VLBI and Effelsberg: a long friendship

Andrei Lobanov
(on behalf of Eduardo Ros)
Bonn, Effelsberg Conference
February 20th, 2018
Outline

• VLBI at Effelsberg: history and present
• VLBI capabilities at Effelsberg
• VLBI arrays and impact of Effelsberg
• Scientific impact: highlights
• Prospects for the next decade
VLBI at Effelsberg: 45 Years and counting

1967 May: The NRAO-Cornell VLBI system Mark-I (360 kHz bandwidth) begins operations (Kellermann & Cohen 1988); correlation is done on a general purpose computer. First successful VLBI experiments in Canada at 75 cm and in the USA at 50 cm wavelength (Broten et al. 1967, Bare et al. 1967); 15 experiments altogether performed in the USA and Canada in 1967.

1971 May 12: Official commissioning of the 100-m telescope; initiator and leader of the telescope project: Otto Hachenberg, Bonn University and MPIfR. NRAO Mark-II VLBI system in operation, bandwidth: 2 MHz (Clark 1973); 2-station correlator at NRAO, Charlottesville, upgrade to 3-station capability 1975, end of operation 1993.

1972 August 1: Start of regular astronomical observations with 100-m telescope at 11 cm wavelength.

1973 June 18–21: First VLBI observation including the 100-m telescope at 13 cm wavelength; VLBI terminal: NRAO Mark-II; frequency standard: Rubidium, stability about $10^{-12}$; receiver: 300 K uncooled paramp; array: Effelsberg, NRAO 140 ft and DSN 26 m antenna ‘Venus’, Goldstone, California.

(Preuss 2002)
VLBI at Effelsberg: Setting many records and milestones

- Pioneering Space VLBI measurements with RadioAstron: one of the many VLBI milestones and records set at Effelsberg

Effelsberg for VLBI: One of the many or a special one?

- **Very Long Baseline Interferometry (VLBI)**, operating at wavelengths of 0.2–90 cm (80 MHz–230 GHz), combines antennas across the Earth and on board of spacecraft.

- **Resolution** is determined by separation between the antennas:
  \[ \theta_{res} \propto \frac{\lambda_{obs}}{B_{max}} \]

- **Image sensitivity** is proportional to the sum of the areas of individual antennas:
  \[ \sigma_{image} \propto \sum D_i^2 \]

- **Detection sensitivity** depends on pairwise products of antenna SEFD
  \[ \sigma_{det} \propto \sqrt{\frac{T_{sys1} T_{sys2}}{D_1 D_2}} \propto \sqrt{SEFD_1 SEFD_2} \]
The quest for resolution

Resolution = Observing wavelength / Telescope diameter

<table>
<thead>
<tr>
<th>Angular Resolution</th>
<th>Optical (5000A)</th>
<th>Radio (4cm)</th>
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<tbody>
<tr>
<td></td>
<td>Diameter</td>
<td>Instrument</td>
</tr>
<tr>
<td>1'</td>
<td>2mm 10cm</td>
<td>Eye Amateur Telescope</td>
</tr>
<tr>
<td>1&quot;</td>
<td>2m</td>
<td>HST</td>
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<td>0.&quot;”05</td>
<td>2m</td>
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<tr>
<td>0.&quot;”001</td>
<td>100m</td>
<td>Interferometer</td>
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Jupiter and Io as seen from Earth

1 arcmin 1 arcsec 0.05 arcsec 0.001 arcsec

Simulated with Galileo photo
Zooming into the heart of Cygnus A

The need for resolution: Black hole studies

Highest resolution is on highest demand.

Gravitational radius:

1 nas in AGN:

\[ M_{bh} = 10^8 \, M_{\odot} \text{ at } 1 \, \text{Gpc} \]

0.1 nas in XRB:

\[ M_{bh} = 10 \, M_{\odot} \text{ at } 1 \, \text{kpc} \]

2 µas in M87

5 µas in Sgr A*

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1 milliarcsecond — a man on the Moon
1 microarcsecond — a child on the Sun
1 nanoarcsecond — a football field on... Alpha Centauri
What can Effelsberg do (as a VLBI station)?
Frequency coverage and sensitivity (SEFD)

<table>
<thead>
<tr>
<th>(\lambda) (cm)</th>
<th>Eb</th>
<th>GBT</th>
<th>Ar</th>
<th>VLBA Dish</th>
<th>OSO (60/85)</th>
<th>Ys</th>
<th>Sr</th>
<th>Tm 65</th>
<th>Comment for Eb</th>
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<td>20</td>
<td>11</td>
<td>3.5</td>
<td>289</td>
<td>350</td>
<td>67</td>
<td>39</td>
<td>PFK</td>
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<td>10</td>
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<td>13</td>
<td>300</td>
<td>12</td>
<td>3</td>
<td>347</td>
<td>1110</td>
<td>1400</td>
<td>46</td>
<td>SFK Strong RFI</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>14</td>
<td>5</td>
<td>359</td>
<td>480</td>
<td>160</td>
<td>26</td>
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<td>5</td>
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<td>5</td>
<td>210</td>
<td>850</td>
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<td>6</td>
<td>327</td>
<td>785</td>
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<td>24</td>
<td></td>
<td>640</td>
<td>1200</td>
<td>200</td>
<td>138</td>
<td>70</td>
<td>SFK New, Works well</td>
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<tr>
<td>0.7</td>
<td>200</td>
<td>50</td>
<td></td>
<td>1181</td>
<td>1310</td>
<td>480</td>
<td>120</td>
<td>SFK New one coming soon?</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>1150</td>
<td>4200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>PFK old, needs replacement</td>
<td></td>
</tr>
</tbody>
</table>

Additional VLBI capabilities at \(\lambda = 30\) cm, 90 cm.
EVN, −20°, 126 mJy, X-band
Global array, $-20^\circ$, 126 mJy, X-band
Science: what can you do with VLBI? (and Effelsberg as VLBI station)

- Geodetic studies
- Doppler tracking of spacecraft
- Light deflection from Jupiter
- Galactic objects: continuum
  - Radio stars (fast rotators, Dme)
  - Pulsar parallax
  - Young Stellar Objects
  - Micro Quasars
  - Young supernovae
- Galactic objects: spectroscopy
  - Astrometry: galactic rotation curve
  - Circumstellar masers dynamics
- Starburst galaxies & supernova factories
- Imaging of transients
  - FRB, GRB, GW
- Megamasers & cosmology
- Gravitational lenses
- AGN
  - jet monitoring
  - spectral studies (spectral index, turnover imaging, core-shift w/ astrometry)
The Structure and Kinematics of the Milky Way

- Over 100 trigonometric parallaxes from BeSSeL Survey
- Distance to GC: \( R_0 = 8.34 \pm 0.16 \text{ kpc} \)
- Circular rotation speed at the Sun distance: \( \Theta_0 = 240 \pm 8 \text{ km s}^{-1} \)
- Nearly flat (slope \(-0.2 \pm 0.4 \text{ km s}^{-1} \text{ kpc}^{-1}\) between 5 and 16 kpc) rotation curve

Reid, Menten, Brunthaler+ 2014ApJ...783..130R

Ros: VLBI with Effelsberg
High-sensitivity, Crab nebula

Lobanov et al. 2011 A&A 533 A10

Post high-energy flare observations of the Crab nebula at 1.6 & 5 GHz
VLBI detection of wisps

EVN+MERLIN

20feb18

Ros: VLBI with Effelsberg
Interacting T Tauri stars: discovery of helmet streamers

- VLBA+Eb observations of V 773 Tau A at seven consecutive days
- Stars: crosses
- Peak flux densities of 0.1-0.7 mJy/beam
- Structures associated with primary and secondary stars
- Direct evidence of interbinary collision and magnetic reconnection: helmet streamers like in the Sun, extending up to 24 R\(\ast\) (separation up to 52 R\(\ast\))

Massi+ 2008A&A...480..489M
PMS stars in the AB Dor moving group: HD 160934, EK Dra, PW And, LO Peg

• Pre-main-sequence stars in the AB Dor moving group
• Estimates of mass from dynamical studies (phase referencing), challenge models
• EVN 5 GHz imaging, Effelsberg sensitivity is essential

Azulay+ 2017A&A...602A..57A

Speak = 0.06 mJy/beam

Speak = 0.16 mJy/beam

Speak = 0.15/0.04/0.12 mJy/beam

Speak = 0.06 mJy/beam
Radio supernovae

SN1993J expansion, global VLBI

I. Martí-Vidal 2011 A&A 526 A142

SN2011dh

I. Martí-Vidal et al. 2011 A&A 535 L10
VLBA+Y+EB imaging of SN 2014C (NGC7331, Type Ic, then IIn, 15.1 Mpc)

- J2237+3424
- Measured expansion of 13600±650 km s⁻¹
- Deceleration by t = 384 d
- Strong circumstellar interaction
- Resolved structure in the last epoch, including Effelsberg
High-sensitivity, ultraluminous x-ray sources

Intermediate-mass black hole with steady jet emission

Source size: 1 pc

1.6 GHz EVN

DSS Image (Lasker 1990)

HST F658N

M. Mezcua et al. 2013 MNRAS 436 1546
Radio identification of transient Swift J164449.3+573451 and its host galaxy

- Paramount example of multi-band study
- Radio image, position located from VLBA+Eb (02apr2011) at X+K bands
- Phase referencing: Noise level of 30uJy beam$^{-1}$
- Upper bound of $\Gamma \leq 15$

Zauderer+ 2011Natur.476..425Z
High-fidelity imaging of gravitational lenses with global VLBI: MG J0751+2716

- GM070 observations at 1.65 GHz
- Object with \( z_L = 0.35 \) and \( z_S = 3.2 \)
- New components detected in global images (circles)
- Peak flux density: 37 mJy/beam

Spingola+ EVN Symposium 2016
RadioAstron imaging of BL Lac

- Polarimetric images of BL Lac from 2013/11/10 at 22 GHz
- Natural/uniform/super-uniform weighting images
- Ground array of 15 dishes
- Effelsbeg essential for space baseline detections
- World record of angular resolution (21 \( \mu \text{as} \))... now supressed by another RA observation (OJ287: 10 \( \mu \text{as} \))
Transition from parabolic to conical streamlines in M 87

• High-fidelity imaging of jet in M 87 constrains its geometry over several orders of magnitude in scale

• HST1 caused by overcollimation of jet
Cygnus A as studied with the GMVA
Stacked image, 86 GHz, 0.1mas

- Jet structure recovered, limb-brightening
- Central region is resolved transversally: jet anchored in disk?
- Parabolic shape of disk $r \propto z^{0.55 \pm 0.07}$

Boccardi+ 2016A&A...585A..33B
20feb18 Ros: VLBI with Effelsberg
Magnetic field determination in the core of NGC 1052 (GMVA)

- The veil over the central region in the twin jet in NGC 1052 disappears at 3mm
- Intercontinental detections possible
- Magnetic field estimated

\[ B_{sc,1R_s} \propto d^{1/3} \]

\[ 360 \, \text{G} < B_{sc,1R_s} < 7 \times 10^4 \, \text{G} \]

Baczko et al. (A&A 593, A47, 2016)
Triple supermassive black hole in J1502+115

- Triple black hole system at $z = 0.39$
- Closest pair separated by 140 pc (VLBI)
- EVN observations including Eb+Ar at 5 GHz (eEVN") and 1.4 GHz (EVN)
- Proper motion limits of $\lesssim 5$ pc yr$^{-1}$

$S_{5\text{GHz}} = 857 \pm 49$ and $872 \pm 49$ $\mu$Jy
$S_{1.7\text{GHz}} = 954 \pm 50$ and $920 \pm 49$ $\mu$Jy

Deane+ 2014 Nature 511...57D
VHE/VLBI synergies: IC 310: the ‘lightning’ blazar

Perseus cluster, nearby blazar with $z=0.01888$

Aleksić... Eisenacher... et al. 2014, Science

Looking forward

Higher baseband sensitivity (4 Gbps standard), new technologies…
A new leap forward: multi-frequency receivers

BRAND (BRoad-bAND EVN)
- Prototype of continuous band 1.5-15.5 GHz under development, funded by RadioNet
- Prototype to be installed in Effelsberg in 2020
- Collaboration MPIfR/INAF/ASTRON/INAF/OSO

PI: W. Alef (MPIfR)

KVN 4 or 3-freq suite box
- 22/43/86/130 GHz receiver implemented at the KVN

Han et al.
A new leap forward: multi-frequency receivers

• Enhanced science
  • Core-shift in extragalactic and galactic jets
  • Several molecular species imaged simultaneously
  • Faraday rotation measure probed over the whole radio spectrum
  • Survey science largely enhanced
  • Frequency phase referencing performed automatically

3-band prototype for other telescopes
Advanced imaging with BRAND Receiver

- Turnover frequency imaging: Magnetic field distribution
- Faraday rotation imaging: Magnetic field and ambient medium
- Multifrequency synthesis: sensitivity to extended and diffuse emission; velocity fields
- Core-shift and opacity profiles: Total strength of magnetic field

Mertens + 2016
Astrometry and Imaging with KVN Box

- **Ultraprecise astrometry**: positional accuracy
  \[ \sigma_{\text{pos}} \approx 50 \mu\text{as} \left( \frac{B}{500\text{ km}} \right) \]

- **High fidelity imaging**:
  \[ \sigma_{\text{phase}} \approx 10^\circ \text{ at } 130\text{ GHz.} \]

- May even be the preferred path for millimeter and sub-millimeter VLBI:
  “Next Generation” GMVA?

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Rioja+ 2015, Dodson+ 2017
Final comments

• Effelsberg is a cornerstone of the European and Global arrays.
• Partner antennas under study or construction in Asia (T65, QTT, etc.)
• Excellent polarization capabilities with large collecting surface (antenna design)
• Frequency agility of 40s in most receivers suitable for many studies (e.g., Faraday RM)

• An extremely broad range of VLBI science.
• Benefiting from strong synergy with other departments in house (VLBI correlator, receiver development, etc.)
• Next generation broadband (BRAND) and multiband (KVN) receivers would open up exceptional opportunity for physical and astrometric studies.
Thank you!