni Tammi

EVN Program Committee

The EVN Program Committee (PC) is appointed by the EVN CBD to carry out an independent scientific and technical assessment of all standard EVN, e-VLBI and global VLBI requests for observing time. The revolving membership of the EVN PC at the end of 2016 consisted of 12 voting members, of which 7 affiliated with EVN institutes and 5 at other European institutes. In addition the EVN Scheduler attends PC meetings as a non-voting member. The PC membership through 2015-2016 is listed in Table 2, including other representatives (non-voting) who contribute to the EVN PC's process.

Table 2: List of members of the EVN PC during 2015-2016 and their roles

Name	Institute	Remarks
Ivan Agudo	IAA-CSIC Granada, ES	from 1 May 2016
Tao An	Shanghai, CN	from 1 December 2016
Anna Bartkiewicz	Torun, PL	until 1 May 2016
Angela Bazzano	INAF, Rome, IT	until 1 August 2016
Bob Campbell	JIVE, Dwingeloo, NL	EVN correlator representative
Sandor Frey	FOMI, Budapest, HU	
Marcello Giroletti	INAF-IRA, Bologna, IT	
Liz Humphreys	ESO, Garching, DE	until 1 December 2016
Katarina Immer	ESO Garching, DE	from 1 July 2016
Michael Lindqvist	OSO, SE	Chair from 1 January 2015
Andrei Lobanov	MPIfR, Bonn, DE	
Tom Muxlow	JBCA/e-MERLIN, Manchester, UK	
Alexey Melnikov	Saint Petersburg, RU	
Miguel Perez-Torres	IAA-Granada, ES	until 1 May 2016
Antonis Polatidis	ASTRON, Dwingeloo, NL	
Zhi-Qiang Shen	Shanghai Observatory, CN	until 1 February 2016
Valeriu Tudose	ISS Bucharest, RO	from 1 August 2016
EVN Scheduler		
Alastair Gunn	JBCA/e-MERLIN, Manchester, UK	
NRAO/GBO/LBO Representatives		
Jeremy Darling	USA	NRAO TAC since June 2015-June 2016
Matt Lister	USA	NRAO TAC since October 2016
Bob Zavala	USA	NRAO TAC until May 2015
Toney Minter	USA	GBO Scheduler
Mark Claussen	USA	NRAO VLBA/VLA Scheduler

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 2015-2016 are given in Table 3.

All standard EVN, global VLBI and e-VLBI proposals are evaluated at the PC meetings, for observations in upcoming standard and e-VLBI scheduled sessions. Each EVN PC member provides a review and a pre-grade of the proposals before the meeting, then a thorough discussion on each proposal and the final evaluation are carried out during the meeting itself. For the consideration of global VLBI proposals, independent grades are provided by NRAO. In addition, voting members from NRAO join the PC meetings for extended discussions. 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.

Budapest	March 4, 2015	Trimester 15A
St. Petersburg	July 1, 2015	Trimester 15B
Dwingeloo	November 11, 2015	Trimester 15C
Zaragoza	March 8, 2016	Trimester 16A
Rome	July 1, 2016	Trimester 16B
Garching	November 17, 2016	Trimester 16C

Table 3: PC meetings during 2015-2016

Proposal statistics

The EVN operates an open-sky observing policy with proposals scheduled into 3 main observing sessions per year, plus regular (monthly) additional e-VLBI days. A Call for Proposals is distributed three times a year, with proposal deadlines on 1st February, 1st June and 1st October. It is also possible to submit Target-of-Opportunity proposals. Proposal statistics from 2010 to 2016 are shown in Figure 2. The total numbers of hours proposed and the EVN network hours are shown in Figure 3. Since the peak in proposal numbers in 2011, the numbers of conventional proposals have subsided somewhat but the total hours requested has remained the same (with the exception of 2014 and 2016). The total network time (EVN and RadioAstron hours requested within conventional sessions) has also remained the same. The typical over-subscription rate, (hours requested)/(EVN network hours), stands at 2.3.

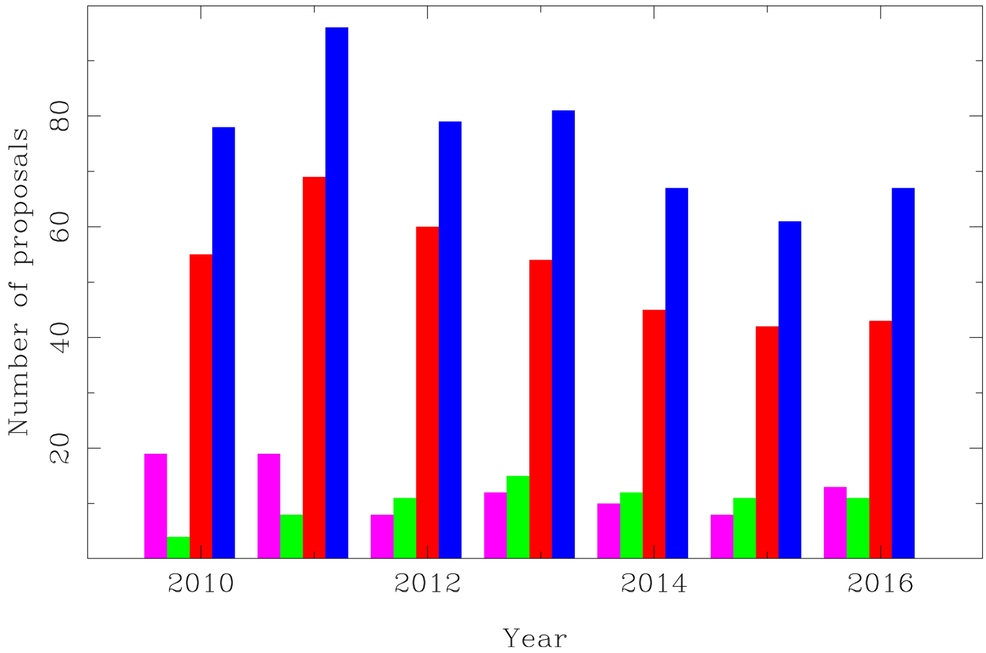


Figure 2: Total numbers of proposals submitted between 2010 and 2016 (blue), subdivided into EVN alone (red), global (green) and ToO+short observations (magenta)

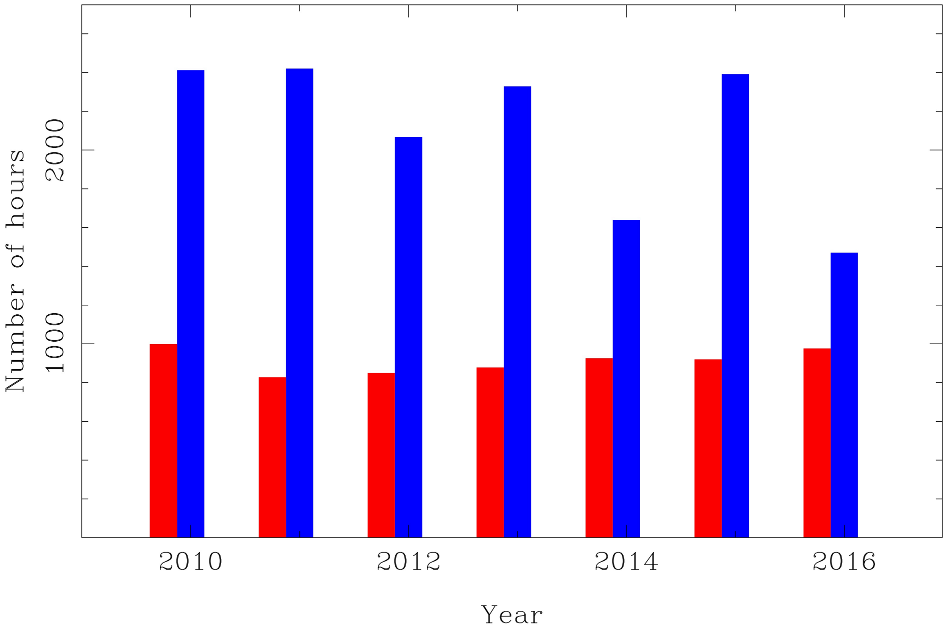


Figure 3: Total number of hours proposed between 2010 and 2016 (blue) and the EVN Network hours (red).

Requested Science Research Areas and Observing Bands

The dominant research areas still remain those of AGN/QSO, Radio Galaxies/Jets, and Star/Stellar Evolution which account for almost 70% or more of proposals received (Figure 4). Thus, the research areas proposed through 2015-2016 do not differ significantly from those reported in the previous biennial reports, although there are variations between individual Trimesters (an example of a new category is Fast Radio Bursts). The requested frequency bands are likewise dominated by these research areas, resulting in large numbers of proposals requesting the 18/21 cm and 6 cm bands.

However, the remaining bands are still rather populated with proposal requests, (Figure 5). There is a large international pool of users of the EVN and Global VLBI array that stretches significantly beyond the EVN member institutes and countries. Although the majority of PIs are based within Europe, a significant and growing number of EVN users are found worldwide.

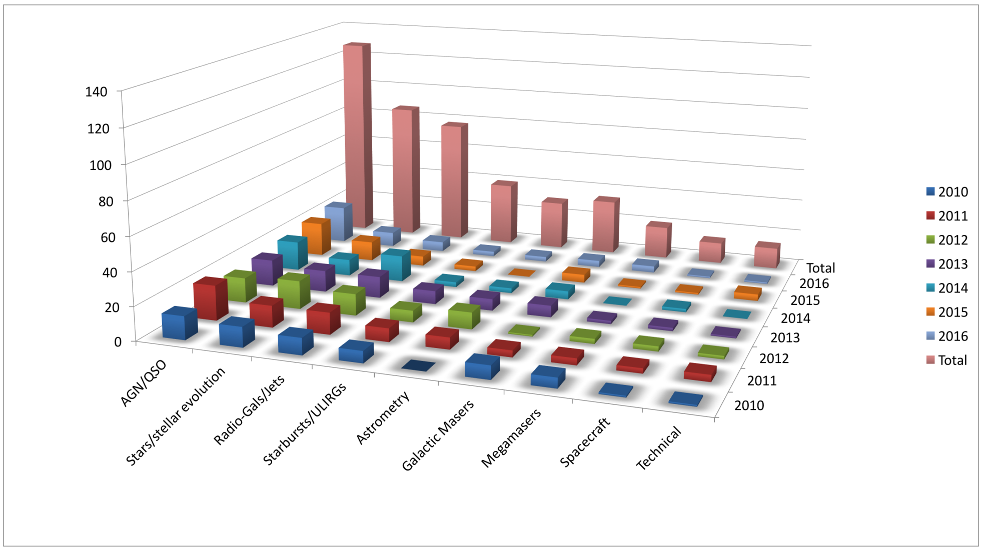


Figure 4: The distribution of scientific categories for proposals submitted from 2010 to 2016.

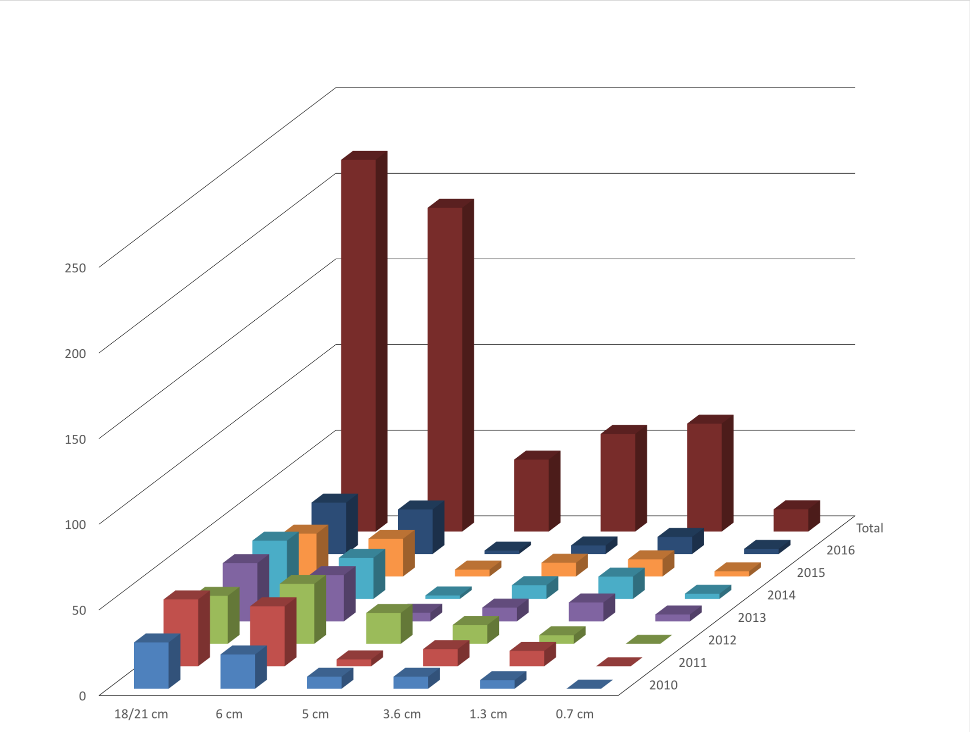


Figure 5: The distribution of requested wavebands for proposals submitted from 2010 to 2016. In addition, occasionally we receive proposals also for 90 and 13 cm..

EVN Scheduler Report

The EVN offers a variety of observing modes that provide the users with extra flexibility, but add some complexity to the operations. The figures below show the evolution of annual EVN network hours and the next figure focuses on the e-EVN experiments, showing a division of annual observing hours into different categories. By their nature, all e-EVN observations are correlated at JIVE and run in a single correlator pass.

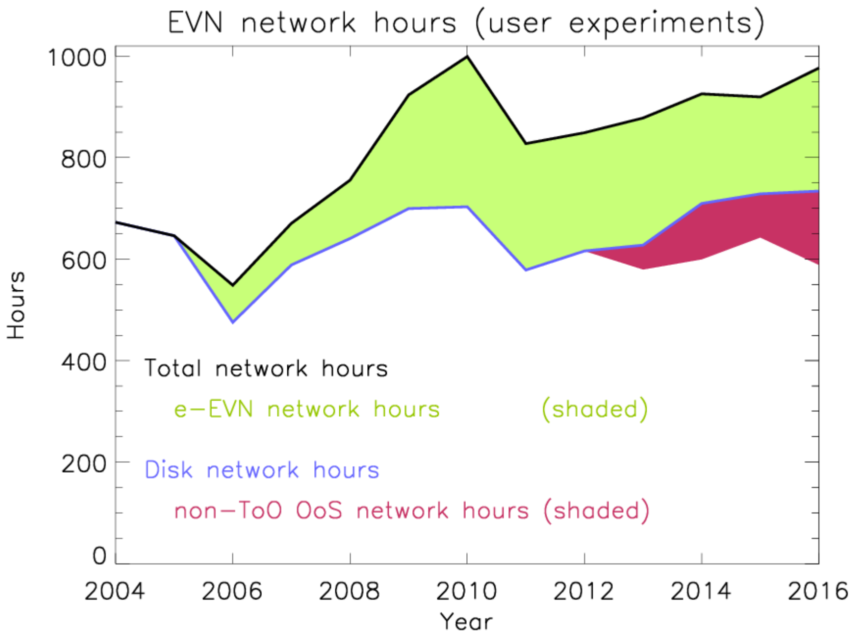


Figure 6: The total amount of observing hours of the EVN in 2004-2016

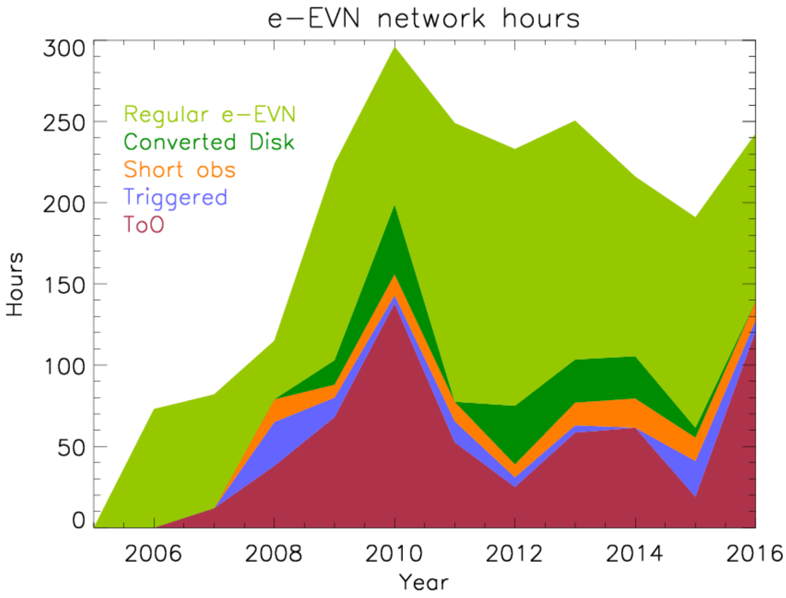


Figure 7: The total amount of eVLBI hours from 2004 to 2016

Scheduling and Operations

As in previous years, in each of 2015 and 2016 there were three major (disk-based) EVN observing sessions, each of three weeks duration, and ten e-VLBI runs of 24 hour duration (plus 4 hours fringe-finding time). The basic parameters of these sessions are summarized in Table 4.

Table 4: Summary of EVN Sessions 2015-2016.

Session	Dates		Length (days)	Efficiency (%)	Wavelength (cm)					
					0.7	1.3	3.6	5	6	18/21
2015-I	26 Feb	19 Mar	21.0	43.3				✓	✓	✓
2015-II	28 May	18 Jun	21.0	53.3	✓		✓		✓	✓
2015-III	15 Oct	5 Nov	21.0	38.1			✓	✓	✓	✓
2016-I	18 Feb	10 Mar	21.0	41.4				✓	✓	✓
2016-II	26 May	16 Jun	21.0	53.0		✓	✓	✓	✓	✓
2016-III	20 Oct	8 Nov	20.0	43.3		✓	✓	✓	✓	✓

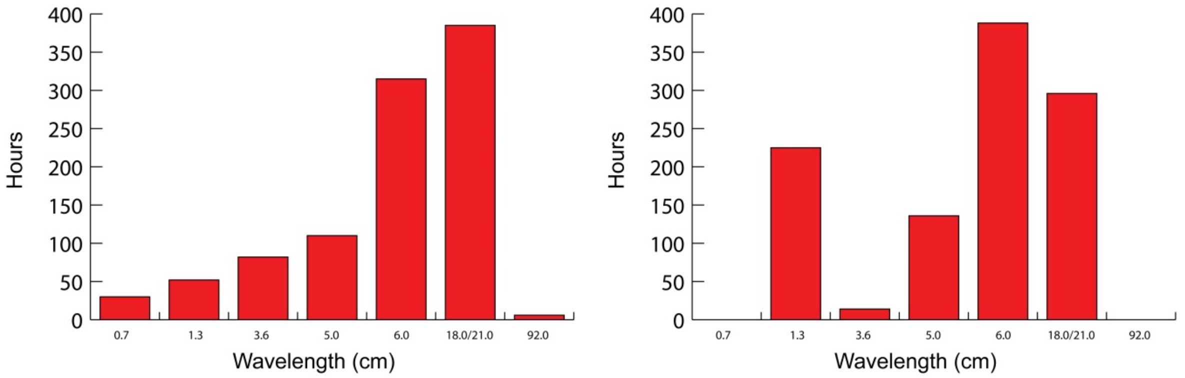


Figure 8: Distribution of EVN hours against observing waveband for 2015 (left) and 2016 (right)

Figure 8 shows the distribution of EVN hours against observing band for 2015 and 2016. These figures include hours observed during regular disk-based EVN sessions, eVLBI runs and out-of-session observations. In 2015 the total number of hours scheduled was 980.0 and in 2016 it was 1059.0. As usual, C-band and L-band observations were the most common, whilst a large campaign of spectral line 1.3cm observations was begun in 2016.

Table 5 and Table 6 give details of the regular disk-based EVN sessions for 2015 and 2016 respectively. Observations in each disk-based session utilised between 3 and 5 different observing bands. The efficiency (defined as the percentage of available time actually scheduled) in the disk-based sessions ranged from 38.1% to 53.3%. This efficiency is primarily dictated by the time needed to change observing band and the demand on GST range (which is far from uniform).

Table 5: Details of EVN Sessions in 2015, showing the number of observations, hours and TBytes scheduled, correlators used and number of observations for associated antennas.

	Session 2015-I			Session 2015-II			Session 2015-III		
Experiments	No.	Hours	TBytes	No.	Hours	TBytes	No.	Hours	TBytes
Total	24	218.0	773.4	34	269.5	1542.8	28	192.0	940.3
EVN-only	19	194.0	674.7	21	202.5	1071.7	20	150.0	561.2
Global	1	13.0	51.4	8	54.0	427.6	2	27.0	337.6
Short	0	0.0	0.0	0	0.0	0.0	1	2.0	11.0
Tests	4	11.0	47.3	5	13.0	43.5	5	13.0	30.5
Correlator									
EVN	22	200.0	734.6	34	269.5	1542.8	28	192.0	940.3
Bonn	2	18.0	38.8	0	0.0	0.0	0	0.0	0.0
VLBA	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
eEVN	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
Other	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
CAL	3	12.0	0.0	4	16.0	0.0	4	16.0	0.0
e-MERLIN	2			0			4		
VLBA	1			5			2		
VLA	0			4			0		
GBT	0			0			1		
Arecibo	2			8			0		
Robledo	2			0			3		
Goldstone	0			0			0		
RadioAstron	0			0			5		
KVN	0			3			0		
Wettzell	0			3			3		
LBA	0			0			0		

Table 6: Details of EVN Sessions in 2016, showing the number of observations, hours and TBytes scheduled, correlators used and number of observations for associated antennas.

	Session 2016-I			Session 2016-II			Session 2016-III		
Experiment	No.	Hours	TBytes	No.	Hours	TBytes	No.	Hours	TBytes
Total	24	208.0	1028.8	33	267.0	799.6	28	208.0	1441.5
EVN-only	18	137.0	457.7	28	241.0	519.6	21	165.0	1010.2
Global	3	62.0	548.6	1	14.0	238.7	2	28.0	338.6
Short	0	0.0	0.0	0	0.0	0.0	0	2.0	0.0
Tests	3	9.0	22.5	4	12.0	41.3	5	15.0	52.7
Correlator									
EVN	23	206.0	1020.5	27	185.5	738.8	27	194.0	1287.0
Bonn	1	2.0	8.3	1	24.0	60.8	1	14.0	154.5
VLBA	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
eEVN	0	0.0	0.0	5	57.5	0.0	0	0.0	0.0
Other	0	0.0	0.0	0	0.0	0.0	0	0.0	0.0
CAL	3	12.0	0.0	4	16.0	0.0	5	20.0	0.0
e-MERLIN	6			1			4		
VLBA	3			1			2		
VLA	0			1			1		
GBT	1			1			1		
Arecibo	0			0			1		
Robledo	6			2			8		
Goldstone	0			0			0		
RadioAstro	2			2			1		
KVN	0			6			3		
Wettzell	0			4			0		
LBA	0			0			1		

Figure 9 shows the distribution of observing hours against EVN station and affiliate antennas for 2015 and 2016. Of special note are the now routine observations with the KVAZAR network of antennas (Sv, Zc, Bd) and the KVN network (Kt, Ky, Ku) at higher frequencies, the gradual shift from Shanghai (Sh) to Tianma (T6), the inclusion of new member Irbene into some observations in late 2016, and the reduction in the number of hours scheduled for Noto because of its current lack of an L-band receiver. A small number of hours were jointly scheduled with e-MERLIN (202 hours in 2015-2016) but these projects were observed separately since full integration of e-MERLIN into the EVN was not possible during this period. 140 hours were scheduled in 2015-2016 with the EVN-affiliate Robledo, a significant increase on previous reporting periods.

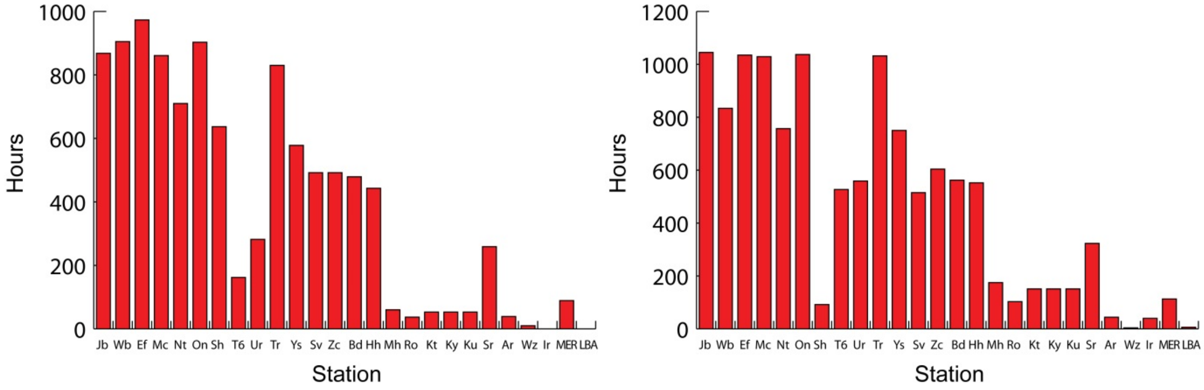


Figure 9: Distribution of observing hours for EVN stations and affiliates for 2015 (left) and 2016 (right).

Details of EVN eVLBI observations in 2015-2016 are shown in Table 7 and details of out-of-session (OoS) EVN observations for 2015-2016 in Table 8.

Table 7: Details of EVN eVLBI runs 2015-2016, showing dates and waveband, number of hours scheduled per run, the type of observation and the number of trigger observations scheduled and actually triggered.

Run	Date	Wavelength	Hours	eVLBI Proposal Type				
				Queued			Trigger	
				Normal	Short	ToO	Scheduled	Triggered
15e01	13 Jan 2015	18cm	24	2	0	0	0	0
15e02	10 Feb 2015	18cm	19	2	1	0	0	0
15e03	24 Mar 2015	6cm	22.5	3	0	0	2	0
15e04	14 Apr 2015	18cm	10	1	1	0	0	0
15e05	12 May 2015	18cm	16.5	2	1	0	0	0
15e06	23 Jun 2015	18cm	22.0	2	0	0	0	0
15e07	15 Sep 2015	18cm	14.0	2	0	0	1	0
15e08	6 Oct 2015	6cm	21.5	3	0	0	3	0
15e09	17 Nov 2015	6cm	24.0	1	1	1	0	0
15e10	1 Dec 2015	18cm	19.5	2	1	1	1	0
16e01	12 Jan 2016	18cm	15	2	0	0	1	0
16e02	2 Feb 2016	6cm	19.5	3	0	0	3	0
16e03	15 Mar 2016	6cm	34	2	0	2	2	0
16e04	12 Apr 2016	5cm	7	1	0	0	0	0
16e05	10 May 2016	6cm	24	1	3	1	2	0
16e06	21 Jun 2016	6cm	21	2	0	1	2	0
16e07	21 Sep 2016	6cm	18	1	1	1	2	0
16e08	11 Oct 2016	6cm	15	2	0	0	2	0
16e09	15 Nov 2016	6cm	15	1	1	1	2	0
16e10	6 Dec 2016	5cm	10	1	0	0	0	0
Total			371.5	36	10	8	23	0

Table 8: Details of EVN out-of-session (OoS) observations 2015-2016 showing number of observations, hours and TBytes scheduled, correlators used and number of observations for associated antennas.

	2015 OoS			2016 OoS		
Experiment	No.	Hours	TBytes	No.	Hours	TBytes
Total	9	86.0	151.2	20	163.0	968.8
Correlator						
EVN	4	42.0	43.7	3	21.0	32.3
Bonn	2	26.0	91.6	8	101.0	915.5
ASC	3	18.0	15.9	4	11.0	11.0
eEVN	0	0.0	0.0	5	30.0	0.0
e-MERLIN	0			0		
VLBA	2			14		
VLA	1			3		
GBT	1			2		
Arecibo	3			5		
Robledo	5			8		
Goldstone	0			0		
RadioAstro	9			11		
KVN	1			5		
Wettzell	0			0		
LBA	0			1		

Technical and Operations Group Report

The TOG is in charge of the operations and technical developments of the network. It is composed of VLBI friends at the stations and personnel at the correlators. The TOG meets periodically approximately every nine months rotating the location through the different observatories. The meetings are open and are also regularly attended by non-EVN members, like the FS main developer or staff from Haystack and NRAO. The meetings are scheduled outside of EVN sessions and, since 2014, every third meeting coincides with the EVN symposium and the EVN user's meeting, to stimulate direct interaction between the technical personnel and the users. Since 2016, the TOG meets together with the Global Millimeter VLBI Array (GMVA) Technical Group (GTG) every other meeting. In these cases the meetings last two days, devoting one day for the TOG and another for the GTG. The goal is to exploit synergies, looking for common developments and benefiting from the exchange of information between both communities.

The TOG chair reports to the CBD every 6 months providing information about the EVN sessions, technical developments and any other relevant information that may help the CBD to take decisions. Pablo de Vicente of Observatorio de Yebes (IGN) chaired the TOG during 2015–2016.

TOG Meetings: There were three meetings during 2015–2016. Reports from the meetings are available on the EVN web–site. The locations and dates of the meetings are given below.

Table 9 TOG Meetings held during 2015-2016

Robledo de Chavela, Spain	June 24, 2015
Madrid, Spain	February 8-9, 2016
Saint Petersburg, Russia (see Figure 10)	September 29, 2016

Figure 10: Participants of the TOG meeting in IAA RAS, St. Petersburg. September 2016

The TOG activities are focused on the one hand on keeping the high performance achieved in previous years, stressing the importance of reliability and the quality of calibration; on the other hand, the TOG focuses on continued development of common techniques and tools at the stations to progress their VLBI capabilities in a uniform way.

The network efficiency based on the reliability of the individual stations is roughly 90% for the 2015-2016 period (Figure 11)

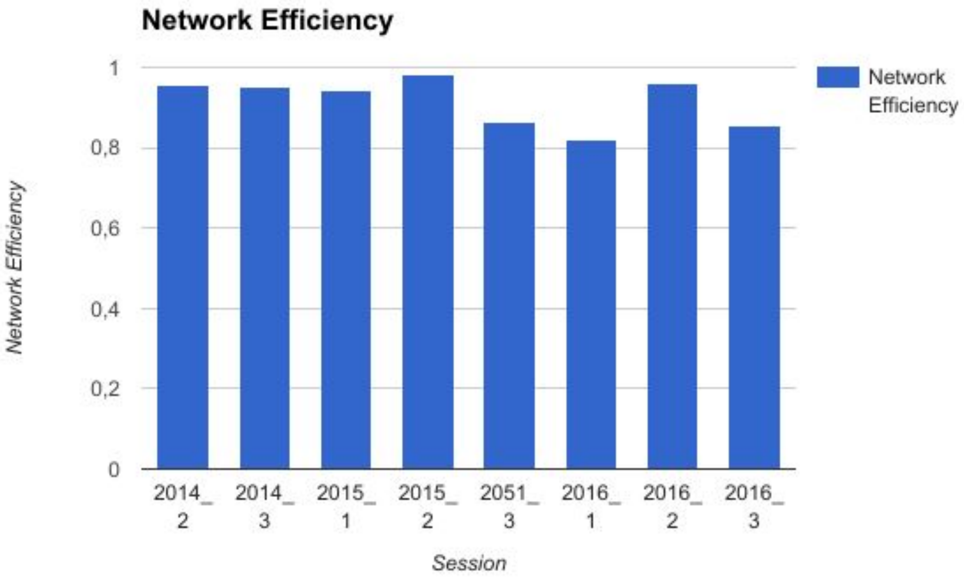


Figure 11: Evolution of the EVN efficiency in the period 2014 to 2016

During these two years the contract between IVS Inc and the EVN was completed and as a consequence the EVN can now operate at 2 Gb/s, yield data in VDIF and support continuum calibration using the DBBC2 backends.

The main outcomes are listed below:

- Implementation of VDIF at jive5ab and the FS for DDC and PFB observations when using either a Mark5C, a Mark6 or a Flexbuff as recorders. This involved adding support at the FS for the DBBC2 Fila10G module.

- Implementation of Polyphase Band mode at 2 and 4 Gb/s at all stations using DBBC2s as data acquisition.

- Adoption of Flexbuffs at four stations (Ys, On, Ef and Mh) for regular observations.

- Deployment of several Flexbuffs at JIVE correlator purchased by the stations and installation of all required software and tools.

- Implementation of continuous calibration at the FS and fixes at the DBBC2 software.

- Adoption of continuous calibration as standard calibration mode at several stations.

- Implementation of a new antabfs.py procedure that manages continuous calibration.

- Implementation of 2 Gbps mode in eVLBI. This involved changes at the correlator and the installation of proxies at the stations that allow the correlator to control the data flow from the Fila10G.

- First eVLBI observations with two Quasar antennas at 512 Mb/s.

- Participation in regular observations for Irbene station at several frequencies: C, M and X band.

- Participation of Irbene in 2 Gbps eVLBI observations.

- Participation of Kunming station at C, M and X bands.

- Successful observations at a rate of 4 Gb/s using PFB mode with more than 4 antennas.

- Successful observations at 43 GHz with several EVN antennas after several years without observing this frequency

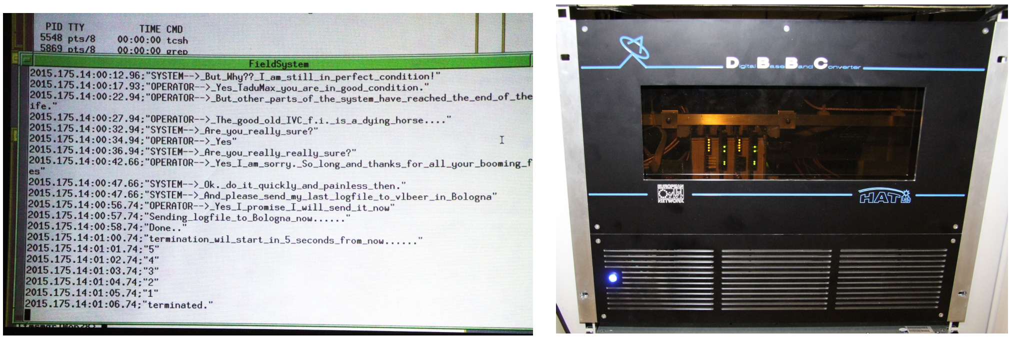
EVN Observatory Reports

ASTRON - WESTERBORK SYNTHESIS RADIO TELESCOPE

2015 was a transformational year in the history of the Westerbork Synthesis Radio Telescope. On June 24, 2015 a chapter closed, with the decommissioning of the Multi-Frequency Front End receiver systems and the associated backends. By coincidence, the last operational experiment of the array was the eVLBI session of June 23/24, 2015, exactly 45 years to the day that Queen Juliana opened the WSRT. At the end of the experiment, a small gathering marked the ceremonious switch off of the backends, and the start in earnest of rollout of the APERTIF system to all of 12 of the WSRT telescopes

Figure 12: Past and present ASTRON staff marking the end of MFFE operations

Meanwhile, early 2015 saw the commissioning of a single-dish multi-frequency VLBI facility, which uses one of the remaining non-Apertif dishes, RT0 or RT1, on the west side of the array, equipped with modified Multi- Frequency-Frontends (to supply circular polarization) or the 5cm receiver. The new backend consist of a DBBC (with 8 BBC's, 2Cores and a VSI input), which was delivered in January 2015, and a Mark5B. New software to control and monitor the telescope, and interface with the Field System was developed.
The new single dish VLBI system is in use since the e-VLBI session of September 2015.



```
  PID TTY          TIME CMD
 5548 pts/8    00:00:00 tcsh
 5869 pts/8    00:00:00 grep
```

```
2015.175.14:00:12.96;"SYSTEM-->_But_Why??_I_am_still_in_perfect_condition!"
2015.175.14:00:17.93;"OPERATOR-->_Yes_TaduMax_you_are_in_good_condition."
2015.175.14:00:22.94;"OPERATOR-->_But_other_parts_of_the_system_have_reached_the_end_of_the
ife."
2015.175.14:00:27.94;"OPERATOR-->_The_good_old_IVC_f.i._is_a_dying_horse...."
2015.175.14:00:32.94;"SYSTEM-->_Are_you_really_sure?"
2015.175.14:00:34.94;"OPERATOR-->_Yes"
2015.175.14:00:36.94;"SYSTEM-->_Are_you_really_really_sure?"
2015.175.14:00:42.66;"OPERATOR-->_Yes_I_am_sorry._So_long_and_thanks_for_all_your_booming_f
es"
2015.175.14:00:47.66;"SYSTEM-->_Ok._do_it_quickly_and_painless_then."
2015.175.14:00:47.66;"SYSTEM-->_And_please_send_my_last_logfile_to_vlbeer_in_Bologna"
2015.175.14:00:56.74;"OPERATOR-->_Yes_I_promise_I_will_send_it_now"
2015.175.14:00:57.74;"Sending_logfile_to_Bologna_now......"
2015.175.14:00:58.74;"Done.."
2015.175.14:01:00.74;"termination_wil_start_in_5_seconds_from_now......"
2015.175.14:01:01.74;"5"
2015.175.14:01:02.74;"4"
2015.175.14:01:03.74;"3"
2015.175.14:01:04.74;"2"
2015.175.14:01:05.74;"1"
2015.175.14:01:06.74;"terminated."
```

Figure 13: The former WSRT VLBI backend gives way to the new DBBC2

The WSRT array is now equipped with the APERTIF receivers and backends at 12 telescopes. The APERTIF system consists of 121-element phased-array feeds

(PAFs) and digital beamformers, with a digital correlator and Tied Array beamformer to match, and is transforming the WSRT to a flexible wide-band survey instrument at L-band, with scientific operations to start in 2018. It is planned that WSRT will again offer tied-array capability at L-band, using the APERTIF receivers.

Operations: The WSRT participated in first two EVN sessions of 2015 with the tied-array and since then with a single telescope, as well as scheduled and Target–of–Opportunity e–VLBI observations. In general observations were very successful; only a very small fraction of time was lost due to backend or diskpack problems during EVN sessions.

The WSRT also participated in RadioAstron Space–VLBI observations, both under the auspices of EVN projects as well as RadioAstron projects submitted to the WSRT Programme Committee. RadioAstron observations outside of EVN sessions were recorded on disk packs and data were subsequently sent via FTP to the server in Moscow.

ASTRON staff roles in EVN activities: Rene Vermeulen represented ASTRON at the EVN CBD Meetings and took up the chairmanship of the Consortium from 1st July, 2015. Antonis Polatidis was ASTRON’s representative on the EVN PC, and EVN Secretary from 1st July 2015.

HARTEBEESTHOEK RADIO ASTRONOMY OBSERVATORY

Hartebeesthoek continues to operate two VLBI capable antennas, the original 26-m equipped with multiple receivers ranging from L-band to K-band and the newer 15-m with a co-axial S/X receiver, with the possibility of simultaneous operation of both. Both antennas are equipped with DBBC2 recording terminals and Mark5B+ recorders, with additional recording capability via integrated FiLa10G interfaces to a Mark5C recorder and a new Flexbuf system.

To help with the on-going demand for higher bit-rates and associated disk space requirements, the observatory contributed 160 TB (5x32 TB) diskpacks in early 2015 and a matched pair of 110 TB Flexbuf systems (at the station and at the correlator) during 2016.

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. It also continues to be quite heavily used in support of the RadioAstron survey program, typically switching frequency band in the middle of each observation.

No new receivers have been added over this period, but there has been a slow but steady uptake of the of the K-band capability added to the 26-m in 2016. EVN usage has been almost exclusively of the 26-m, with the 15-m taking up most of the geodetic VLBI load.

An order for a new 13.2-m ring-focus fast-moving VGOS compatible antenna was placed with MT Mechatronics at the end of 2015, with site establishment and construction of the concrete pedestal commencing in late 2016. The antenna itself should be completed by mid- to late-2017.

From the 13 - 19 March 2016, the observatory hosted the 9th International VLBI Service (IVS) General Meeting and related workshops. Prior to that, from 9 - 12 March 2016, an IVS VLBI School was run at the observatory.

INSTITUTE OF RADIO ASTRONOMY (INAF), ITALY

Medicina station

Antenna

In May 2015 a long maintenance period was been concluded by painting the antenna structure and by the restoration and painting of the antenna basement. The painting of the primary mirror surface is scheduled for 2017. The azimuth rail track is at the end of its life, showing cracks and wear. Its substitution is scheduled for 2017.

Receivers and observations

Medicina routinely makes observations in the 18, 21, 6, 5, 3.6, 1.3 cm bands. A dual-feed receiver is under construction in the 13.5-18 GHz band (2cm band). Construction of a 6cm receiver is ongoing for the SRT telescope.

VLBI back-end

The overall system DBBC+FILA10G+Mark5C is running smoothly now; VDIF data format has been definitively adopted.

A Continuous cal system able to continuously monitor the Tsys has been implemented for the receivers mounted in the Cassegrain focus (6, 5, 1.3 cm). The next step will be to implement the same facility for the oldest ones mounted in Primary focus (21, 18, 13, 3.6 cm)

Two FlexBuff systems has been bought and integrated in the system. Operational use is expected after March 2017. At the end of 2016 the overall contribution by the station to the EVN is 72 modules amounting to 540.5TB.

e-VLBI

Medicina is routinely running e-VLBI experiments. The most recent development is that fringes at 4Gbit/sec at C band, 512MHz dual polarization bandwidth, PFB firmware 32x32MHz, and 2 bit sampling were obtained.

Space VLBI

Medicina continues to participate in RadioAstron observations (on average 24 experiments/month).

Figure 14: A recent image of the 32m Medicina antenna, May 2016

Noto station

Antenna

The coaxial cables of both the polarizations were replaced in 2015. In 2016 the mechanics of the subreflector and the secondary mirror were completely replaced. The work for the frequency agility project is in progress and the implementation of the quick change of the C- band receiver is planned for 2017.
The Enhanced Single-dish Control System, developed in Medicina, has been installed at Noto and at present is under test; this system will control the antenna operations both in single dish and VLBI observations.

Receivers

The Noto antenna can observe at the frequencies of 2.3,5,6,8.4,22, and 43 GHz. An SXL receiver on primary focus is at the moment under evaluation.

VLBI back-end

Two FlexBuff systems have been acquired; the station unit, equipped with 160TB, arrived in February 2016 and will become operational in 2017. At the end of 2016 the overall contribution by the station is 64 modules amounting to 445.6TB.

e-VLBI

FiLa10G is used for e-VLBI observation. DBBC proxy software is temporarily installed on Mark5B recorder. The purchase of a dedicated APU system is planned.

Space VLBI

Noto is still involved in the RadioAstron observations at C and K bands.

RFI

Spectrum evaluation surveys for VLBI bands were done in the year 2016 in collaboration with SRT, using the RFI mobile laboratory. Reporting interventions at the Ministry were performed with success on C-Band against different RLan radio link signals. The purchase of equipment that will allow the monitoring of the received bands remotely has been proposed.

Sardinia Radio Telescope

Operations:

The SRT started regular EVN Operations in the February 2015 Session and participated in six EVN Sessions in 2015-2016, OoS observations, and a number of RadioAstron sessions, with the following equipment:

- L-band receiver, covers the band 1300-1800 MHz;
- M-band receiver, covers the band 5700-7700 MHz;
- K-band receiver, covers the band 18-26 GHz;
- 4-channel DBBC2 system (dual polarisation, dual IF), 512 MHz broad each;
- MK-5C recorder;
- MK-5B+ recorder.

The SRT will be offline for the whole of 2017 for repair works of the active surface and migration to the control room and equipment rooms of the new completed buildings. It is expected that the SRT will re-join EVN observations in 2018. The already purchased second 2-channel DBBC2 unit is also expected to become operational in 2018.

Figure 15: SRT in the winter season.

INSTITUTE OF APPLIED ASTRONOMY - QUASAR VLBI NETWORK

The Institute of Applied Astronomy of Russian Academy of Sciences is the host institution for the QUASAR VLBI network consists of three VLBI stations – Svetloe (Sv), Zelenchukskaya (Zc) and Badary (Bd). Each station equipped with 32-m fully steerable radio telescopes RT-32 and co-located GPS/GLONASS, DORIS (Bd) and SLR systems.

Stations Zelenchukskaya and Badary are also equipped with a 13-m VGOS radio telescopes marked as Zv and Bv. At present both new RT-13 are under setting and intensive testing works.

Personnel: Alexander Ipatov (Director), Andrey Mikhailov (Technical friend), Mikhail Kharinov (VLBI friend and Scheduler).

Observations: During the period 2015 – 2016 the QUASAR network performs geodetic and astrophysical VLBI observations on domestic (IAA weekly 24-h EOP and daily e-VLBI 1-h UT sessions) and international projects with our partners: IVS, EVN and RadioAstron.

The 32-m radio telescopes of Sv, Zc and Bd participated in six EVN sessions at L, C, X and K bands with total duration 131.4 days. In addition, the QUASAR network of radio telescopes has been used for 24h IVS experiments: Sv – 72, Zc – 69, Bd – 71. Also, a total of 6.4 days of telescope time was scheduled for RadioAstron observations, not included in EVN schedules.

Antennae: At Bd the antenna alignment was conducted – correction models of azimuth and elevation axes were updated in January 2016. Geodetic measurements on RT-32 were carried out in February 2015 and May 2016. Rail track the single joint №13 was repaired in April 2016. Tacho-generator of low speed on azimuth cart №4 was repaired in July 2016.

At Sv the rail track alignment was conducted during 1-23 July 2016. In 25 July 2016 the azimuth reducer of low speed was replaced.

At Zc the geodetic measurements on RT-32 and local network were conducted in November 2015. Restoration of corrosion-resistant paint on antenna was finished in the beginning of 2015. The cable for transmission of the cont-reflector coordinates, and elevation encoder were repaired.

Receivers: All RT-32 QUASAR radio telescopes are equipped with receivers in the next bands: L, S, C, X and K. At Bd the K-band one-channel front-end units was replaced on the new two-channel unit in May 2016. Another three cryogenic systems was repaired: one for L-band in October 2015 and two for X and S-bands in December 2015. At Sv the installation of the two-channel cryogenic receiver unit for K-band is finished in 2013 March. C-band receiver RCP channel was repaired and cooled unit restored in November 2014. At Zc the cryogenic systems for X-band was repaired and for S-band was replaced in the end of 2016. Water vapour radiometers were put into operation at Zc and Bd in 2015.

IAA Correlator Center

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

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

In 2014 the Russian Academy of Sciences' FX (RASFX) 6-station near-real time GPU-based VGOS correlator was developed (Ken V., Surkis I., et al. "IAA VGOS GPU-based Software Correlator: current status and broadband processing", Proceedings of the 22nd European VLBI Group for Geodesy and Astrometry Working Meeting processing. p. 40-42). The correlator software is installed on HPC cluster, which contains 40 servers, each equipped with 2 Intel CPUs and 2 Nvidia GPUs.
Since 2015 the DiFX software correlator was installed on the HPC cluster.

JODRELL BANK OBSERVATORY

Jodrell Bank Observatory performed a total of 145 regular EVN experiments during 2015-2016. Fifty-three experiments at 18/21cm, 50 at 6cm, 32 at 5cm and 14 at 1.3cm were scheduled to use Jodrell Bank's Lovell and Mk2 antennas. During this period, fifteen of the EVN experiments were joint e-MERLIN projects, although none were observed simultaneously due to the ongoing efforts to assimilate e-MERLIN into the EVN.

A total of 1266.5h of telescope time was scheduled for regular EVN observations during 2015-2016. This consisted of 511h on the Lovell and 755.5h on the Mk2 telescope. In terms of waveband this was 437h at 18/21cm, 465.5h at 6cm, 221h at 5cm and 143h at 1.3cm. The total reported data loss at the telescope for 2015-2016 was 31h05m (3.5%), i.e. a success rate of 97.5%. JBO also contributed 247h of observing time to out-of-session experiments (mostly EVN+RadioAstron observations) and a further 371.5h of observing time for 20 regular eVLBI observing sessions during 2015-2016.

Common reasons for data loss during this period were high winds, disk recorder problems, failure of the OTCX antenna control computer, power glitches and servo faults. The most costly error during this period occurred several times after changing between DBBC firmware for 'pseudo-2Gbps' recording (the firmware change allows 32MHz channels on the DBBC). This change occasionally resulted in a loss of sync between the FS and DBBC which took many cycles of restarting both machines to fix.

In the February/March 2016 session, the C-band receiver was found to be faulty during the first NME experiment and was changed immediately. Unfortunately the replacement warmed up over a weekend so that all C-band observations were with reduced sensitivity. There were also problems at M-band which used another replacement broad-band C-band receiver that subsequently was discovered to have low sensitivity. This was fixed in time for the final M-band user observation. The entire May/June 2016 EVN session was performed on the Mk2 telescope due to the Lovell telescope being in an early maintenance mode.

Normal technical operations have run relatively smoothly during this reporting period. From Session II 2015 JBO was permanently operating with the DBBC unit. After being tested for initial operations, the DBBC was fitted with the 'Core2' boards to allow 2Gbps recording and one of the Mark5 units upgraded to 5B+ which includes the Amazon card plus VSI interface. Most routine observations were performed with the 5B unit. The other Mark 5C unit was not formally tested but appeared to be functioning correctly.

Some effort was expended on the e-MERLIN data path now that the system is relatively stable, and because VLBI operations share a requirement with the pulsars group for the data path. After difficulties in finding fringes between data in the e-MERLIN post-correlator and VLBI data paths, an experiment was performed using pulsar timing. This identified an unexplained 120ms delay between the two data paths (about equal to half the size of the e-MERLIN correlator delay buffer). Using this information, fringes between EVN and e-MERLIN antennas were found in data from a Network Monitoring Experiment in the October/November 2015 EVN session.

Concurrently, options for e-MERLIN data transport to Mk5 recording and possibly as an eVLBI stream to JIVE were considered. Recording of the e-MERLIN VDIF data appeared to be functioning correctly on a local Flexbuff for later e-shipping.

The JBO network connection through JANET was expanded to 2.5 Gbps during 2016. However, eVLBI at 2Gbps is not yet possible as the 100G Ciena router has yet to be commissioned at Manchester/JBO. A backup plan in which the 3x1G links were aggregated was set up using a spare PC and the hardware was tested. Data has been successfully transmitted with this system to JIVE at 2Gbps.

The old MkIV and VLBA racks have been decommissioned and replaced with new racks intended for Flexbuff and 10GE eVLBI. A stabilised calibration diode was installed on the Mk2 telescope for 6cm observations and a unit was built for continuous calibration control and to provide 10MHz referenced from the 5MHz signal. This system remained untested.

Simon Garrington represented Jodrell Bank Observatory at EVN CBD meetings and on the JIVE board. Throughout this period Tom Muxlow was the JBO representative on the EVN PC and Alastair Gunn continued to serve as the EVN Scheduler.

MAX-PLANCK-INSTITUT FUER RADIOASTRONOMIE, BONN

The MPIfR was a founding member of the EVN and plays a full role in all EVN activities. Its 100m radio telescope in Effelsberg is a crucial component of EVN observations due to the telescope's very high sensitivity and wide range of observing frequencies. The MPIfR Correlator Centre, a joint facility of the MPIfR and the German geodetic VLBI community, continues to play a role for some EVN projects, notable those involving the Russian Space-VLBI project RadioAstron.

MPIfR Staff involvement in EVN activities

EVN-CBD: Prof. J. Anton Zensus attended meetings and was CBD Chair until 30 June 2015. Richard Porcas attended meetings as Secretary until 30 June 2015.

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

EVN TOG: Uwe Bach and Walter Alef attended TOG meetings.

EVN Technical & Administrative Support: Alex Kraus is the Scheduler for the Effelsberg telescope and responds to requests for EVN Out-of-Session and Target-of-Opportunity observations. Uwe Bach is the "VLBI Friend" at Effelsberg, responsible for the execution of EVN observations. Walter Alef is Head of the MPIfR Division of VLBI Technology, responsible for the MPIfR Correlator Center and other VLBI technical matters. In 2015-2016 this included development of the DBBC2 and DBBC3 digital backends together with Gino Tuccari, and support for EVN tests at higher data-rates. Gabriele Bruni is responsible for the correlation of EVN/Global RadioAstron projects at the MPIfR Correlator.

Other MPIfR VLBI activities

MPIfR staff are involved in many other VLBI activities including:

- participation in the **RadioAstron** International Science Council (RISC) and Program Evaluation Committee (RPEC)
- leading the organization of the **GMVA** (Global 3mm VLBI Array) including PI support, scheduling, correlation and technical coordination; in 2015-16 this included planning the participation of **ALMA** in GMVA sessions
- contributing to the **APP** (ALMA Phasing Project)
- participation in the **EHT** (Event Horizon Telescope) interim Consortium and preparing the **APEX** telescope for taking part in 1mm EHT observations

Effelsberg Station Report

Figure 16: The Effelsberg 100m radio telescope as seen from the public visitors pavilion in Autumn 2016. The main dish panels were freshly painted during the maintenance periods in summer 2015 and 2016. (photo N. Junkes, MPIfR)

Activities during 2015-2016

About 30% of the observing time of the Effelsberg telescope is used for VLBI observations. Most of them are astronomical observations for the EVN, the High Sensitivity Array (HSA), the Global mm VLBI Array (GMVA) or other global networks, but also geodetic VLBI observations within the IVS are performed. Since 2011 the Russian Astro Space Center (ASC) has been operating a 10-m space radio antenna on board the satellite SPEKTR-R (RadioAstron) to perform VLBI observations. Effelsberg is highly involved in the ground based support of this mission, and 296 of a total of 428 VLBI observations in 2015 were connected to RadioAstron observations and 208 of 368 observations in 2016.

Two Mark6 recorders have been installed for recording data from the DBBC2 backend. The two recorders are equipped with large 32TB or 64TB diskpacks which stay in Effelsberg, providing a total local storage capacity of 256 TB. All recorded data is transferred via the e-VLBI network to the correlators in Bonn, at the ASC in Moscow, and at JIVE in Dwingeloo. For storage of Effelsberg EVN data at JIVE the MPIfR provided a 120TB raid system for JIVE as well.

The K-band receiver (18 to 26 GHz) that was installed in the secondary focus in 2014 has been commissioned and is in regular use for VLBI observations with the EVN, HSA and RadioAstron.

In 2015 a new broad band receiver for C- and X-band, covering a frequency range of 4 GHz to 9.3 GHz (7.5 cm to 3.2 cm), was installed in the secondary focus cabin. Primarily, the receiver has been build for high sensitivity continuum observations and spectroscopy of molecule transitions, like formaldehyde and methanol. With its two linear polarizations it is not the natural first choice for VLBI observations as most stations in VLBI record left and right circular polarization (LCP and RCP) signals. In December 2016, the regular real-time eVLBI observations were scheduled at 6.65 GHz, but the standard VLBI 6 GHz prime focus receiver box at Effelsberg was not available due to maintenance. To support the observations the new C+ receiver was used. The correlation and calibration of the recorded data was successful and Effelsberg showed good and stable fringes from the start of the experiment. After correlation a newly developed algorithm (Marti-Vidal et al. 2016, A&A, 587, 143) was used to convert the linear to circular polarization**.** This has worked successfully and, depending on further test with higher data-rate continuum observations, the new receiver might be an option for C-band observations in general.

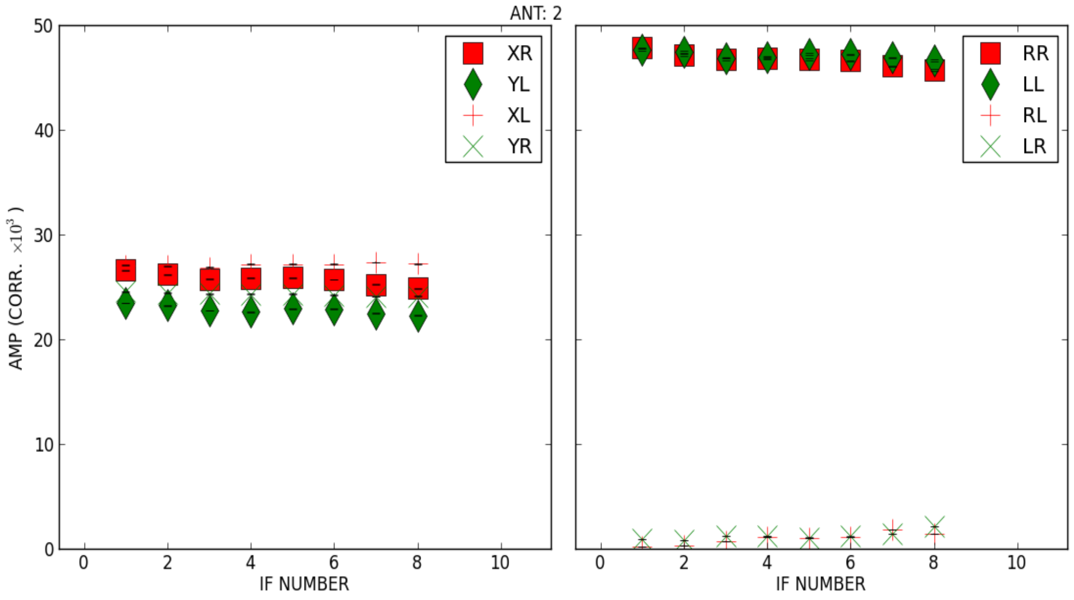


Figure 17: Correlated amplitudes (uncalibrated) for the eight BBCs of EO014 in December 2016 illustrating the successful conversion of linear to circular polarization for the Effelsberg 6.65 GHz data. On the left correlations of linear vs. circular polarization resulting in equal amplitudes for all cross products and on the right the converted RCP/LCP signal for Effelsberg, resulting in strong detection in total intensity and low cross polarization.

In late 2016 a DBBC3 was ordered for Effelsberg to replace the DBBC2 and also to allow recording at data-rates of up to 32 Gbps for receivers with 4 GHz-wide IFs.

Current Status: Effelsberg uses the DBBC2, Fila10G and a Mark6 recorder for all EVN, global, RadioAstron, and geodetic VLBI observations. Most of the recorded data is e-transferred to the correlators in Bonn, at the ASC in Moscow, and JIVE.

In addition there are two NRAO RDBEs and a Mark5C recorder that are used for observations with the VLBA, HSA, and GMVA. Mark5 diskpacks to Socorro are still being shipped. Both VLBI backends and their recorders are controlled by the Field System (current release FS-9.11.8). The observatory is connected via a 10 GE optical fibre to the e-VLBI network and can do real time e-VLBI observations (performed about monthly within the EVN) and e-transfers.

Future Plans: Upgrades for several receiving systems are planned for 2017. The construction of a new Q-band receiver (38 to 50 GHz) was delayed because of unexpected problems in the RF chain, but is planned to be installed in summer 2017. In parallel the installation of a Ku-band receiver (12 to 18 GHz) is planned as well. The new receivers will provide wideband IF signals of 2.5 GHz and 4 GHz bandwidth which can be used with the next generation of digital VLBI backends and recorders (e.g. DBBC3 and Mark 6) to record data at recording rates of up to 32 Gbps. The installation of a DBBC3 is planned for summer 2017.

Bonn Correlator Report

The Bonn correlator is operated jointly by the MPIfR, the Bundesamt fuer Kartographie und Geodaesie (Frankfurt) and the Institut fuer Geodaesie und Geoinformation of Bonn University. It is mainly used to correlate data from GMVA, IVS and EVN-RadioAstron observations, and also from a small number of EVN and EHT observations.

The DiFX Correlator: All VLBI observations are processed using the DiFX software correlator. A number of additional software features were introduced during this period including freezing the special RadioAstron version (J. Anderson, GFZ Potsdam), developing native Mark6 playback - currently 95% completed (W. Brisken, NRAO) - and the handling of Mark6 modules (H. Rottmann, MPIfR).

Cluster upgrade: The aging HPC cluster which ran the correlator for many years was replaced in December 2015. The new system has 3 head nodes (of which 2 are for correlation), 68 nodes each with 20 compute cores (=1360 cores) and Infiniband 56 Gbps interconnect. In addition the data RAIDS and Mark5 units work as data-stream nodes. More than one correlation can be run in parallel.

Playback: 15 Mark5 units can be used for playback from disk modules in all flavours of Mark5 data (A,B,C). All Mark5 systems are currently using SDK 9.4.

In addition, data can be played back from 10 large RAID systems (a total of >1 PB). This set-up allows significantly more than 20 stations to be correlated in parallel, including data sent to Bonn via e-transfers.

In April 2015 6 Mark6 recorders, capable of recording at 16 Gbps, were installed in the newly-built part of the correlator room. Native playback from Mark 6 disk modules will soon be possible.

Data Archive: RAID storage for correlated data is 57 TB. Data is archived on the archive server in raw DiFX format, FITS and MKIV (if desired). FITS (default) or MKIV formatted data is made available to users.

Transfer of GMVA data to the VLBA archive for public access was completed by 2016.

Disk purchases: 11 more disk modules (352 TB) for RadioAstron observations, all financed by the ASC Moscow, were added to the pool in April 2015. Effelsberg has been equipped with 2 Mark6 units with 4 big disk modules (128 TB) and MPIfR has purchased an "Effelsberg" RAID for playback at the JIVE correlator. No new Mark5 modules have been purchased as this system is becoming obsolete. A number of Mark6 modules were purchased for EHT observations.

EVN code	**PROJECT**	**λ**	**OBSERVING DATE**	
GL041A	RA-AO2 AGN Jets:0716+714	1.3 cm	03-Jan-15	Out of Session
GL042B	RA-AO2 AGN Jets:1642+690	6+18 cm	21-Jan-15	Out of Session
EG086A/B	RA-AO2 Mrk 501	6+1.3 cm	05-Mar-15	Session I
EA057B*	GPS Satellites	18 cm	05-Mar-16	Session I
GG079A	RA-AO3 AGN Jets:3C345	18 cm	30-Mar-16	Out-of-Session
GG079B	RA-AO3 AGN Jets:OJ287	18 cm	16-Apr-16	Out-of-Session
GG079C	RA-AO3 AGN Jets:OJ287	1.3 cm	25-Apr-16	Out-of-Session
GG079D	RA-AO3 AGN Jets:3C345	1.3 cm	04-May-16	Out-of-Session
EL054	KVN/SRT Positions	3.6 cm	15-Jun-16	Session II
GG080	RA-AO4 3C84	1.3 cm	11-Sep-16	Out-of-Session
GG081A	RA-AO4 AGN Jets:3C454.3	1.3 cm	08-Oct-16	Out-of-Session
GG081B	RA-AO4 AGN Jets:CTA102	1.3 cm	17-Oct-16	Out of Session
GB079	RA-AO4 NGC1052 Twin-Jet	1.3 cm	05-Nov-16	Session III

(* EA057B raw data subsequently transferred to GFZ Potsdam for processing)

Table 10: EVN and EVN-RADIOASTRON projects for Bonn correlator 2015-2016

Figure 18: New computer cluster, January 2016 (photo H. Rottmann)

Figure 19: Mark5 and Mark6 playback units, January 2016 (photo H. Rottmann)

OBSERVATORIO ASTRONOMICO NACIONAL, IGN - YEBES OBSERVATORY

VLBI Staff: The representative of IGN Yebes Observatory at the EVN CBD was Rafael Bachiller as director of the National Astronomical Observatory (Observatorio Astrónomico Nacional, OAN-IGN), the technical VLBI friend was Pablo de Vicente, and Francisco ("Paco") Colomer was coordinator of VLBI activities. Pablo de Vicente was appointed chair of the EVN TOG for three years starting in January 2015.

VLBI Observations:

IGN Yebes Observatory continued playing an important role in VLBI observations during 2015 and 2016. The 40-m radio telescope is equipped with receivers that work in 7 different frequency bands at 2.2, 5, 6.6, 8, 22, 43 and 87 GHz. Its size and its reliability guarantees its importance in the VLBI networks where it takes part, the EVN, GMVA, RadioAstron and IVS.

During 2015, the 40-m radio telescope took part in 342 VLBI observations with a total amount of 1682 hours. The number of EVN observations were 69 lasting 630 hours, of which 5 were tests lasting 9 hours, 5 Out of Session observations (OoS) lasting 58 hours, 5 eVLBI sessions lasting 85 hours and 50 standard observations within the session periods. Other than with the EVN, the telescope took part in 230 RadioAstron observations, 7 GMVA observations, 6 observations with the KVN and 28 IVS observations. During 2016, the 40-m radio telescope took part in 449 VLBI observations with a total amount of 2108 hours. The number of EVN observations were 79 with a total of 848 hours, of which 4 were tests lasting 18 hours, 6 Out of Session observations lasting 9 hours, 12 eVLBI observations lasting 289 hours and 57 standard observations within the sessions lasting 447 hours. Out of the EVN the telescope took part in 322 RadioAstron observations, 13 GMVA observations, 3 observations with the KVN and 30 IVS observations. The table below summarizes the number of VLBI observations and the hours observed.

Table 11:VLBI observations performed by the Yebes Observatory in 2015-2016

	2015		**2016**	
	Observations	**Hours**	**Observations**	**Hours**
EVN	69	630	79	848
GMVA	7	68	13	199
RadioAstron	230	277	322	323
IVS	28	671	30	722
KVN	6	27	3	8
Others	2	9	2	8
Total	342	1682	449	2108

Observations with the KVN were in two simultaneous observing frequencies: 22 and 43 GHz. The phase for the former are applied to the second to improve the signal to noise ratio.

Technical progress:

The 40 m radio telescope

IGN Yebes Observatory is running two DBBC2 units as VLBI backends, equipped with 4 IFs, 4 ADB2 and 4 CORE2s each. Both DBBC2s are equipped with an internal Fila10G unit. During 2015 the DBBC2s were used generating VSI data which were sent to the old Mark5 recorders. In 2016 we started using the Fila10G and VDIF data via optical fibres to the new recording systems.

During 2015, IGN Yebes Observatory was using 2 Mar5kB+ recorders which allowed us to take part in standard observations with a recording rate of 2 Gbps and in e-VLBI observations with a recording rate of 1 Gbps. Besides, until mid 2016, we were also operating a Mark5C unit, on loan from JIVE, which was regularly used for transferring geodetic, astronomy and RadioAstron experiments to the correlators. For both types of experiments tsunami protocol was used. The Mark5C unit was returned to JIVE by mid 2016.

In 2015, IGN Yebes Observatory acquired 2 new recording systems, known as Flexbuff, with 144 TB of capacity, one of which was delivered to JIVE correlator. In 2016 a third Flexbuff unit with 216 TB was acquired. Both units are operational since 2016 and regularly used in place of the 2 Mark5B+ units which are no longer used. In 2016 all observations started being recorded in VDIF format which is delivered by the Fila10G using optical fibres.

In 2016 the Observatory also started using a proxy server for e-VLBI observations that allowed JIVE to control the data flow. The server was updated to the latest Debian Linux version. The data are directly sent from the DBBC2 to JIVE correlator in VDIF format.

A Technical Report on the usage of VDIF and scripts developed at Yebes for viewing data during experiments is available at our web site (CDT Technical Report 2016-12, de Vicente, Barbas & González, 2016).

The backends room where the VLBI backends for the 40-m and 13.2-m radio telescopes are installed was equipped in June 2016 with an accurate A/C system that keeps the environment temperature with a precision of 0.2 degrees. That solved problems with the phase stability that arose several months before. This improvement had an important impact on the astronomical and geodetic observations, being especially relevant for the latter ones.

Since 2016 the 40-m radio telescope started using continuous calibration at 80 Hz for all receivers except for Q band. The reference signal is generated in the DBBC2s and used by all receivers. The noise diode driven by this signal is synchronous detected at the DBBC2s to compute the system temperature. IGN

Yebes Observatory developed code to process the log files with the system temperature computed in this new way and generate ANTAB files, required by the correlator, with the calibration of each VLBI experiment. This code has been shared within the TOG with the rest of EVN telescopes. (de Vicente, Moreno & Barbas 2017, technical report in preparation).

The 40-m radio telescope uses since June 2016 an Extended FFTs (Fast Fourier Spectrometer) with 8 modules 2.5 GHz wide each. New code was developed for its usage in single dish observations mainly at Q band (observing frequencies of 41 to 50 GHz). There has also been a development to implement frequency switch observations. This method is now regularly used with two modules from the XFFTS when requested by the observers.

IGN Yebes Observatory staff has also developed and implemented algorithms to track satellites using the VLBI Field System. Previously this was possible from the single dish control, but now the procedure allows to do this from a VLBI schedule run by the FS. This allowed some VLBI observations of the RadioAstron satellite for experiments to measure the Earth's gravity. This code was also implemented at the 13.2-m radio telescope. A Technical report is being written (de Vicente & Beltran, 2017).

The 13.2m radio telescope

In 2015, IGN Yebes Observatory acquired 2 Mark6s, to be used for VGOS geodetic VLBI observations, and by the end of 2016 it also acquired 4 RDBEG units for that same purpose. The installation procedure and tests for the RDBEGs are summarized in CDT Technical Report 2016-21 (de Vicente, Barbas, González, 2016).

During 2015, the 13.2-m telescope performed 36 regular IVS observations: 20 R1 experiments, 15 R4 experiments and one T2 experiment. Regular observations started on February 2015 and stopped on October 2015. Observations were discontinued because the tri-band receiver was dismounted and replaced by a broad band VGOS compatible receiver.

The broad band receiver for the 13.2 m was installed in late 2015 and first single dish observations were performed on March 2016. On April 28, 2016 the telescope started taking part in test observations together with Wettzell, Westford, Kokee Park and GGAO. The goal of these observations was to debug the hardware: frontend and backends, software at stations and correlator and iron out the observational procedures. The observations required a Mark6 recorder and one or two DBBC2 depending on their availability. An internal report with information about the tests is in preparation (de Vicente, González, & Barbas, 2017).

Five observations (ft6118, ft6126, ft6140, ft6161 and ft6188) were performed between April and July 2016. The first observations with fringes in all four bands were in June 2016. Yebes telescope tested the 4 bands in two runs, since simultaneous bands were not possibly because the 2 DBBC2 backends were not available simultaneously. All these observations were performed with one or two DBBC2 as backends. A second set of 3 experiments (vgt001, vgt002, vgt003) waw observed between July and August 2016 to debug and fix some issues with the DBBC2 firmware. The tests continued with observations vgp001 and vgp002 but in this case Yebes 13.2m antenna was using 2 RDBE-G backends mixed with one DBBC2 backend. In the last test performed in 2016 Yebes VGOS telescope used four RDBE-G backends. The test was fully successful.

The installation of the broadband receiver required the development of software code to monitor and control its frequency and attenuation, the noise diode and the phase cal system. The integration in the antenna control system and the data acquisition in single dish mode was also developed and tested.

We have also designed and developed the control system for the VGOS twin telescope at Ny Alesund based on the Yebes 13.2-m one. The design allows to control both telescopes independently or linked together. We have also developed the software to monitor the Vaisala weather station equipped with several sensors, a continuum detector for single dish observations and a counter for measuring the cable delay. All this software together with the underlying infrastructure was installed at Yebes on the computers sent from the Norwegian Mapping Authority. A description of the works performed is in report IT-CDT-2016-17 (Beltrán, Barbas & de Vicente 2016).

Onsala Observatory asked Yebes observatory for a report on the tests performed at the VGOS Yebes antenna to use it as a guide for testing their VGOS twin telescopes recently built at Onsala. We delivered IT CDT 2016-27 (de Vicente 2016b) report from the Yebes 13.2m telescope that describes the tests performed to check the servo system and the control system developed at Yebes VGOS telescope.

Figure 20: The 40m Yebes radio telescope

ONSALA SPACE OBSERVATORY

Operations: The Onsala Space Observatory (OSO) telescopes continued during 2015 and 2016 to play a full role within the global observing program for astronomical VLBI.
In total 9 astronomical VLBI-sessions (6 EVN sessions and 3 global mm-VLBI sessions) were conducted. OSO is also regularly involved in e-VLBI sessions (typically 10 24 hour sessions per year) within the EVN. In addition, the Onsala 20~m telescope has been used for 45 and 53 geodetic VLBI experiments in 2015 and 2016, respectively, as part of the observing program of the International VLBI Service for Geodesy and Astrometry (IVS).

Between February 2009 and the end of 2016 Rüdiger Haas was the Technology Development Centre's Representative in the Directing Board of the IVS. He is also since 2009 the IVS delegate to the Directing Board of the International Earth Rotation and Reference Frames Service (IERS). Rüdiger Haas is the chairman of the European VLBI Group for Geodesy and Astrometry (EVGA).

Michael Lindqvist is chairman of the EVN Programme Committee since January 2015.

Technical R&D: During 2015-2016, personnel from OSO have been very much involved in introducing both new observational methods as well as technical upgrades of the EVN. A new e-VLBI mode was introduced in 2015, automated generic e-VLBI trigger observations. It is an observation mode to be scheduled automatically during an e-VLBI observation if a specific set of triggering criteria (e.g., through a VOEvent or other form of automated/manual trigger response) is met. The expected response time to execute a new program is about 10 minutes. Successful tests were also done in e-VLBI mode at 2 Gbit/s with participation of telescopes from Sweden (Onsala), Germany (Effelsberg), Italy (Medicina), Spain (Yebes) and South-Africa (Hartebeesthoek). In order to achieve this the digital backend (DBBC2) at the stations were connected to a piece of equipment called FILA10G. The FILA10G reformats and packetizes the data and sends it over its 10 GbE network interface directly onto the internet to JIVE. There the data is fed into the SFXC software correlator, which runs on a 400-core computer cluster, that processes the data in, real-time. e-VLBI at 2 Gbit/s was first offered the user community in 2016.

EVN is moving towards a disk-shipping-less model where VLBI data is buffered locally at the station and e-shipped to the correlator at JIVE. OSO has been very much involved in the development during the last years and was one of the first EVN stations introducing this concept in 2016. Turning to disk-less operations will have many significant advantages. Stations, such as OSO, would not need to bother with conditioning, changing and shipping disk packs, and no recording media would need to be sent out before each session. Furthermore, transfers could be done practically automatically, and the results of a significant sub-set of the EVN network will be available in real-time.

OSO continued the work within the EU RadioNet3 Joint Research Activity DIVA (Developments for VLBI in Astronomy)which concluded successfully 2015. This project had two parts, and OSO was involved in both. The first part concerned the development of a broadband receiver from 1.5 GHz to 5.5 GHz, in collaboration with MPIfR (Germany), ASTRON (the Netherlands), and IAF Fraunhofer (Germany). MPIfR developed the design of state-of-art LNAs, and the MMIC (Monolithic Microwave Integrated Circuit) chips for the LNAs was processed at IAF Fraunhofer. OSO had the responsibility of designing the broadband feed, integrating it with the LNAs and performing the sensitivity tests. The prototype cryostat with the integrated Quad-Ridge Flared Horn (QRFH) and the DIVA LNAs can be seen in Figure 21. The RF chain consists of two DIVA LNAs directly connected to the corresponding ports of the feed, coaxial semi-rigid cables connected to vacuum feed-throughs at the back plate of the cryostat, and a room temperature amplifier. The measured receiver noise was ~50K at 1.5 GHz and ~20K at 3 GHz, respectively. From 3 to 5.5 GHz the receiver noise has an average value of about 15K, which is a very good result.

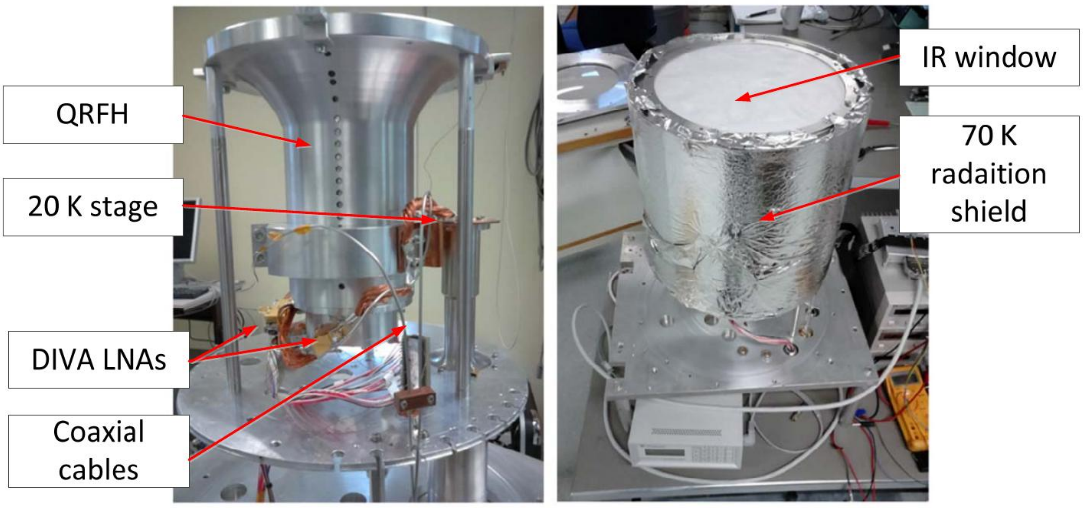


Figure 21: The prototype QRFH integrated in the prototype cryostat with the DIVA LNAs (left) and with mounted 70 K radiation shield (right).}

In the second part of DIVA, a system called the FILA40G has been developed at OSO for recording of VLBI data at rates up to 32 Gbit/s. Combined with a digital backend called DBBC3, also developed in DIVA, and broadband receivers, observational sensitivity can be increased by four fold compared to the recently improved maximum data rate of 2 Gbit/s used in the EVN today. The DBBC3 and FILA40G can also serve well in providing a backend and recorder for the geodetic VGOS system, which includes the twin telescopes currently being built at OSO (see below). Late 2015, two sets of test observations were performed, recording at 16 Gbit/s at OSO and Effelsberg in Germany, and in the beginning of 2016 data recording tests were performed on the FILA40G to verify its capability to successfully record at 32 Gbit/s. In once such test, more than 280 TB were recorded across 54 hard disks over an uninterrupted period of 21 hours with no data lost.

OSO has further developed PolConvert as part of the ALMA phasing project (APP), Marti-Vidal et al. (2016). Inclusion of ALMA in a VLBI network would not be possible without the PolConvert code which converts the linear polarisation base of ALMA into the circular polarisation base needed for correlation in the VLBI network. Staff of the Nordic ARC node at OSO has successfully tested the code using actual phased-up ALMA data. The PolConvert code itself will also be useful for inclusion of other telescopes with linearly polarised receiver feeds (e.g. BRAND) in a VLBI network. ALMA was offered as part of the GMVA in 2016. The first observations will take place in the spring of 2017.

Instrument development and upgrades: A major physical change at Onsala in 2016 has been the construction of the Onsala Twin Telescopes (OTT), two 13.2~m diameter dishes for geodetic VLBI. The new telescopes and their network, the VLBI Global Observing Service (VGOS), meet global needs, as expressed in a resolution which was adopted by the General Assembly of the United Nations in February 2015. The resolution, A Global Geodetic Reference Frame for Sustainable Development, recognised for the first time the importance of coordinating geodetic measurements on a global scale. The resolution strengthened existing work in the UN initiative Global Geospatial Information Management (UN-GGIM) and with the Global Geodetic Reference Frame (GGRF).

The construction and installation of the Onsala Twin Telescopes has been funded by a generous grant from the Knut & Alice Wallenberg Foundation and Chalmers University of Technology.

Figure 22: The Onsala Twin Telescopes, OTT

SHANGHAI ASTRONOMICAL OBSERVATORY

The SESHAN25 and TIANMA65 telescopes take part in international VLBI experiments on astrometric, geodetic and astrophysics researches. Apart from its international VLBI activities, the telescope spent a large amount of time on the Chinese Lunar Project, including the testing before the launch of the Chang'E test satellite, and the tracking campaign after its the launch and other single dish observation.

Figure 23: The Tianma 65m and the Sheshan 25m radio telescopes.

The TianMa 65m Radio Telescope

The Tianma station ('TIANMA65') is located about 6 kilometers west of Sheshan 25 m radio telescope. The telescope construction started in the early 2009, and the majority of the mechanical system was completed in October 2012. On December 2, 2013, Tianma 65 telescope passed the acceptance evaluation. By design, the Tianma telescope with a diameter of 65 meter, is a multifunction facility, conducting, astrophysics, geodesy, astrometry, as well as space science. By the end of 2014, Tianma 65 has been fitted with five cryogenic receiver systems (L, C, S/X, Ku). The Ka band receiver was built and installed in 2015. The K and Q band cryogenic receiver systems have been installed at the end of the 2016. CDAS and DBBC2 have been installed in Tianma station for VLBI terminal.

Tianma 65m radio telescope participated in fringe test observations in the May and October sessions in 2015 at 18, 6, 5 and 3.6 cm bands with the CDAS & DBBC2. Tianma 65m radio telescope participated in fringes test observations in the February, May and October sessions in 2016 at 18, 6, 5 and 3.6 cm bands with DBBC2.

Some maintenance has been done. From March 19 to April 26, 2015, the elevation drive structure installation and commissioning has been done. From April 28 to May 23, 2016, we also do some antenna maintenance such as painting at rusted place, replacing nylon wheels guided rail coat, screwing primary panel bolts, replacing winding at central pivot, maintaining and testing azimuth and elevation code, replacing actuators of the active surface. The accuracy of primary reflector surface is reach to 0.25mm(the elevation is 52 degree), after screwing primary panel bolts. The elevation speed motor has been replaced during June 2016.

The SESHAN25 telescope

The Sheshan 25m ('SESHAN25') radio telescope was built in 1986 with the observed frequencies of 3.6/13, 5, 6 and 18cm wavelengths. It is a full member of EVN since 1993. The Sheshan 25m radio telescope participated in the VLBI experiments in 2015 February, May and October sessions at 18, 6 ,5, 3.6 and 1.3 cm band and in the EVN OoS sessions at 18cm band in 2016. The K-band receiver was not available due to a serious equipment failure since 2016. So all of the K-band EVN OoS sessions from the beginning of 2016 were missed. From November 26, 2015 to February 13, 2016, the rail and the gearbox were replaced. From November to December in 2016, there was maintenance work with antenna structure reinforcement and spray paint, etc.

Update and current status of equipment: After nearly three years of technical research, Shanghai 65m Radio Telescope project team successfully developed the first set of Q-band dual-beam cryogenic receiver in China, which was installed in Tianma Telescope on March 11, 2016. Q-band dual-beam cryogenic receiver, operating frequency from 35 to 50 GHz with relative bandwidth of 35% while simultaneously receiving the LHCP and RHCP signals, consists of feed horn, noise injection coupler, differential phase shifter, ortho-mode transducer, low noise amplifier and etc. which all work at 20 K cryogenic platform greatly improving the detection sensitivity of the receiver. After testing, the receiver average noise temperature is roughly 40 K which reaches the international advanced level. In addition, the interval of two beams in the sky is about 90” of 3-4 HPBW. After the Y-factor measurement with microwave absorber and cold sky respectively, the four receiver channel system noise temperatures are from 55 to 125 K. In Sep. 2016, an international VLBI observation with KVN was successfully conducted of a high-quality fringe observing the source 3C345. A new DBBC2 bought from HAT-Lab, arrived in November 2015, was installed and tested at Sheshan in December 2015 and became operational in March, 2016.

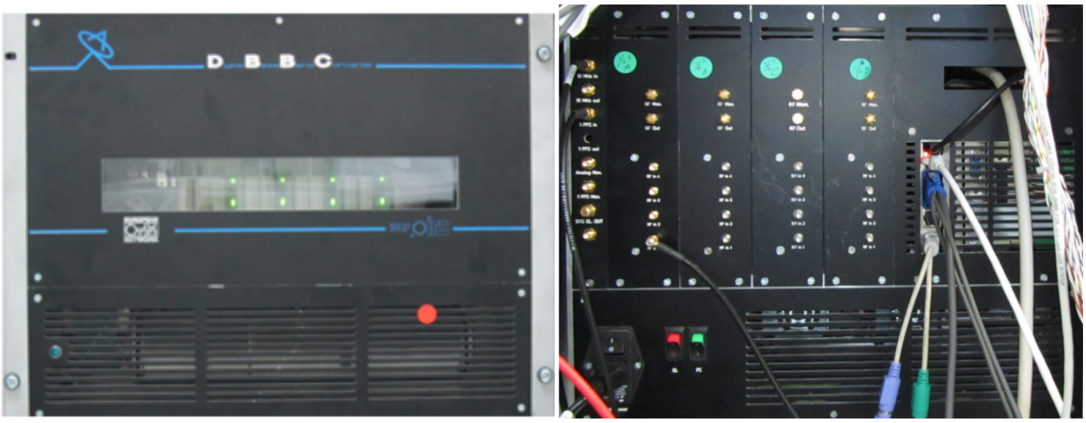


Figure 24: the new DBBC2 system

e-VLBI: More than eleven e-VLBI experiments among the EVN have been carried out in 2015 & 2016 at a data rate of 1024 Mbps with the Sheshan station. Tianma 65m has got the first e-VLBI light on April 14, 2015 at a data rate of 521Mbps in L-band.

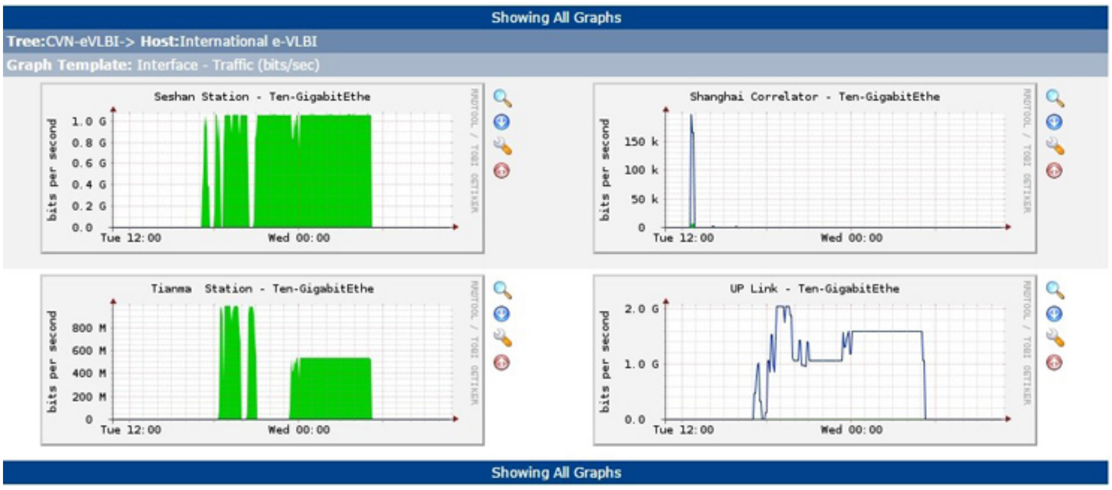


Figure 25: Network traffic monitoring

Tianma 65m works at a data rate of 1024 Mbps for each e-VLBI session and more than six e-VLBI experiments among the EVN have been carried out in 2016.

TORUN CENTRE FOR ASTRONOMY

Figure 26: The 32m radio telescope at Torun Radio Astronomical Observatory

TRAO participated in the majority of the EVN observations. In 2015, TRAO observed for 772.5 hours during disk-based experiments and 252.5 hours during e-VLBI experiments, whereas in 2016, the respective numbers were: 983.5 hours and 279.5 hours.

The most important development at TRAO during 2015-2016 period was that on 26 November 2015 it was connected to the Polish fibre optic network distributing time and frequency (T&F) signals from UTC(PL) and UTC(AOS) laboratories. This paved the way for the investigation of alternative methods of T&F synchronization during VLBI observations. The first proof-of-concept VLBI observation using remote synchronization via optical fibre link was carried out during a dedicated session on 18 December 2015. Data from Tr, Wb, Mc, and Ys were correlated in real-time at JIVE but also recorded there for possible further processing. The T&F signals from a remote H-maser, i.e. 1 PPS and 10 MHz, were delivered from UTC(AOS) to Tr over a 345-km long fibre link. To make the comparison of both methods of synchronization possible, the observation began under synchronization from the local H-maser and then shifted to remote synchronization with each segment lasting about an hour.

The analysis carried out at JIVE showed that the fringe visibility phase noise is very similar for both synchronization schemes for all baselines to Tr over timescales ranging from two seconds to 45 minutes.

The initial success was confirmed in the operational use of the remote H-maser during the e-VLBI session of 12-13 January 2016. Starting from that session, Tr has been using the remote T&F delivery on a regular basis. Apart from the higher reliability, the main advantage of this method is that, unlike the old H-maser at Tr, AOS T&F standard has a zero drift.

During the test hours of the e-VLBI session of 15-16 March 2016, we carried out yet another successful test using our fibre link. Instead of the signal transmitted from AOS H-maser, we used the signal generated by an experimental strontium atomic-lattice optical clock operated at the National Laboratory for Atomic, Molecular, and Optical Physics in Toruń. Again, it turned out that it works equally well as a local H-maser. The strontium clock is two orders of magnitude more stable than a H-maser but to make this difference noticeable one has to use a similar standard at other stations. We plan to carry out a test in which one EVN baseline would have optical clocks at both ends, one of which would be Tr. (A&A accepted)

ENGINEERING RESEARCH INSTITUTE 'VENTSPILS INTERNATIONAL RADIO ASTRONOMY CENTRE' OF VENTSPILS UNIVERSITY COLLEGE (VIRAC)

Located in the woodland in Irbene, near Ventspils city, Latvia, the Irbene observatory was originally founded in late sixties as a secret Soviet military space centre. It originally consisted of a 32-metre telescope, along with two smaller telescopes and a communications centre, and was known as "Zvezdochka", meaning "Little Star". After the withdrawal of the Soviet Army in 1994 it became a scientific research facility as part of the Latvian Academy of Sciences, before becoming a part of Ventspils University College in 2004.

Currently, Irbene radio observatory operates two fully steerable radio telescopes – RT-32 and RT-16 with diameters of 32 and 16 meters respectively. The main operating frequency bands are C, M, X and L bands, which are available for VLBI and single dish observations.

VIRAC became a full member of the EVN on October 26, 2016 but EVN related activities took place during the whole of the 2015-2016 period.

RT-32 participated in observations at L, C, M and X bands during EVN regular and e-VLBI sessions of 2015-2016. On December 2015, RT-32 joined C and L band RadioAstron observations and on November 2016 in eVLBI observations at 2 Gbps.

Additionally, thanks to the IVS team and especially Leonid Petrov and Alessandra Bertarini, RT-32 participated in IVS geodetic sessions using only the X band receiver; this improved the RT-32 coordinates by 26 m.

Figure 27: The RT-32 and the RT-16 telescopes at Irbene Radio Observatory

During 2015 and 2016 VIRAC greatly rebuild both radio telescopes RT-32 and RT-16.

Main refurbishment activities on the RT-32 finished by October 2015:

- Installed new motors, angular sensors, stow pin mechanics;
- Installed new Antenna Control Unit;

- Renovated RT-32 antenna backup structure and vertex room;
- Installed conditioning system for receiver's room;
- Installed broadband cryogenic receiver 4.5-8.8 GHz, including cryogenic system and dry air generator, two channels (RCP and LCP), intermediate frequency convertors, local oscillators, noise diodes and Pcal calibration units. Measured system temperature for RT-32 is ~30 K.
- Installed "warm" L band receiver (one RCP channel).

Table 12: The characteristics of the Irbene Radio Astronomy Observatory telescopes

Telescope	**RT-32**	**RT-16**
Location		
geographic longitude:	21° 51′ 17″	21° 50′ 50″
geographic latitude:	57° 33′ 12″	57° 33′ 33.5″
altitude above sea level:	87.3 m	50.12 m
diameter of the telescope:	32 m	16 m
minimum elevation:	2.7°	2.5°
Performance Overview		
C/M/X band system		
Developer:	TTI	TTI
Frequency range:	4500 – 8800 MHz	4500 – 8800 MHz
	RHCP/LHCP	RHCP/LHCP
Bandwidth:	1000 - 1200 MHz	1000 - 1200 MHz
SEFD (C/M/X):	300 - 1300 Jy	~700 - 800 Jy
G/T:	44 dB/K	41 dB/K
Gain:	~0.1 K/Jy, 61 dBi	~0.05 K/Jy, 57 dBi
System temperature:	30 - 50 K	30 - 50 K
L band system		
Developer:	VIRAC	VIRAC
Frequency range:	1370 – 1720 MHz	1400– 1800 MHz
	RHCP	RHCP
Bandwidth:	100 MHz	60 MHz
SEFD (C/M/X):	1385 Jy	8600 Jy
G/T:	28 dB/K	20 dB/K
Gain:	~0.06 K/Jy, 49 dBi	~0.02 K/Jy, 43 dBi
System temperature:	80 - 200 K	180 - 250 K
Antenna tracking system performance:		
Developer:	MTM Mechatronics	MTM Mechatronics
Az/El range:	-328…+328	-328…+328
Az/El maximum velocity:	deg/+2.7…95.5 deg	deg/+2.5…94 deg
Az/El maximum	2.8/2.25 deg/s	5/4 deg/s
acceleration:	0.5/0.5 deg/s/s	1.5/2 deg/s/s
Az/El pointing precision:	0.6/0.3 arcsec (RMS)	3.3/3.3 arcsec (RMS)

After the renovation, the antenna max speed and accuracy were greatly increased (azimuth - 2.8 deg/s; elevation – 2.1 deg/sec; pointing and tracking accuracy < 5 arc sec).

The main refurbishment activities on the RT-16 finished by December 2015:

- Installed new motors, angular sensors, stow pin mechanics;
- Installed new Antenna Control Unit;
- Completely new carbon-fibre antenna;
- Installed conditioning system for receiver's room;
- Installed broadband cryogenic receiver 4.5-8.8 GHz, including cryogenic system and dry air generator, two channels (RCP and LCP), intermediate frequency convertors, local oscillators, noise diodes and Pcal calibration units.
- Antenna equipped with a new DBBC2 system.

During April - May 2016 first observational tests on RT-16 were conducted. They showed antenna efficiently ~ 60% with Tsys ~ 30 - 35 K at 5 GHz.

XINJIANG ASTRONOMICAL OBSERVATORY, NANSHAN STATION

Telescope Reconstruction and Operations: The overall upgrade project of Nanshan 25m radio telescope started in early 2014 and finally finished in late 2015 (see Figure 28). Now the telescope aperture is 26 meters, one meter larger than the old one. The new Ur telescope is currently equipped with L-, S/X-, C-, and K-band receivers and a Q-band receiver is on its way. From late 2015, the antenna parameters were measured systematically to allow the telescope to participate in science observations as soon as possible. In 2016, the telescope participated in most of the EVN and IVS experiments, some of the East-Asia VLBI Network (EAVN) commissioning, as well as single-dish observations.

Figure 28: The refurbished Nanshan 26m telescope ready to re-join the EVN

Upgrade of Backend and Recording Systems: In late 2016, DBBC2 was set up (see Figure 29) and commissioned. The DBBC2 is expected to be involved in the formal EVN Sessions in 2017.

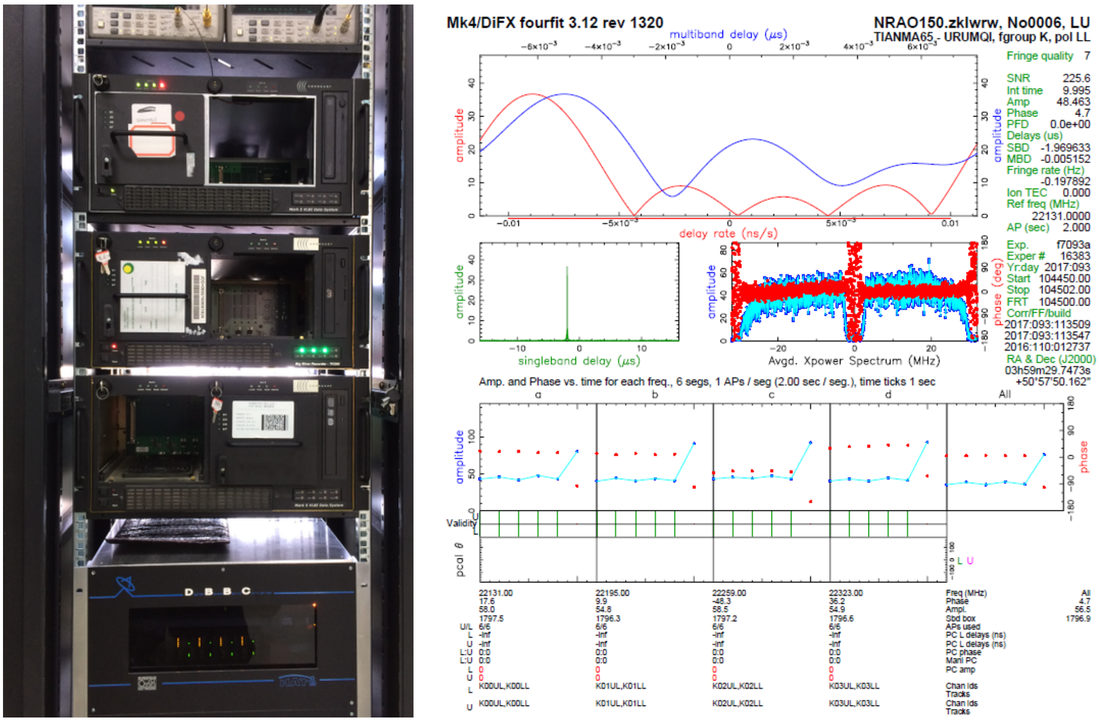


Figure 29: The new digital backend of DBBC2 in Nanshan station and the correlation fringe between Ur and T6

ARECIBO - NATIONAL ASTRONOMY & IONOSPHERE CENTER, PUERTO RICO

Between January 2015 and December 2016, Arecibo participated in 204 VLBI observations in total, including 35 EVN-related runs, covering EVN and Global Network disk-recording, and EVN eVLBI observations and some common observation with the Russian space antenna, RadioAstron. However, Arecibo's major co-observing with RadioAstron takes place via several independent proposals. In these two years, 154 sessions were conducted under that arrangement.

Recently, Arecibo-RadioAstron space-VLBI observations of the quasar 3C273 revealed a brightness temperature greater than 10^13 K, sufficiently high that it questions the traditional model - synchrotron radiation - for emission emanating from the vicinity of its central super-massive black hole. Arecibo's sensitivity was also essential for the VLBI result that resolved the Pleiades distance controversy with measurements of ultra-faint Pleiades radio stars, a result recently confirmed by the Gaia Collaboration. Arecibo joined forces with the EVN and VLBA to pinpoint the location of the repeating transient FRB 121102, testing the association with a compact, quasi-coincident, continuum source, and supporting optical evidence that its host galaxy is a surprisingly small, unimpressive dwarf.

Presently, Arecibo provides a maximum of 2-Gbps data recording rate, using the RDBE+Mark5C systems in the PFB mode. Most of the regular EVN (and RA) observations are carried out using the legacy VLBA4+Mark5A system. Plans are in place to initiate a further upgrade to a recording rate of 16-Gbps via the new Mark6 recorder.

Arecibo is also commissioning a 12-m diameter antenna to aid correction for atmospheric phase fluctuations. In 2016, first fringes were detected in test observations between the 305-m and the 12-m antenna (using locally developed software). When operational, this will make Arecibo VLBI observations considerably more time-efficient.

GEODETIC OBSERVATORY WETTZELL, GERMANY

The Geodetic Observatory Wettzell (GOW), Germany, 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), contributed very successfully to the IVS observing program of the years 2015 and 2016. Technical changes, developments, improvements, and upgrades have been made to increase the reliability of the entire VLBI observing system. While the 20m Radio Telescope Wettzell (RTW, Wz) and the 13.2m Twin radio Telescope Wettzell North (TTW1, Wn) are in regular S/X sessions, the 13.2m Twin radio Telescope Wettzell South (TTW2, Ws) is equipped with a new VGOS receiving system. A main task was, to bring this new technique into operation, so that the first common, transatlantic VGOS observations became possible.

Figure 30: The Geodetic Observatory Wettzell with the two 13.2 m TWIN radio telescope antennas in the foreground on the left and the 20 m Radio Telescope Wettzell in the background on the right.

In addition to the VLBI, an ILRS laser ranging system, several IGS GPS 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 also operated. Meanwhile, Wettzell also operates a DORIS beacon and is now a complete fundamental station with all space geodetic techniques. A new project focuses atmosphere monitoring and a new timing distribution, using compensated fibre-optic transfers, is under development together with external contractors. The developments also need to meet the requirements for future operation strategies, so that projects to increase automation and remote control are on-going.

The GOW is also responsible for the AGGO system in La Plata, Argentina (which is the former station TIGO in Concepción, Chile), and the German Antarctic Research Station (GARS) O'Higgins on the Antarctic peninsula.

The 20-m RTW has been supporting the geodetic VLBI activities of the IVS and partly other partners, such as the EVN, for over 33 years now. The telescope is still in a very good and stable state. The main priority was laid to the participation in all daily one hour INTENSIVE-sessions (INT/K) in order to determine UT1-UTC. The antenna also supported all main IVS 24h sessions and is still one of the main components of the IVS.
The complete VLBI data from the 20m RTW is transferred with e-VLBI techniques to Bonn, Tsukuba, Haystack, Washington, and Socorro, using TSUNAMI or jive5ab on the 1 Gbit/sec connection of the Wettzell observatory.

In addition to the standard sessions, RTW was active for other special observations such as the tracking of the Mars Express (MEX) spacecraft and the RadioAstron satellite for the EVN. Progress was also made in tracking of Glonass and GPS satellites using an additional L-band receiver in the S-band path. Observations can be scheduled, observed, correlated, and analysed directly here on location, using the telescope triple of the Wettzell observatory.

Another project, initiated by Chinese colleagues, was to observe the Rosetta spacecraft (September 20-21 2015), as it passed bright calibrator and other ICRF sources. The idea was to adjust the troposphere and ionosphere components of the delay model to get higher accuracy of the tracking. The schedule was prepared by colleagues at JIVE and the Wettzell 20m antenna observed together with 10 other telescopes worldwide. The 20m antenna together with the northern twin telescope Wn also supported Wettzell high-speed VLBI session (WHISP) sessions in February 2015, August 2016, and November 2016, which schedule a large number of observations to validate turbulence models in a local application. During WHISP, common clock tests were made where all telescopes were connected to maser EFOS-39 to find issues in technical solutions for stable frequency transfers over hundreds of meters.

The GOW further developed a 10Gbit/sec transfer network, so that the baseband converter of all antennas can send their data to a selectable set of recording systems, consisting of Mark6 and FlexBuff machines. It meets the requirements of the new VGOS sessions, but can also be used for classic S/X- sessions. Each DBBC is connected to a FILA10G board, which is connected to a 10 Gbit/sec switch via fibre. The configuration of the FILA10G decides about the target machine where the data stream is recorded. The network should replace current setups with EVN PCs and connects the data acquisition in a safe way with the e-VLBI possibilities.

KOREA ASTRONOMY & SPACE SCIENCE INSTITUTE - KOREAN VLBI NETWORK

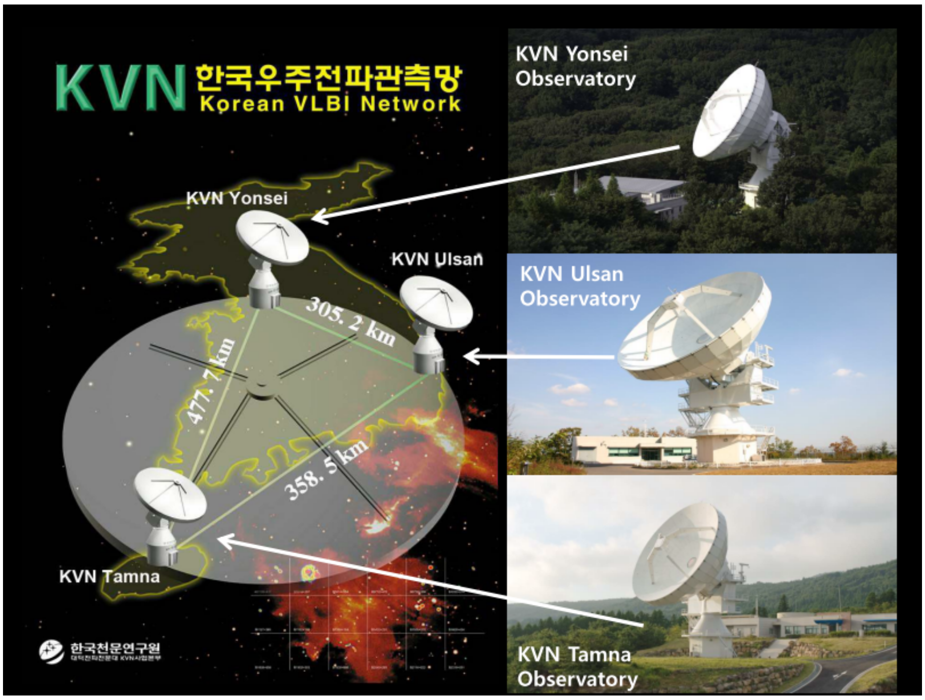


Figure 31: An illustration of the Korean VLBI network

The Korean VLBI Network (KVN) was built in 2007 as a dedicated to mm-VLBI (2–13mm) observations with a simultaneous multi-frequency (22/43/86/130 GHz) receiving system. Three 21-m radio telescopes are located in Seoul, Ulsan and Jeju island, Korea; KVN Yonsei Radio Telescope (ky), KVN Ulsan Radio Telescope (ku), and KVN Tanma Radio Telescope (kt). The baseline lengths are in a range of 300-480km.

Operations

During the period 2015-2016, KVN carried out most of the scheduled EVN observations (~30 experiments) at 7 and 13 mm wavelengths including out-of-sessions with the RadioAstron. KVN is also participating in global VLBI observations such as GMVA and EAVN (East Asia VLBI Network) including Korea-Japan joint VLBI array of KaVA. Annually, around 10% of total KVN observing time per year (~300hr) has been spent for EVN, GMVA and EAVN sessions.

In order to support the KVN operation, three teams of operation, engineering and correlation have been organized and closely working together. We also have 6 operators who are dedicated for the KVN VLBI observations. The KVN operation workshop takes place on a regular basis (twice per year) to educate operators and to manage the KVN operation.

System Updates and Technical Developments: Currently, the KVN recording rate for EVN sessions is limited to 1Gbps with Mark5B systems. In 2015, we installed FILA10G and Mark6 systems in order to support recording rate up to

8Gbps (e.g. 2Gbps per 22/43/86/130GHz). In case of 2Gbps operation, we directly record the data via FILA10G from the sampler, which has a single 512MHz bandwidth (no filtering is available).

Figure 32: KVN data acquisition system with newly installed FILA10G and Mark6 systems

The development of a compact triple bands receiver system for millimetre VLBI observations is under way (lead by Dr. S. –T. Han). The size of receiver system is significantly reduced, making easy to adopt other existing radio telescopes, and it has much wider frequency coverage (e.g. K-band: 18-26.5 GHz, Q-band: 35-50 GHz, and W-band: 85-116 GHz) compared with the current KVN system. In2016 November, we carried out the simultaneous K/Q band observations between KVN and Mizusawa/Iriki of VERA has been conducted successfully. At present, the KVN, Yebes and two of VERA antennas are available for simultaneous K/Q bands observations. Further extension of a simultaneous multi-frequency system and observation campaign is also planned, especially in the East Asian regions.

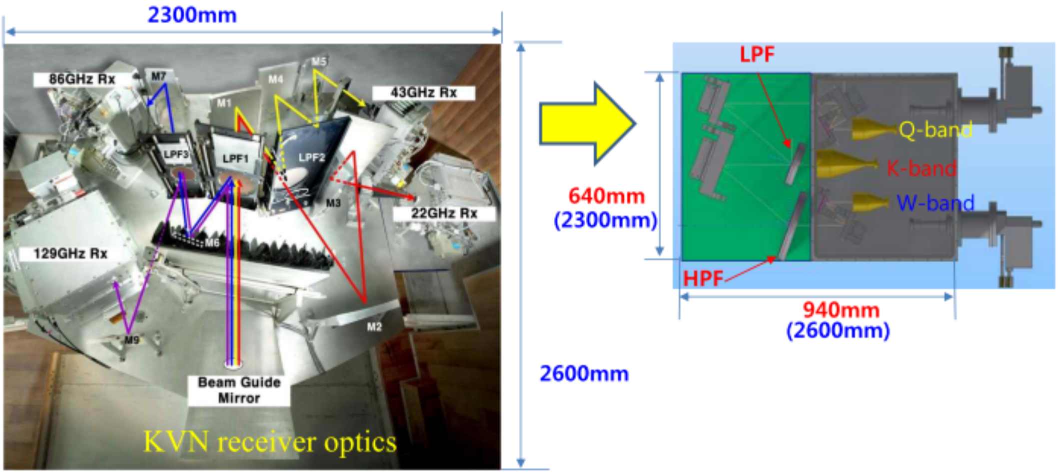


Figure 33: (Left) current multi-frequency receiver system, (Right) Conceptual design for a compact triple bands receiver.

METSÄHOVI RADIO OBSERVATORY

Metsähovi Radio Observatory (MRO) is located on the premises of Aalto University at Metsähovi, Kylmälä, Finland about 35km from the university campus. MRO has operated a 13.7-meter radio telescope since 1974. The telescope radome and surface panels were replaced in 1992-1994. The current surface accuracy is 0.1mm (rms) and the drive speed is 1.2 degrees per second. Metsähovi is known for its long-term quasar and solar monitoring. Astronomical VLBI observations are carried out with receivers at 22, 43 and 86 GHz. An S/X receiver, owned by the Finnish Geodetic Institute (FGI), is used for Geodetic VLBI observations (RHC polarization only). MRO also does spacecraft tracking observations.

Figure 34: Left: Metsähovi in fall season. Right: The first of four Metsähovi Compact Array (MCA) antennae with a dish diameter of 5.5-metre. (Photos: Merja Tornikoski)

EVN operations: In 2015 MRO participated two EVN sessions (I and II) at 22 GHz and 43 GHz. In 2016 MRO took part in EVN sessions II and III at 22 GHz. In addition MRO participated several target-of-opportunity RadioAstron observations. MRO also takes part in regular Global 3mm VLBI Array (GMVA) observations. MRO staff providing operational support in 2015-2016 at MRO are listed below:

Name	Position	Responsibility
Dr. Juha Kallunki	Laboratory manager, VLBI friend (since 12/2015)	VLBI equipment, EVN scheduling & observations (since 12/2015)
M.Sc. (tech.) Petri Kirves	Operations engineer	Receivers
M.Sc. (tech.) Ari Mujunen	Laboratory manager	VLBI equipment
D.Sc. (tech.) Minttu Uunila	Postdoctoral researcher, IVS on-site technical contact, VLBI friend (until 11/2015)	VLBI equipment, IVS observations, EVN scheduling & observations (until 11/2015)

Table 13: Operational support in MRO during 2015-2016.

Receivers: S/X, 22, 43 and 86 GHz receivers were fully operational during 2015-2016. Some modifications for 86 GHz receiver has been made which has been improved instability issues. The IF-part of the receiver will be renewed in the near future. The 22 GHz receiver also has continuous calibration option, but it has never tested in during the observation sessions.

H-masers: Two Kvarz H-masers arrived to MRO in January 2015. The previous ones were almost 15 years old. Since February 2015 the new masers have been operational and worked without any failures.

DBBC status: In June 2016 cause of heavy thunderstorm and lightning DBBC's 1pps distribution board went broken (1pps TTL driver board MAX9372). This was fixed locally in the observatory July 2016. During 2015 we had several problems and peculiarities with dBBC's firmware versions. The situation improved a lot in 2016.

Antenna upgrades: In January 2015 all the motors of the 13.7-meter radio telescope were replaced.

Joint Institute for VLBI ERIC report

Institute News

2015 was a year of real transition for JIVE. Starting out as a foundation under Dutch law, by the end of the year all of the legal and financial processes of JIVE had been transferred to the structure of a European Research Infrastructure Consortium (ERIC), backdated to January 2015, with a new formal name The Joint Institute for VLBI ERIC.

The most visible part of the transition process was the inauguration ceremony on 21 April 2015 and the international workshop during the preceding days. Many international radio astronomy experts came to Dwingeloo to participate in these festivities, including a large number of former JIVE employees. During the workshop, the past and future scientific significance of VLBI was highlighted. The programme included a number of historic accounts, followed by a wide range of scientific reviews. The workshop concluded with strategic visions of VLBI developments from five continents.

During the inauguration event, representatives from the EVN and JIVE partners, the hosting agency NWO and the Dutch ministry discussed the significance of JIVE and its transition into a truly European entity during a highly interactive programme. The host of the programme also interviewed a number of researchers from the EVN/JIVE user community, who presented their most exciting scientific results. Finally, director-general Robert-Jan Smits of EC DG Research and Innovation handed the ERIC plaque to JIVE. In the presence of all the council members of the new ERIC, the new logo for JIVE was revealed.

Figure 35: JIVE council representatives under the new logo

In addition some good progress was made regarding the partnerships of JIVE. At the beginning of 2015 Spain became the fifth member of the ERIC, joining the

Netherlands, the United Kingdom, Sweden and France. Arrangements were made with Italy and South Africa, who had expressed an interest in becoming members. MoAs with Germany and China were extended, with an intention to further collaborate in the future. Importantly, the ERIC concluded an MoA with NWO, which formalized the secondment of personnel to JIVE.
An important milestone for JIVE in 2016 was the admission of Latvia as a member of the ERIC. The Latvians made great progress retro-fitting their antennas in Irbene (near Ventspils) and subsequently joined the EVN in 2016. In the same instance they also proved to be ready to take the next step and join the ERIC. This brings the number of full members of JIVE to six countries, with four additional organisations supporting JIVE through bilateral arrangements.

By the end of 2016, the EC funded an initiative called "JUMPING JIVE" (Joining up Users for the Maximising the Profile, the Innovation and the Necessary Globalisation of JIVE). Among others things, this will profile JIVE as an attractive future partner for European countries that have an interest in radio astronomy and institutes involved in VLBI world-wide.

The research and development group at JIVE had new assignments from the ASTERICS project, and also made progress on user software implementations through the BlackHoleCam project. Moreover, JIVE worked on the design of the SKA telescope as an associated member of the Dutch SKA-NL programme. In this context, JIVE is a visible contributor to the definition of the SKA signal and data transport infrastructure.

Research and development linked to the EVN focused on progressively increasing the bandwidth of VLBI observations. After recorded 2 Gbps modes were advertised, e-VLBI at increased bandwidth was also tested. During the testing campaigns, it also proved to be possible to get e-VLBI data from two of the KVAZAR stations in Russia. The past investments in the connectivity related research and development have also resulted in the deployment of FlexBuff systems, which allow stations to buffer the data and stream it to the correlator after the observations, alleviating the need for shipping disks.

Personnel

In 2015 Sergei Pogrebenko formally retired, but he continues to play a role as an innovator, expanding the horizon of VLBI through his expert knowledge of digital signal processing. We saw the departure of support scientists Dmitry Duev (to CalTech) and Ivan Agudo (to IAA in Granda), as well as Guifre Molera from his postdoc position (to Finnish Geospatial Research Institute).

In early 2016 two support scientists left JIVE to take up positions elsewhere. Minnie Mao had made a very enthusiastic contribution to JIVE but had an opportunity to pursue a Marie Curie position at Jodrell Bank. After four years of support and very productive scientific collaborations, Gabriele Surcis accepted a post at the telescope on his home island Sardinia. Also in 2016 our chief operator Hans Tenkink retired, which was celebrated in October. However, due to special circumstances he did agree to temporarily fill in for a few months after his retirement.

Research And Development

Data recording and transport

The jive5ab program was originally developed at JIVE to control the Mark5 recording units that replaced tape drives. Versatile and stable, it enabled real-time VLBI as an operational mode within the EVN. Over the years, improvements and increased functionality have steadily been added, in order to accommodate improved versions of the Mark5, the more recently developed Mark6, as well as the FlexBuff system.

Together with the m5copy program, which performs reliable high-speed data transfers using jive5ab instances at start and end points, jive5ab has seen an impressive uptake by the VLBI community both in and outside of the EVN, and is now also in use in geodetic VLBI.

The general applicability of jive5ab was further boosted by adding the capability to record on either Mark6 or FlexBuff recorders in either Mark6 or FlexBuff format, essentially making reading and writing to different hardware completely transparent to the user. It is now capable of handling data rates up to 256 Gbps, which should be sufficient for the foreseeable future. Many small and large improvements were implemented, increasing its ease of use and the fully transparent handling of both Mark6 and FlexBuff formats. As part of the BlackHoleCam project, functionality was added to the m5copy program to detect error/success conditions and thus enable the seamless resumption of interrupted transfers.

In September 2015 Onsala purchased and sent one FlexBuff to JIVE, after which disk pack shipping to and from the station was discontinued. Subsequently, several other stations (Effelsberg, Yebes, Hartebeesthoek, Medicina, and Noto) followed suit by purchasing FlexBuff units to be deployed at JIVE, with Effelsberg intending to use a Mark6 unit instead of a FlexBuff for local storage. (developed during the NEXPReS project, the FlexBuff system is a high-speed, high-capacity COTS data recorder that differs from Mark6 in that it has a large, non-removable pool of hard disks, using data synchronisation between station and correlator rather than physically shipping disk packs).

Figure 36: THe FlexBuff at JIVE

In order to facilitate the increased use of e-shipping, JIVE developed an automatic transfer system to balance the load on the available FlexBuffs at JIVE during the observing sessions, while limiting the number of individual station recordings per experiment to two per FlexBuff. More than two stations per unit might adversely influence the playback speed during correlation. Many additional fixes and improvements were made to the data transfer software and new software tools were created to efficiently handle the transfer and copying of recorded data.

Software correlation

In order to accommodate the EVN upgrade to higher sensitivity, in light of different back-end capabilities across the EVN stations, a mixed-bandwidth correlation mode was developed that also supports observations that combine 1 and 2 Gbps bit-rates at different stations. This resulted in the first "official" 2 Gbps user experiment during the October 2015 EVN session. e-VLBI at 2 Gbps was enabled next, requiring several optimizations in the code to handle the increased data and packet rates. This led to the first successful test in November 2015. The mixed-BW mode in the EVN software correlator at JIVE (SFXC) can also now handle a full 512 MHz unfiltered IF in its standard version, but a modified version of the code exists that can go as high as a 4 GHz IF.

The unique features of SFXC played an important role in the localisation of the fast radio burst FRB121102. Recording e-VLBI data locally at JIVE simultaneously as it correlates in real-time, combined with coherent de-dispersion and the ability to output filter-bank data that can be processed directly with existing pulsar toolkits, formed the basis for the success of these observations.

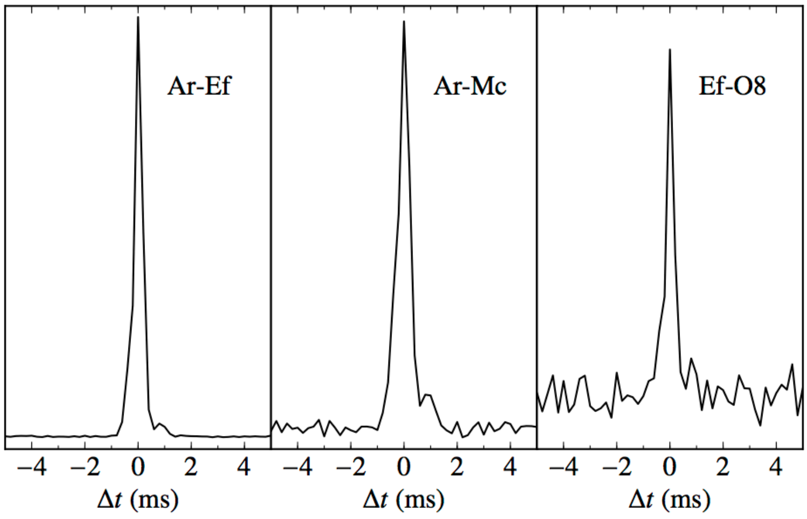


Figure 37: Profile of a burst from FRB121102 on the baselines between Arecibo and Effelsberg, Medicina, & Onsala.

During 2016 a baseline-dependent windowing and averaging method was implemented. This would enable the size of wide-field VLBI dataset to be reduced dramatically, at the cost of some loss of sensitivity. Furthermore, it can be used to restrict the field of view to a region on the sky in order to prevent strong nearby sources from appearing in the sidelobes of the interferometric beam.

The SFXC cluster hardware at JIVE is regularly upgraded. At the end of 2015 was composed of 44 nodes with a total of about 450 cores. In September 2016, a further expansion of four nodes, each containing two 8-core CPUs, brought the total number of cores to over 500. In this configuration SFXC should be able to process in real-time up to 18 stations at 1 Gbps or 10-11 stations at 2 Gbps.

Hardware correlation and digital engineering

Software correlators, such as SFXC, have the advantage that they are highly flexible and adaptable. Moreover, they run on standard computers, which over the years become ever more powerful and affordable as a result of commercial developments. Since general-purpose computing hardware is not particularly suited for correlation, software correlators tend to be not very energy-efficient, and limited in capacity. Particularly in the case of very high data rates and large numbers of stations, a custom-made hardware solution might have considerable advantages.

With that in mind, JIVE embarked on the UniBoard project, a Joint Research Activity in RadioNet FP7. The UniBoard, of which more than a hundred have been produced by now, was designed to be a generic, high-performance computing platform, using Field-Programmable Gate Arrays (FPGAs). The JIVE

UniBoard Correlator is one of the several applications making use of this hardware, and was entirely developed at JIVE. It combines impressive computing performance with minimal power consumption. Although not as flexible as SFXC, it could be of great value in the processing of a subset of EVN observations. In 2016, several features were added to the firmware to support e-VLBI processing. Besides the 16 and 32 MHz personalities, a new 64 MHz firmware version was developed.

During 2015, detailed comparisons were made between the output of JUC and SFXC. After fixing a number of problems, some of which were quite subtle, comparisons of the phase versus frequency and time showed no difference to within the empirical noise.

The JUC was designed to receive data from the stations, packaged in single frequency bins. Unfortunately, during the first e-VLBI test towards the end of 2016, it was found that the hardware at the stations could not quite produce data in this mode. Although this issue is under investigation, it is not clear when a fix will be forthcoming. As a result, the control code had to be rather extensively re-written to deal with mixed-frequency data packets, and further e-VLBI tests had to be postponed to 2017.

UniBoard^2, a Joint Research Activity in RadioNet3, again led by JIVE, was in many aspects a follow-up of the first UniBoard. The prototype board was delivered in May 2015, and after an intense period of testing and debugging by ASTRON and JIVE engineers, the production run of seven boards took place in November 2015. Equipped with the newest Altera Arria10 20nm FPGAs, which then were in fact only available as Engineering Samples, these boards are on the cutting edge of technology. Furthermore, they are pin-compatible with the far more powerful 14nm Stratix 10 devices, due to become available in 2017.

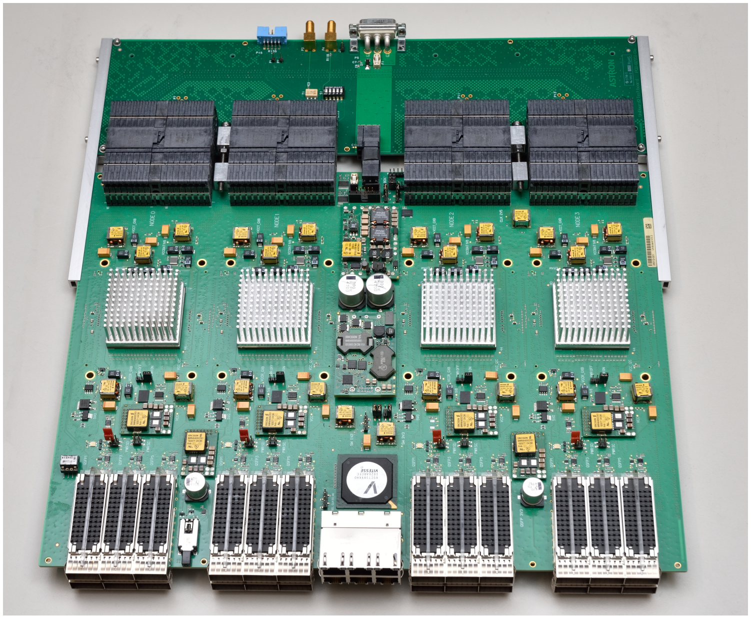


Figure 38: ***UniBoard^2 with test extension board attached***

Alongside this board, a so-called Hybrid Memory Cube (HMC) extension board was designed and sent out for manufacture at the end of 2015. This board will be used to explore the suitability of this completely new type of memory for astronomical data processing systems. In addition a design document was produced, showing ways to map the JIVE correlator onto the UniBoard^2 platform.

User software

User software development at JIVE picked up speed, driven by the BlackHoleCam and SKA-NL Roadmap projects.

As a first step towards a VLBI data reduction pipeline for BlackHoleCam, an inventory and assessment were made of current data reduction packages. For reasons of applicability, support and future sustainability the decision was made to use CASA, which is being developed and maintained by NRAO for ALMA and JVLA data reduction.

After this selection, work got underway to write a fringe-fitting routine, in the first instance in Python. An extensive list of additional modifications and functionality needed for end-to-end VLBI data reduction in CASA was compiled. Discussions were held with several software engineers who have previously worked on fringe fitting algorithms, and contact was made with NRAO to discuss ways of implementing the changes needed to CASA itself and eventually including fringe fitting as a part of the official CASA release. A collaboration was set up with a group at Rhodes University in South Africa to develop the instrument simulations that are needed to validate the calibration aspects.

From the fine-tuned Python prototype a C++ implementation within the CASA framework begun. Extensive comparisons were made between the CASA and AIPS/HOPS results, to which were added MeqTrees simulations in order to study the impact of the troposphere on fringe fitting. Besides the actual fringe fitter, a lot of additional code had to be written to make fringe fitting in CASA possible: translating AIPS calibration tables into CASA calibration tables, applying the solutions, handling VLBI amplitude calibration, and importing Tsys and weather information from FITS-IDI files.

A workshop was held in Leiden, to discuss the requirements for a mm-VLBI processing pipeline. The workshop was very well attended, and resulted in a document with requirements and recommendations for the design of the pipeline, data format and meta-data. This document was distributed within the BlackHoleCam and Event Horizon Telescope communities.

SKA

The development of the Square Kilometre Array (SKA) holds an important place in R&D at JIVE. With its EVN partners, JIVE pioneered real-time e-VLBI, which led to the e-EVN being recognised as an official SKA pathfinder. In line with its expertise in high-speed global data transport, JIVE is strongly involved in the Signal and Data Transport (SaDT) consortium, providing the Synchronisation and Timing (SAT) architect.

Much effort was spent on working out the performance requirements for the SKA time and frequency distribution system, and its interfaces to the rest of the telescope. A system design was made for the distribution of UTC timing at nanosecond accuracy, based on the White Rabbit (WR) protocol (http://www.ohwr.org /projects/white-rabbit). A field trial was organised on location at the SKA-SA support base in Klerefontein, South Africa.

EVN Operations

Correlation

The core of JIVE's service is the processing of EVN data; the table below summarizes experiments that were correlated at JIVE in each year.

2015	User Experiments			Test & Network Monitoring		
	N	Ntwk_hr	Corr_hr	N	Ntwk_hr	Corr_hr
Correlated	96	864.5	1049.5	28	102.5	126.5
Distributed	87	753	923	23	87.5	111.5
Released	84	727	877	21	60	60
e-EVN experiments	27	191	191			
e-EVN ToOs	2	19	19			

2016	User Experiments			Test & Network Monitoring		
	N	Ntwk_hr	Corr_hr	N	Ntwk_hr	Corr_hr
Correlated	90	752.5	969.5	20	71	77
Distributed	97	844	1048	23	81	87
Released	94	835	1047	25	86.5	92.5
e-EVN experiments	39	242.5	258.5			
e-EVN ToOs	19	121	135			

Table 14: Summary of EVN experiments correlated at the EVN Correlator in 2015-2016

Session 2/2014 saw some experiments that required new SFXC features, and correlation of two families of these continued into 2015: GP052, a pulsar scintellometry experiment that used coherent de-dispersion for its target millisecond pulsar (it also needed 3 correlator passes, each using a different gating/binning configuration) , and the first 24-hour epoch of EG078, a survey for faint sources in the Hubble Deep Field, that used multiple phase center correlation with 699 targets, extending out to 27' from the pointing center.

Session 2/2015 saw the first EVN user experiment having 32 MHz subbands, a neutral hydrogen absorption experiment of a galaxy with large HI velocity dispersion.

Session 3/2015 saw the first ever EVN user 2 Gbps experiment (a global), and the first participation of the Irbene 32-m telescope in user experiments.

The first e-VLBI experiment to record onto FlexBuff at JIVE simultaneously to the real-time correlation was one to localize rotating radio transients in the December 2015 e-EVN day

In 2016, user experiments continued to take advantage of new features of SFXC and new observing possibilities with the EVN, especially for e-EVN experiments:

- Ten e-EVN experiments recorded onto FlexBuffs at JIVE, simultaneously to the real-time correlation: eight target-of-opportunity observations aiming to localize fast radio bursts, one looking for pulsed emission in a gamma-ray binary, and one maser observation requiring both continuum line passes. At one point, the sum of recorded e-EVN data was 101 TB.
- User e-EVN experiments were run at 2 Gbps for some stations in June, October, and November. By the Nov.2016 e-EVN day, the 2 Gbps stations were Effelsberg, Medicina, Noto, Onsala, Yebes, Hartebeesthoek, and Irbene, with a total across the array of 17 Gbps streaming into JIVE for real-time correlation (the other stations were run at 1Gbps, covering the upper half of the subbands, which poses no issues for SFXC).
- The test period preceding the June 2016 e-EVN day saw the first e-VLBI from KVAZAR stations: Zelenchukskaya and Badary at 512 Mbps each.
- EG088 was the first joint EVN + Australian LBA experiment under the new policy encouraging linked proposals to both arrays. LBA data was translated to Mark5B format and e-shipped to JIVE. This was also the first experiment in which different sets of subbands from a station had significantly different clocks, arising from the use of two separate back-ends to attain the 1 Gbps data rate at ATCA.

EVN Support

The evolution of the back-end situation in the EVN as a whole continued apace. JIVE coordinated and analyzed tests involving new DBBC firmware, 2 Gbps observing modes and use of the fila10G output from the DBBC. JIVE continued to support parallel-recording tests for stations shifting to the DBBC and to local FlexBuff recording.

JIVE coordinated and correlated a series of tests of the DBBC polyphase filter bank (PFB) personality: four at 2 Gbps and four at 4 Gbps. So far, only a limited number (4-5) of stations have participated because of the LO compatibility requirements implicit in using the PFB personality, which does not feature tunable BBCs.

JIVE coordinated and analyzed test observations for Torun using a remote hydrogen maser for clock and frequency control. By the January 2016 e-EVN day, Torun had shifted entirely to remote H-maser control, and tests with optical-lattice clocks continued.

EVN User Support

JIVE provides support in all stages of a user's EVN observation, from proposal definition to data analysis. There were 14 first-time EVN PIs in 2015 and 13 in 2016, including 5 and 6 students, respectively. At the 2015 European Radio Interferometry School (ERIS), JIVE staff conducted the VLBI lecture and both VLBI tutorials.

JIVE maintains many of the interfaces through which the EVN users interact with the VLBI facility. For example, with back-end configurations at EVN stations still evolving on sub-session time-scales, JIVE continued to provide PIs with experiment-specific scheduling templates. For session 3/2015, a new procedure for depositing schedules was enacted, to avoid instances of stations observing the wrong version of a schedule: PIs send their key-files to JIVE, and JIVE runs SCHED and populates the *vlbeer* server. Additional benefits of the new procedure include using a locally modified version of SCHED at JIVE to enable 2 Gbps recordings with the DBBC/DDC personality and pointing-sector control, as had been requested by some stations.

The archive is another important user service, providing open access to practically all data older than 1 year. The total size of user-experiment FITS files in the EVN Archive at the end of 2016 was 43.34 TB. Almost half of the size of the whole archive has been produced over this past biennial period, illustrating the transformative nature that the new capabilities of SFXC bring to how EVN PIs approach the kinds of experiments they can conduct.

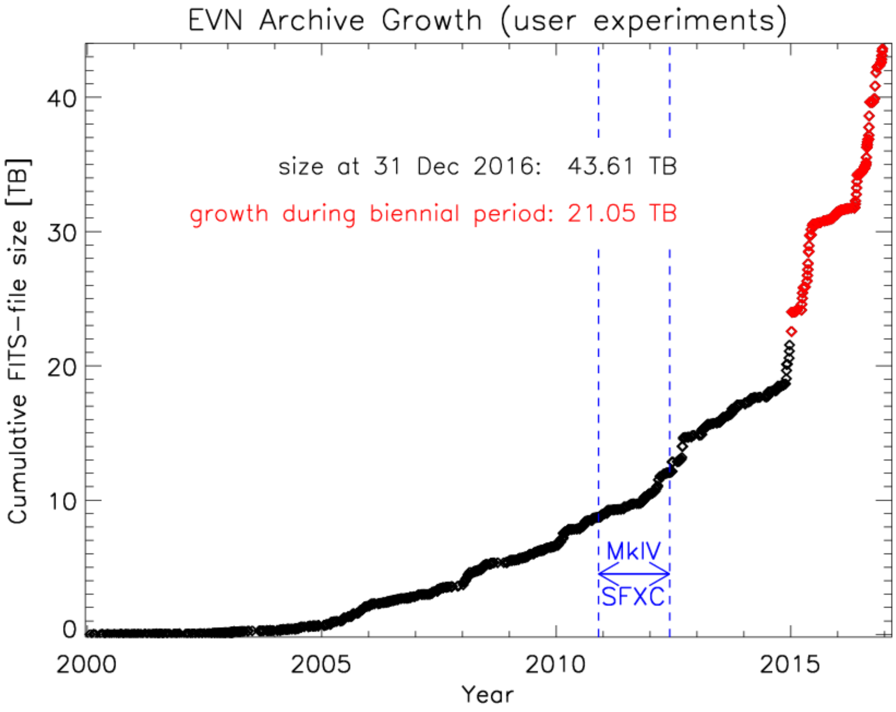


Figure 39: The growth of the EVN Archive with time

VLBI related meetings with significant participation by EVN Institutes

45th Young European Radio Astronomers Conference (YERAC)

The 45th Young European Radio Astronomers Conference (YERAC) was hosted by the Ventspils International Radio Astronomy Centre (VIRAC), in Latvia on August 19-21. This was an important event for the Ventspils International Radio Astronomy Centre (VIRAC), which celebrated 20 years of existence in 2014.

Figure 40: Participants in the 45th YERAC conference, Ventspils, 2015

Thirty five master and doctoral students in radio astronomy as well as early stage postdocs (shown in the photo above along with the hosts) presented their research in an informal but stimulating atmosphere. The meeting was crowned with the inauguration ceremony at Irbene of the recently refurbished RT16 and RT32 telescopes operated by VIRAC.

European Radio Interferometry School 2015 Conference (ERIS)

The European Radio Interferometry School took place in September 5-1 in ESO Garching,. The meeting introduced, graduate students, beginning postdoctoral fellows as well as senior researchers to radio interferometry techniques applicable to the generation of new and greatly enhanced interferometers available to European astronomers, operating at wavelengths ranging from 30m to 0.3mm. Among the 112 participants, JIVE staff made important contributions in the VLBI lectures and tutorials.

Figure 41: ERIS Participants at ESO Headquarters

“Dissecting the Universe”: Workshop on Results from High-Resolution VLBI

MPIfR hosted a workshop in Bonn from 30th November to 2nd December 2015 entitled "Dissecting the Universe - Workshop on Results from High-Resolution VLBI". There were 70 participants and the meeting consisted of presentations and discussion of results from high resolution VLBI observations, in particular RadioAstron and global mm-VLBI imaging (see https://events.mpifr-bonn.mpg.de/indico/event/4/).

Figure 42: Participants in "Dissecting the Universe" Workshop, Bonn, 2015

Conferences and Schools held at KASI

The following conferences and school were mainly hosted by KASI:

- 2015 January 14-15, the 8th KaVA Joint Science Workshop, Gyeongju, South Korea
- 2015 February 10-13, UST-GUAS Radio Astronomy Winter School, Jeju island, South Korea
- 2015 December 14-16, KVN Multi-Frequency Science and Data Reduction Workshop, Paju, South Korea

The 9th International VLBI Service (IVS) General Meeting

The Hartebeesthoek Radio Astronomy Observatory hosted the 9th International VLBI Service (IVS) General Meeting and related workshops from 13 to 19 March 2016. The meeting focused on the new possibilities offered by the VLBI Global Observing System (VGOS) and attracted 143 participants from 22 countries. Prior to that, from 9 - 12 March 2016, an IVS VLBI School was run at the observatory

Figure 43: Participants of the IVS workshop

EWASS Meeting 2016 session on VLBI

During the European Week of Astronomy and Space Science (EWASS 2016) in Athens, Greece, a special session, “Nanoradians on the sky: VLBI across the Mediterranean and beyond” on July 8, 2016 was dedicated to discuss the future of European (and Global) VLBI in general, with particular emphasis on VLBI observations with the Square Kilometre Array (SKA-VLBI). Sessions were organized around three general SKA-VLBI science areas.: Astrometry, AGN & wide-FoV Surveys, and Explosive Phenomena/Transients. The meeting demonstrated the community’s interest in very high-resolution science with the Phase-I SKA components.

46th Young European Radio Astronomers Conference (YERAC)

The MPIfR also hosted the 46th Young European Radio Astronomers Conference (YERAC) from 5-9 September 2016, organized by Rainer Mauersberger. The conference took place at the Annaberg House in Bonn, a castle-like mansion which also provided the accommodation. 41 researchers in their early-career stage from 24 countries spent 5 days discussing their science in a relaxed atmosphere. There were also several talks by senior scientists highlighting the research done at the MPIfR and other institutes in Europe. The program included an excursion to the Effelsberg 100m telescope in order to learn about the potential of this instrument for their research (see https://events.mpifr-bonn.mpg.de/indico/event/13/).

Figure 44: Participants in the 46th YERAC conference, Bonn, 2016

The 13th European VLBI Network Symposium and EVN User's meeting

The 13th European VLBI Network (EVN) Symposium and the EVN Users meeting was hosted by the Institute of Applied Astronomy of the Russian Academy of Sciences (IAA RAS) in St.Petersburg, Russia, on September 20-23, 2016

Figure 45: Participants of the 13th EVN symposium in St. Petersburg

Set at a splendid palace over 110 participants, a large number of them early-career scientists, enjoyed excellent presentations in a large variety of astrophysical topics, that stimulated discussions and further collaborations. The participants also engaged actively in the EVN Users Meeting expressing their wishes and priorities for further improvements of the capabilities of the EVN, related to their scientific ambitions.

Selected EVN Scientific Results

Extragalactic Sources

EVN Observations of HESS J1943+213: Evidence for an Extreme TeV BL Lac Object

Project code: EA056B

The unresolved, steady TeV source HESS J1943+213 is one of the variety of many gamma-ray sources discovered in the Galactic plane by recent systematic surveys with the High Energy Stereoscopic System (H.E.S.S.). The majority of these sources are Galactic objects with extended structures such as supernova remnants, while unresolved H.E.S.S. sources in the Galactic plane have been identified with Galactic high-mass X-ray binaries, or young pulsar wind nebulae (PWNe). On the other hand, outside of the Galactic plane, the vast majority of the unresolved gamma-ray sources are radio-loud active galactic nuclei (AGNs). The nature of J1943+213 is puzzling and subjected to an ongoing debate. In particular, both an extreme high-frequency-peaked BL Lac and a PWN scenario seemed viable on the basis of an early analysis of EVN short observations. With a longer observation and an improved analysis based on the nearly full EVN, it has been possible to resolve the long-standing puzzle: the milliarcsecond-scale structure has a clear asymmetric morphology consisting of a compact core and a diffuse jet-like tail. The core component is characterized by the brightness temperature of T~1.8x10^9 K, typical of low-luminosity blazars in general, supporting the classification as an extreme high-frequency-peaked BL Lac object. Remarkably, since HESS J1943+213 does not reveal any optical or infrared signatures of AGN activity, it would never be recognized and identified as a BL Lac object if not for its location close to the Galactic plane H.E.S.S. survey, and the follow up works. The EVN results suggest, therefore, a presence of an unrecognized, possibly very numerous population of particularly extreme HBLs and simultaneously demonstrate that the low-frequency VLBI observations with high angular resolution are indispensable for a proper identification of such objects.

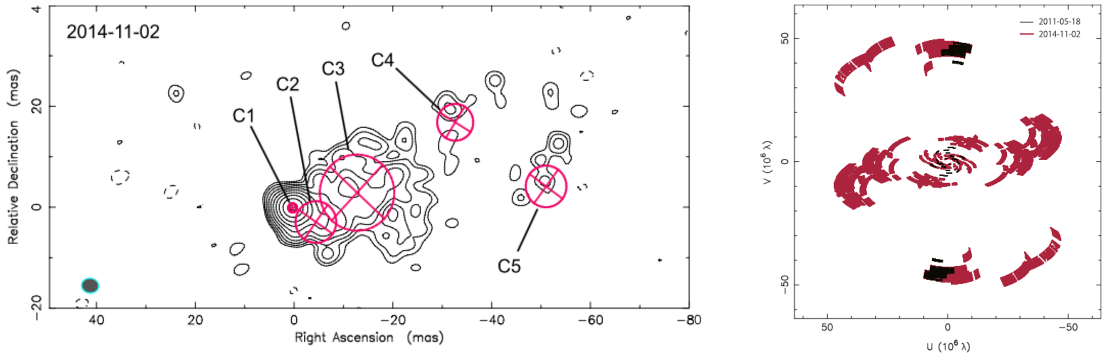


Figure 46: (Left) EVN image of J1943+213 obtained with the 2014 EVN observations; magenta circles show the best-fit circular Gaussian models. (Right) uv-coverages of EVN observations from 2014 in red (nearly full array, long track) and 2011 in black (e-EVN, short observation). The improved uv-coverage has been fundamental to solve the puzzle.

Published in: **Akiyama, K., Stawarz, Ł., Tanaka, Y. T., Nagai, H., Giroletti, M., & Honma, M., 2016, ApJ, 823, L26**

Unveiling the radio counterparts of two binary AGN candidates: J1108+0659 and J1131-0204

Project code: EB050

According to the Λ cold dark matter (CDM) hierarchical models of galaxy formation, more massive galaxies are assembled from smaller ones in a series of minor or major merger events. Since most massive galaxies host a central supermassive black hole (SMBH), a merger between two galaxies nearly always results in the formation of a merger-remnant galaxy containing two SMBHs. If sufficient gas accretes onto both SMBHs, each may be visible as an active galactic nucleus (AGN), forming a so-called “dual” or “binary” AGN. The galaxies SDSS J113126.08-020459.2 and SDSS J110851.04+065901.4 (hereafter J1131-0204 and J1108+0659, respectively) were classified as candidate binary AGNs on the basis of spatially resolved double nuclei in the near infrared (NIR) images, and followed up with 5 GHz EVN observations in e-VLBI mode. For J1131-0204, the VLBI observations detected only one single compact component associated with the eastern NIR nucleus. In J1108+0659, the VLBI observations did not detect any compact components, but the analysis of archival VLA observations revealed a possible compact core in the region of the north-western optical/NIR nucleus. While the presence of binary AGNs could not be confirmed, and seems unlikely in these two sources, the observations provided other important clues on the physics of these cores, such as the presence of intense star formation activity and the presence of dust.

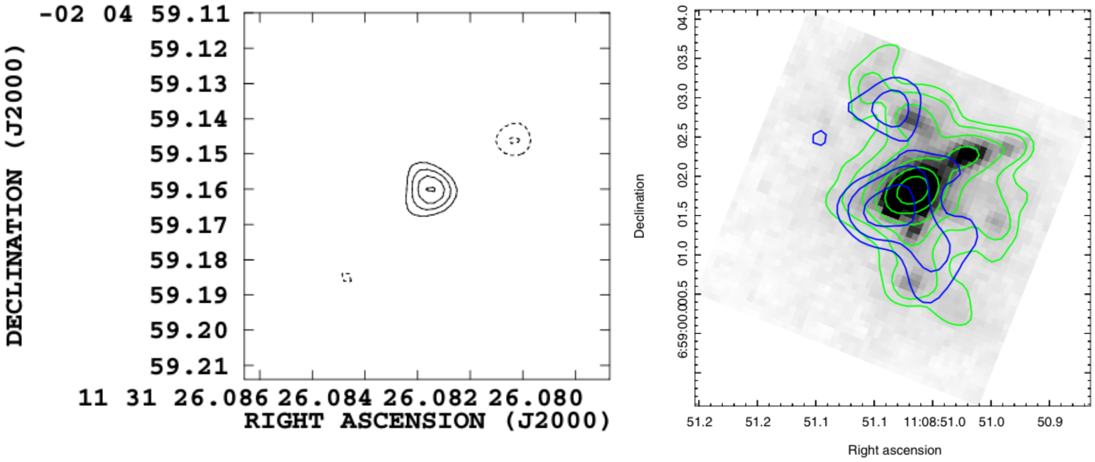


Figure 47: ***Left: EVN image at 5 GHz of J1131-0204 restored with a beam size of 15 × 15 mas. Right: HST image (greys and green contours) of J1108+0659 overplot with the 5.0 GHz VLA image (blue contours), showing that the extended radio emission and the UV continuum are cospatial.***

Published in: **Bondi, M., Pérez-Torres, M. A., Piconcelli, E., & Fu, H., 2016, A&A, 588, A102**

FRB 150418: clues to its nature from European VLBI Network and e-MERLIN observations

Project codes: RG008A-D

FRB 150418 is the first fast radio burst (FRB) for which a host galaxy has been proposed: WISE J0716-19, at z=0.492 (Keane et al. 2016). The importance of localising FRBs is multifold, both for the physics of the source itself (progenitor, luminosity, emission mechanism) and of the intervening medium and cosmology. The association of FRB 150418 with J0716-19 was based on the report of transient radio emission in the latter soon after the FRB discovery; however, later continued variability has cast doubts on the association of the two phenomena. In order to probe the presence of a compact and possibly variable source in the core of J0716-19, 5 GHz EVN observations of the galaxy were carried out in four e-EVN epochs between March and June 2016; at three epochs, e-MERLIN simultaneously observed the source. The four epochs yielded consistent results within their uncertainties for the peak surface brightness, with I_{peak}=(115±9) μJy beam^{-1}, and position, fully consistent with the galaxy nucleus. The brightness temperature of the EVN core is Tb>~$10^{8.5}$K, close to the value requested to explain the short-term radio variability properties of WISE J0716−19 in terms of interstellar scintillation.

The EVN observations provided direct and independent evidence of a nuclear compact source in J0716−19, with a bolometric radio luminosity of $\nu L\nu = 5.6 \times 10^{30}$ erg s^{-1} that is not variable within the uncertainties. The VLBI data, including those presented by Bassa et al. (2016), are fainter and less variable than those obtained with the VLA. One may hypothesise that the parsec-scale source varies on short (<hr) timescales due to scintillation, so that the VLA- based light curve resolves the variations, while they are averaged out by the longer EVN observations. The connection with the radio burst remains unclear.

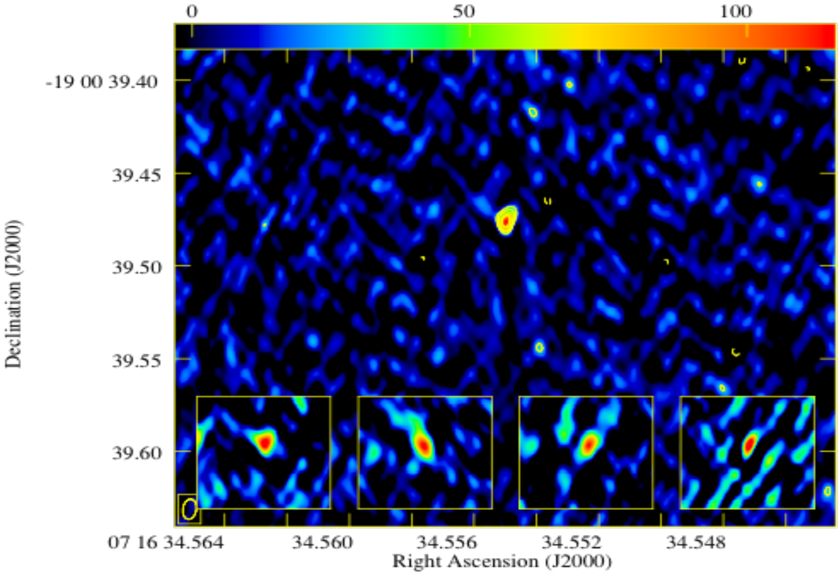


Figure 48: ***EVN 5.0 GHz images of WISE J0716−19. Main panel: average image obtained combining all observations; contours at ±3, 5, 10× local rms noise of 8.9 μJy beam⁻¹; peak 115 μJy beam⁻¹; restoring beam 10.9 mas × 6.1 mas in PA = −70; the colour scale indicates a surface brightness of between −3.0 and 115 μJy beam⁻¹. Insets: central part of the field as obtained from each individual dataset; pixel size and colour scale are the same as in the main panel to facilitate comparison***

Published in: **Giroletti, M., Marcote, B., Garrett, M. A., et al., 2016, A&A, 593, L16**

A sample of weak blazars at milli-arcsecond resolution

Project codes: EM077, EM097

A follow-up investigation of the "Deep X-ray Radio Blazar Survey" objects was started for a deeper understanding of the blazar phenomenon, aiming particularly at a comparison between high- and low-power samples of blazars. Initially, simultaneous flux density measurements with the Effelsberg 100-m telescope were made at 2.64 GHz, 4.85 GHz, 8.35GHz and/or 10.45 GHz for all DXRBS sources with declination > -20 deg, to properly compute their spectral index. Those measurements also allowed a check for flux density variability through a comparison with previous measurements found in the literature.

Since it is reasonable to expect that the objects in the DXRBS are potential gamma-ray sources detected by the Fermi Gamma-ray Space Telescope, information on their radio structure at milli-arcsecond resolution is also essential for a comparison with bright blazar samples. The EVN was thus used to carry out a survey at 5 GHz to obtain images of DXRBS objects. All of the 87 sources observed were detected. Point-like sources are found in 39 cases on a milli-arcsecond scale, and 48 show core-jet structure. The total flux density distribution at 5 GHz has a median value of 44 (+23/-10) mJy. A total flux density ≤150 mJy is observed in 68 out of 87 sources. Their brightness temperature Tb ranges between 10^7 K and 10^{12} K. 58 sources show a flat spectral index, and 29 sources show a steep spectrum or a spectrum peaking at a frequency around 1-2 GHz. Objects observed with ATCA in the Southern sky, were 14 blazars and a Steep Spectrum Radio Quasar, are associated to gamma-ray emitters. In conclusions 56 sources can be considered blazars and the correlation found between the source core flux density and the gamma-ray photon fluxes down to fainter flux densities is confirmed. 22 sources are Steep Spectrum Radio Quasars or Compact Steep-spectrum Sources, and 7 are Giga-Hz Peaked Sources. The available X-ray ROSAT observations suggest that CSS and GPS quasars are not obscured by large column of cold gas surrounding the nuclei.

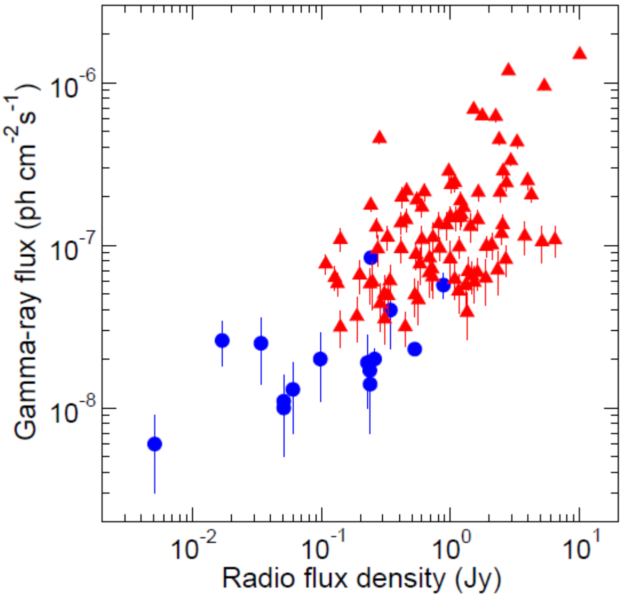


Figure 49: Integrated 0.1-100GeV Fermi LAT photon flux vs. 15 GHz VLBA core flux of Pushkarev 2010 (triangles), complemented with data pairs from this work (circles).

Published in: **Mantovani, F. et al. 2015: Astronomy & Astrophysics 577, A36**

The stratified two-sided jet of Cygnus A: Acceleration and collimation

The formation mechanism of relativistic jets is among the most unclear topics in the study of the AGN phenomenon. From an observational standpoint, its description require the possibility to probe the plasma flow on extremely small scales, comparable to the Schwarzschild radius (R_S) of the central black hole. Thanks to the rapid improvement of their performance, radio interferometers can now provide, in selected nearby targets, a high dynamic range imaging of those regions where the fundamental processes of jet acceleration and collimation are expected to take place. In particular, Global VLBI observations at millimeter wavelengths are ideally suited for these studies, since they can penetrate the synchrotron opacity barrier at the jet base and unveil unexplored emission regions with a resolution down to tens of micro-arcseconds.

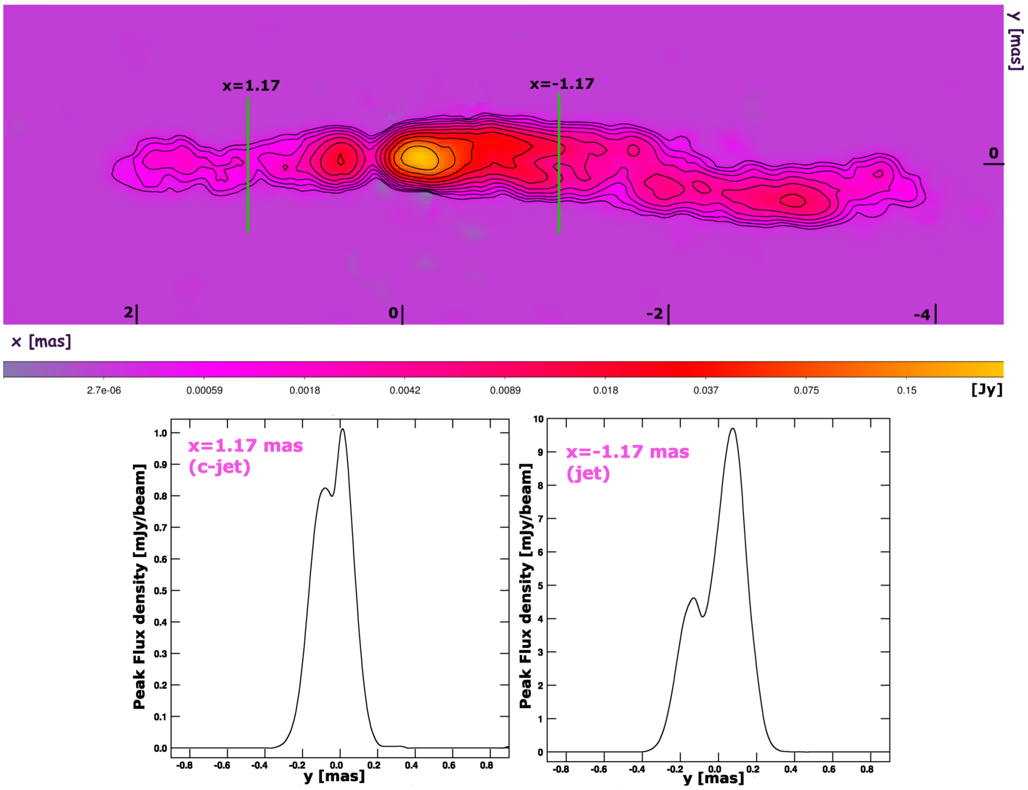


Figure 50: Top: Stacked 43 GHz image from Global VLBI observations in 2007-2009. The map was rotated by 16 clockwise and convolved with a circular beam of 0.15 mas. Contours represent isophotes at 0.3, 0.6, 1.2, 2.4, 4.8, 9.6, 19.2, 38.4, 76.8, and 153.6 mJy/beam. Bottom: double peaked intensity profiles at the location of the cuts indicated in the top image.

At a distance of 249 Mpc, the powerful FR II radio galaxy Cygnus A is an optimal target for such an investigation. Global VLBI observations at 7 mm (project codes GB060, GB065) enabled the two-sided jet base to be imaged with a resolution down to ~400 Schwarzschild radii (for $M_{BH}= 2.5\times10^9$ $M_\odot$), and to be resolved in the transverse direction. The latter is a necessary condition when aiming at understanding the collimation properties of the flow and its internal structure. Both jet and counter-jet appear limb-brightened on the examined scales (Fig. 1). This transverse stratification is not only observed in the intensity, but also in the speed. In fact, the kinematic analysis suggests the existence of a fast (with bulk Lorentz factor $\Gamma\sim2.5$)

and a slow (Γ~1) layer, both accelerating on a scale of ~10^4 R_S but with different gradients (Fig. 2). In the acceleration region, the plasma flow is also collimating with a parabolic profile. These characteristics are in good agreement with theoretical expectations for a magnetically-driven jet with spine-sheath structure.

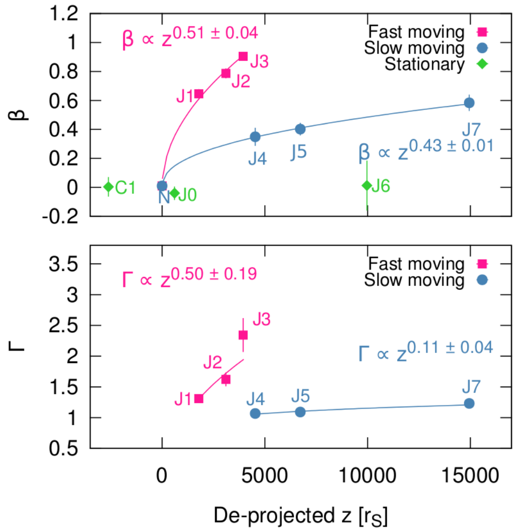


Figure 51: Top: intrinsic speed as a function of de-projected distance from the core. A fast and a slow component with different acceleration gradients can be identified. Bottom: corresponding Lorentz factor versus de-projected distance from the core.

Published in: **Boccardi B. et al. 2016, Astronomy & Astrophysics 585, A33**

Radio observations of a sample of BAL quasars

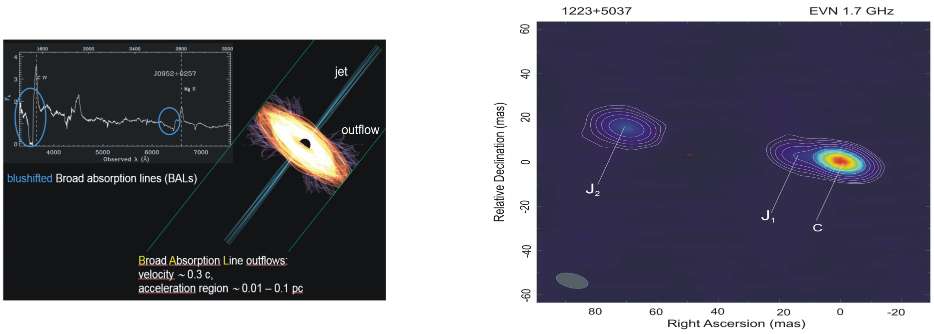


Figure 52: (Left) Scheme of AGN and a spectrum of BAL quasar with indicated two broad absorption lines: CIV 1549Å and MgII 2800Å. (Right) Quasar 1223+5037 observed with EVN at 1.7 GHz. J_1 and J_2 indicate parts of a radio jet; C indicates a radio core.

Jets and outflows are two main powerful processes transporting material out of the active galactic nuclei (AGN). Both are important feedback processes which means that they can efficiently interact with the surrounding medium or even self-regulate the growth of the supermassive black hole. Outflows are moving outward at lower speeds than jets but they can carry thousands of times more mass flux per unit of kinetic luminosity than the collimated relativistic jets (observed in ~10% of all AGNs) and can be observed indirectly as blueshifted Broad Absorption Lines (BALs) in quasar spectra (Fig.1). However, only ~ 15% of the whole population of quasars shows BALs in their spectra. This could be explained by the quasar unification scheme in which outflows are present in every quasar but appear as BALs in the spectrum only when seen under specific inclination. Another explanation, which emerged with the discovery of radio-loud BAL quasars, suggests that absorption lines are only present in the early evolution phase of quasars.

The discovery of radio-loud BAL quasars gave us another opportunity to study the BAL phenomenon, using the radio emission as an additional tool to understand the orientation and age by the VLBI imaging (detection of radio jets and their direction, size determination), the radio-loudness parameter distribution and variability study.

Studies of a sample of compact radio-loud BAL quasars with multi-frequency high resolution radio observations with the EVN at 1.7 GHz and the VLBA at 5 and 8.4 GHz offered new insights to the BAL phenomenon. Most sources were resolved showing, typical for radio-loud quasars, core-jet morphology. Their high radio luminosities and small linear sizes (<6 kpc) indicate they are strong young AGNs. Studying the relationship between the radio and optical properties in the largest available sample of BAL quasars, showed that the stronger absorption is connected with the lower values of the radio-loudness parameter and thus with larger viewing angles. Therefore, the orientation is an important parameter that affects the amount of the measured absorption. Nevertheless the lack of correlation between the value of absorption and parameter R suggest that some additional factors may be significant here, e.g. weak radio emission.
Published in: **Cegłowski et al. 2015, Kunert-Bajraszewska et al. 2015**

A pair of monster black holes revealed in a nearby galaxy

Project codes: RSY003

Cosmological simulations suggest that giant galaxies grow through merging with other galaxies, and this process will result in a large number of dual - or even multiple - supermassive black holes in the centre of some galaxies. There are however only a small number of confirmed cases. Pairs of active black holes that grow by attracting gas from the interstellar medium (called accretion) are quite hard to find observationally.

Recently, a pair of active supermassive black holes in the nearby giant spiral galaxy NGC 5252 was identified with analyzing EVN data by an international research team comprised of astronomers from both China and Europe. NGC 5252 is about 320 million light years away from the Milky Way. At the centre, it has an active galactic nucleus with a supermassive black hole, recognized by its optical, radio and X-ray properties. A second very luminous X-ray source, catalogued as CXO J133815.6+043255, was found in the outskirts of NGC 5252 in 2015. The follow-up EVN observations carried out on 2015 December 2 showed that this powerful X-ray source appears quite compact even when looking at the radio waves with the VLBI technique with superior resolution. All the available data point to an origin of the radio emission in a supermassive black hole, just like the one in the galaxy nucleus. Such pairs are very rare up to now, but it is expected that more of them will be discovered benefitting from the improving of sensitivity of VLBI arrays.

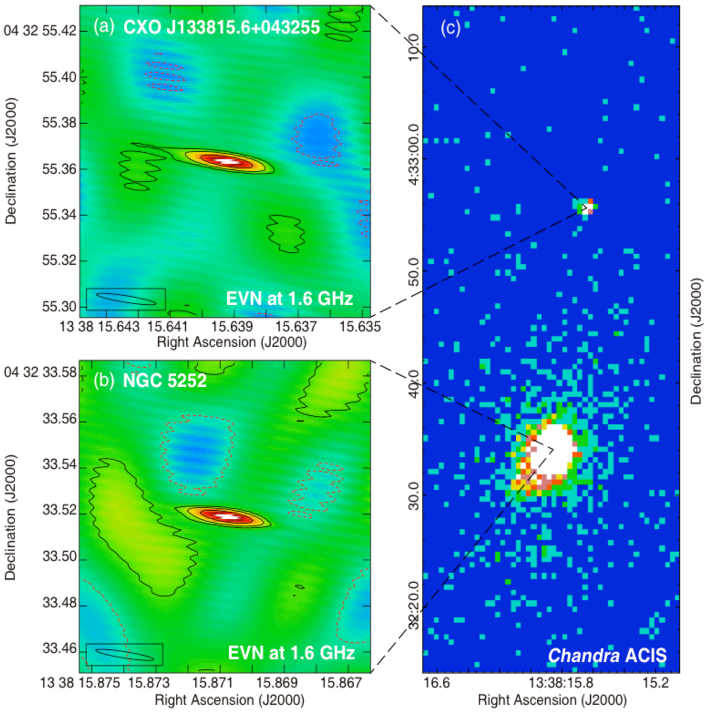


Figure 53: The pseudo-colour images of the pair of supermassive black holes observed by the European VLBI Network in the radio band (left) and Chandra in the X-ray band (right).

Published in: **Yang, X.- L. et al. 2017: MNRAS 464, L70 (Advance Access publication 2016 August 12)**

Galactic Sources

Accretion disks in luminous young stellar objects

An important review of recent EVN observations of masers in the accretion disks of luminous young stellar objects was published by Beltrán, M. T., & de Wit, W. J.

Much recent work has been aimed at understanding the formation process of early-type stars. While there is evidence that B-type stars may form through disk accretion (Beltrán & de Wit 2016), the formation of O-type stars exceeding 10^5 $L_\odot$ requires further study.

In recent years, an ever growing number of circumstellar disks around young stellar objects (YSOs) with luminosities up to ~10^5 $L_\odot$ (B-type stars) have been discovered thanks to millimeter interferometric observations. The inner regions of these disks have been investigated with EVN observations of maser emission, in particular of CH_3OH emission at 6.7GHz. Multi-epoch have allowed to derive the 3-D velocity of the maser spots, and the velocity field derived from such observations has been successfully modelled with a disk in Keplerian rotation at spatial scales of a few 100 AU (e.g., Moscadelli & Goddi 2014, 2015; see Fig. 1).

For YSOs with luminosities >10^5 $L_\odot$ (O-type stars), millimeter observations have revealed large rotating circumstellar structures that cannot be rotationally supported. Single-epoch EVN maser emission observations of early-O type (proto)stars have revealed CH_3OH maser features in elongated structures of <1000 AU in size that could be tracing circumstellar disks (e.g., Surcis et al. 2015). However, only multi-epoch EVN observations that permit to measure the proper motions will confirm whether the masers are tracing indeed the rotation of a disk.

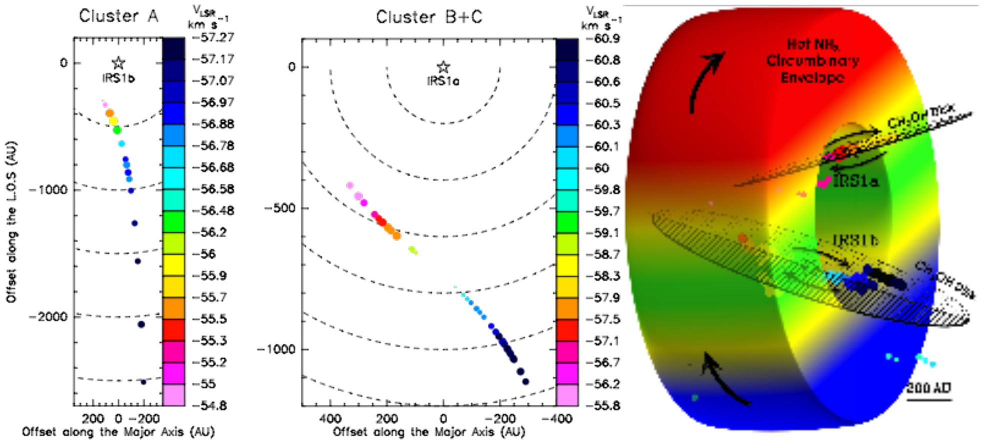


Figure 54: ***Estimated positions of individual 6.7 GHz CH3OH maser features towards the YSOs IRS1b and IRS1a in the high-mass star-forming region NGC7538 IRS1 derived from an edge-on disk model. The colors of the dots denote the maser velocity. From Moscadelli & Goddi (2014). Right panel: Schematic model showing the nearly edge-on circumstellar rotating disks around IRS1a and IRS1b traced by the methanol maser emission surrounded by a circumbinary envelope traced in NH3. From Goddi et al. (2015).***

Published in: **Beltrán, M. T., & de Wit, W. J. 2016, A&ARv, 24, 6**

Velocity and magnetic fields within 1000 AU of a massive YSO

Project code: ES067

G023.01-00.41 is a luminous star-forming region at an Hot Molecular Core (HMC) stage, which stands out among the strongest Galactic methanol maser sources, and shows a unique methanol maser fountain spouted from its HMC center.

EVN observations provided the very first detailed picture of both the three-dimensional kinematics and magnetic field morphology of the methanol gas in the vicinity (< 1000 AU) of a massive young stellar object (YSO). The methanol maser transition at 6.7 GHz was used to track each individual maser cloudlet at the VLBI resolution of 10 AU.

EVN observations disentangled the complex gas dynamics close to the jet launching region for the first time and resolved different gas flows that develop both along the outflow axis and across the disk plane with an average speed of 7 km/s. In the direction of the outflow axis, a collimation of the gas flow at a distance of about 1000 AU from the disk plane was established. In the disk region, gas streams outward along the disk plane for radii greater than 500–600 AU and inward for shorter radii. Observations reproduced the magnetic field lines for the outer regions (>600 AU) of the molecular envelope, where the magnetic field orientation shows a smooth change with the maser cloudlets position. Overall, the velocity field vectors accommodate the local magnetic field direction well, but still show an average misalignment of 30 degrees. This finding is interpreted as the contribution of a turbulent velocity field of about 3.5 km/s, which would be responsible for breaking up the alignment between the velocity and magnetic field vectors.

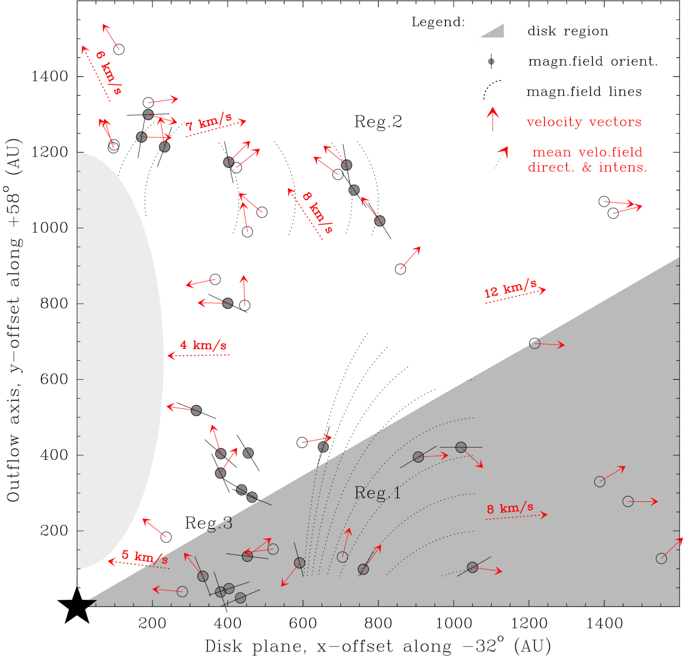


Figure 55: Gas dynamics and magnetic field configuration revealed by the 6.7 GHz methanol masers cloudlets (empty/fill dots for unpolarised/polarised emission) observed with the EVN in the vicinity of a massive YSO (star) in G023.01-00.41. Maser cloudlets are plotted with respect to the outflow axis and the disk plane.

Published in: **Sanna, A. et al. 2015, A&A, 583, L3**

Studies of circumstellar shells in AGB stars by multifrequency (sub)mm-VLBI observations of maser emission

Colomer, Desmurs, Bujarrabal and collaborators have performed a VLBI study of the SiO emission in AGB circumstellar envelopes with high resolution and sensitivity using the European telescopes of the Global Millimeter VLBI Array (GMVA), finding that up to 40% of the maser flux is recovered in some frequency channels. Previous observations of the 86 GHz v=1 J=2-1 SiO masers in R Cas with the GMVA had demonstrated that there is very compact emission, since it is detectable even with the longest VLBI baselines. Similarly, maser spots as small as 0.2 mas were observed in v=1 at 43 GHz. It is however well known that a large amount of SiO emission, which is present in the single dish data, is missed with current arrays and/or filtered out with the longest VLBI baselines, where a ratio of correlated to total SiO maser flux at 86 GHz of no more than 10% is shown. In order to better compare the SiO maser distributions at 43 and 86 GHz, it is crucial to improve the fraction of flux recovered in VLBI maps, particularly at 86 GHz. The large amount of missing flux at this frequency has been preventing any sensible comparison of both distributions. Good quality maps of the 86 GHz SiO v=1 J=2-1 line are needed to compare these with the existing 43 GHz SiO distributions in a physically meaningful way. The new GMVA data is very promising, and there are many regions of SiO emission identified probably due to the larger sensitivity of these VLBI baselines.

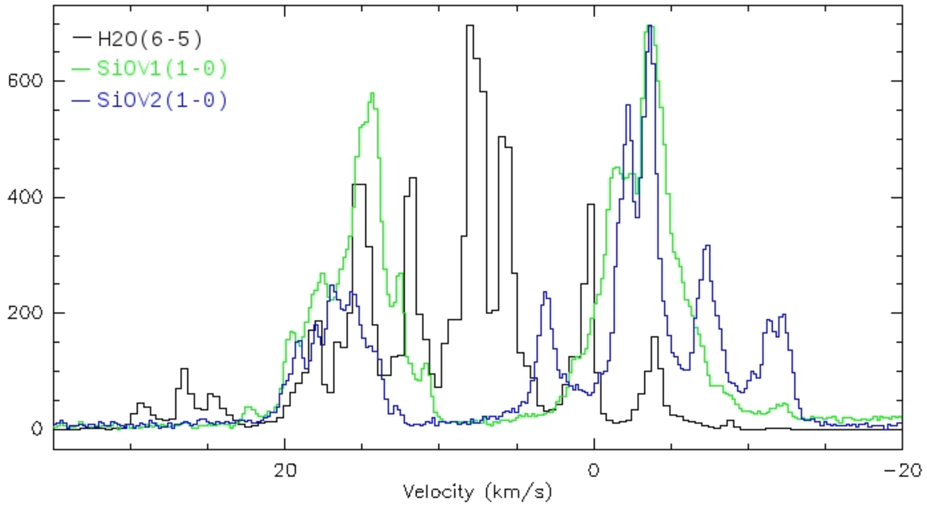


Figure 56: Spectra of stellar masers of H_2O (at 22 GHz) and SiO (at 43 GHz) obtained simultaneously with the KVN-type receiver system installed at IGN Yebes Observatory

Published in: **Colomer F., Desmurs J.F., Bujarrabal V., et al. (2016a).** In: Highlights on Spanish Astrophysics IX, Proceedings of the XII Scientific Meeting of the Spanish Astronomical Society held on July 18 – 22, 2016, in Bilbao, Spain. F. Figueras, A. Sánchez-Lavega, S. Pérez-Hoyos, A. Alonso Herrero, S. Arribas, C. Hernández Monteagudo (eds.)

EVN studies of Methanol Masers

Project codes: EN003, EB031, EB043, ES060

Several studies have been undertaken of high-mass star-forming regions using the EVN at the methanol maser line 6.7 GHz. In total, more than 60 sources were imaged at milliarcsecond resolution and a few mJy sensitivity with the significant majority where the absolute coordinates were derived successfully With this unique database, detailed studies were done aiming to determine the morphology and velocity structure. The ring-like morphology appeared in 17 % of 63 sources, arcs were seen in 8 %. In 46 % emission was complex, in 21% was linear, while in 6% paired and in just one case was simple. The mean projected size of maser clouds was 17.4AU, the full width at half maximum of the line profiles of clouds was 373 m/s. The majority of maser clouds showed velocity gradients ranging from 5 to 210 m/s/AU. The kinematic models of a rotating and expanding disk or a bipolar outflow in few cases, were supported by the maser spots distributions. Still, there is a lack of high-angular resolution studies using thermal lines to verify the methanol maser association with the large-scale outflows. Using the available database it was shown that only 13% of methanol masers coincided with the ultra-compact H II regions indicating that the 6.7 GHz maser transition appears at the very early stage of stellar evolution.

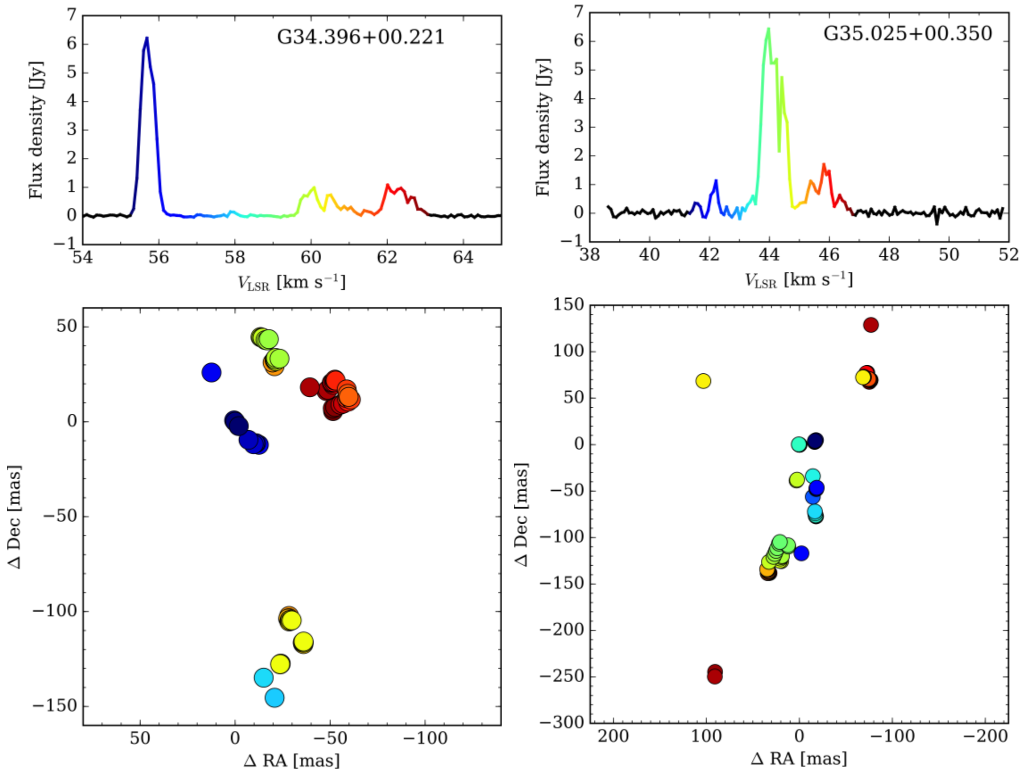


Figure 57: Example images of 6.7 GHz methanol masers detected using the EVN. The colours of circles relate to the LSR velocities as shown in the spectra.

Published in **Bartkiewicz, A., Szymczak, M., van Langevelede, H.J. 2016, A&A, 587, A104**

EVN observations of flaring maser source

Project code: ES076

The discovery of periodic and alternating flares of the methanol and water masers in G107.298+5.639, classifying it as an intermediate-mass protostar was one of the biggest surprises revealed by the Torun 32m radio telescope in the ongoing monitoring programme of star forming regions.

The first epoch EVN observation (March 2015) showed that the methanol maser clouds are primarily grouped in two clusters separated by ~400 mas in the south-east – north-west (NW) direction. Both maser clusters are oriented along position angle -43° that agrees perfectly with the major axis of large-scale (~20 arcsec) outflow B traced by CO lines. The NW cluster of methanol spots coincides in position and velocity with the water maser emission mapped earlier with VERA. Preliminary conclusion is that both masers showing periodic (34.4 d) variations appear in a region of size of 350 AU. The maser flares could be caused by variations in the infrared radiation field induced by cyclic accretion instabilities in a circumstellar or protobinary disc. Investigations are underway comparing the methanol maser emission with the water and hydroxyl masers.

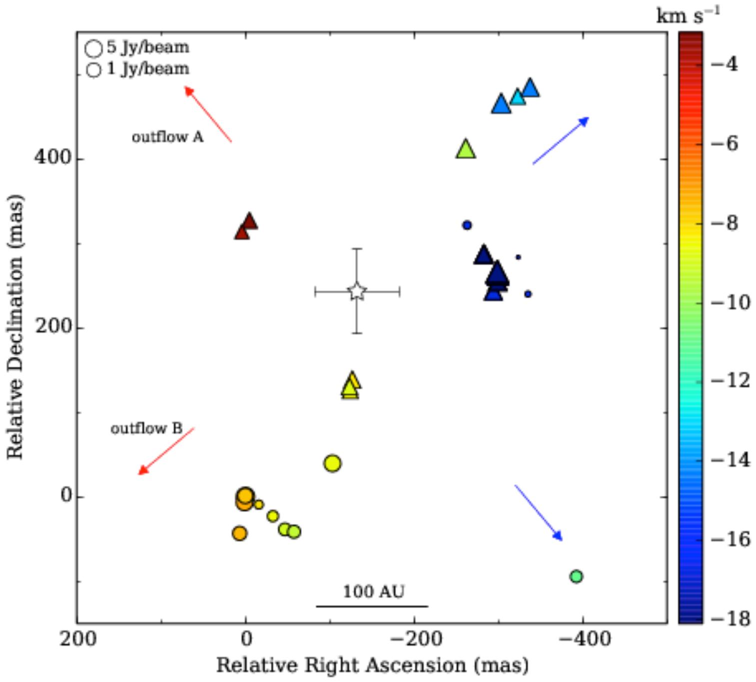


Figure 58: Map of 6.7 GHz methanol maser components (circles) in G107.298+5.639 obtained with the EVN. Circle size is proportional to the logarithm of maser brightness of component and its colour indicates the velocity according to the colour scale on the wedge. The triangles indicate the position of the 22 GHz water maser components detected with VERA. The velocity scale of these components is the same as for the methanol line. A star symbol with the marked positional uncertainty indicates the peak of 1.3 mm continuum emission which is likely the location of an exciting source. The red and blue arrows refer to the directions of molecular outflows.

Published in: **Szymczak, M. Olech, M. Wolak, P. Bartkiewicz, A. Gawroński, M. 2016MNRAS. 459 L56**

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