From single-dish to space-VLBI

The pivotal role of Effelsberg in AGN studies

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This presentation has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730562 [RadioNet]
Goals in AGN jet physics

- Launching and collimation mechanism of relativistic jets
- Direct detection and imaging of radio emission from accretion disks and SMBH vicinity
- Connection between jet and various constituents of AGN (BLR, NLR, and relativistic outflows)
Space-VLBI during the decades

**VSOP**

- ~2 ED at apogee
- Orbit period: ~6 hours
- L and C band receivers

**RadioAstron**
(2011 – 2020?)

- ~25 ED at apogee
- Orbit period: ~9 days
- P, L, C, K band receivers

**Millimetron**
(2020+ – ?)

- ~70 ED at apogee (L2)
- Orbit period: ~180 days
- 20-950 GHz receivers
The RadioAstron telescope on the Spektr-R satellite

- Feeds
- Instrumental module
- Solar panels
- Transmission antenna

- 10-m dish, 27 “petals”
- ~400 000 km
- 330 000 km
- ~400 000 km

Ground segment

- VLBA
- Green Bank T.S.
- EVN
- Kvasar
- KVN
- Pushino T.S.
- Astro Space Center (Moscow)
- LBA
- Kalyazin

Moon
Mission timeline

- Launch
- End of engineering commissioning
- End of early-science program – start of AO-1

3 AGN KSPs observations

- Different WGs for AGNs, pulsars, and masers.
- Both GOT (PI) and KSPs
- About 50% PI and 50% KS Projects after AO-2
UV-coverage
The cluster at MPIfR

- Funded by MPIfR and BKG
- Upgraded in December 2015
- 68 nodes, 20 cores each
- 15 playback units for diskpacks
- 2 head nodes for correlation
- Total storage volume ~500 Tb

Used for:
- Correlation of Geodesy and Astronomy (GMVA, EHT, RadioAstron) experiments
- Simulations
- Pulsar analysis
- Reduction in CASA
RA-DiFX: a software correlator for Space-VLBI

- RA first branched from version 2.0, second branch in 2015 from version 2.4
- RDF-Mark5B conversion routine, to read in data from RadioAstron
- Introducing general relativistic corrections in the delay model
- Changing DiFX metadata system to deal with variable position/velocity of the spaceborne antenna
Getting fringes...

Orbit file:

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Orientation file:

# RadioAstron position information for experiment raks03a
# Coordinates are equatorial J2000 measured in degrees
# Time is UTC

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Getting fringes...

Fringe search is performed with a dedicated software, able to handle big correlation windows.

NUM_IF is 2
NUM_TIME is 5690
NUM_CHAN is 512
NUM_STOKES is 4
INT_TIME is 1.000000E-01
CHAN_BW is 3.125000E+04

FFT along the channel direction for many timeslots
FFT along the time direction for many channels, for 1 stagger groups

Stagger 0 Mean 1.9093617E+02 StdDev 9.9786536E+01
Stagger 0 Peak 0 Delay_Pos 27 8.437E-07 [s] Rate_Pos -174 -1.529E-01 [Hz] Value 1.1176270E+01
Stagger 0 Peak 8 Delay_Pos 457 1.428E-05 [s] Rate_Pos -3596 -3.160E+00 [Hz] Value 6.7450432E+00
Stagger 0 Peak 9 Delay_Pos -437 -1.366E-05 [s] Rate_Pos -2309 -2.029E+00 [Hz] Value 6.6589090E+00
Stagger 0 Peak 11 Delay_Pos -2 -6.250E-08 [s] Rate_Pos 3751 3.296E+00 [Hz] Value 6.3564898E+00
Stagger 0 Peak 13 Delay_Pos -123 -3.844E-06 [s] Rate_Pos 4276 3.757E+00 [Hz] Value 6.2546752E+00
Stagger 0 Peak 14 Delay_Pos -108 -3.375E-06 [s] Rate_Pos 3098 2.722E+00 [Hz] Value 6.2131167E+00
Stagger 0 Peak 15 Delay_Pos -428 -1.337E-05 [s] Rate_Pos 3721 -3.270E+00 [Hz] Value 6.1976198E+00
Stagger 0 Peak 17 Delay_Pos -180 -5.625E-06 [s] Rate_Pos 545 4.789E-01 [Hz] Value 6.1765788E+00
Stagger 0 Peak 21 Delay_Pos 270 8.438E-06 [s] Rate_Pos -2191 -1.925E+00 [Hz] Value 6.0806752E+00
Peak closest to 0,0
Stagger 0 Peak 0 Delay_Pos 27 8.437E-07 [s] Rate_Pos -174 -1.529E-01 [Hz] Value 1.1176270E+01
Fringe-fitting has 1024 frequency channels (center at 512)
Fringe-fitting has 11380 time slots (center at 5690)
On the shoulders of giants…

- **Effelsberg** has a pivotal role for RadioAstron space-fringes search. At the longest baselines, only **100m-class antennas** can reach the necessary SNR to spot fringes at correlator stage.
- Fringes peak delay and rate are then used to **center the correlation window**, and perform further fringe-search with baseline stacking in AIPS.
- **Effelsberg** is also used in single-dish mode to measure polarization angle and flux of calibrators, as complementary observations to the RadioAstron ones (AGN polarization KSP)

### Table 1: Basic performance of RadioAstron

<table>
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<th>Observing Bands (cm)</th>
<th>Frequency range (MHz)</th>
<th>Bandwidth per polarization (MHz)</th>
<th>Smallest spacing (µas)</th>
<th>SEFD (kJy) LCP; RCP</th>
<th>Gain (mK Jy⁻¹)</th>
<th>1σ baseline sens. (mJy) LCP; RCP</th>
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<td>316 – 332</td>
<td>1 × 16</td>
<td>530</td>
<td>13.3; 13.5</td>
<td>11</td>
<td>14; 14</td>
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<td>18 (L)</td>
<td>1636 – 1692</td>
<td>2 × 16</td>
<td>100</td>
<td>—; 2.93</td>
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**K-band observing** can be done at one of the eight central frequencies: 18392, 19352, 20312, 21272, 22232, 23192, 24152, 25112 MHz (with further fine tuning, see section 4.1.1 and Table 4).
On the shoulders of giants…

- Example of Effelsberg contribution to a RadioAstron experiment: UV range from 4 up to 8 ED would have not been possible without the space-fringe detection at correlator.

- Indeed, when even Effelsberg or Green Bank are not enough, fringes delay and rates are extrapolated from good scans, hoping that final AIPS can see more signal at long baselines.

- This allowed to reach 8 ED for BL Lac during the AGN polarization KSP, allowing to reach the record 21 uas angular resolution.

Gómez et al. 2016
Key Science Projects at MPIfR

- **Structure of compact jets in strong AGN (AGN-S)**
  M. Perucho, A.P. Lobanov et al.

- **Nearby AGN at scales of 5 - 500 gravitational radii (AGN-N)**
  T. Savolainen, G. Giovannini et al.

- **Polarization and magnetic fields in compact jets (AGN-P)**
  J. L. Gómez, A. P. Lobanov, G. Bruni et al.
Polarization KSP results
BL Lac imaging at record angular resolution at 22 GHz

Gómez et al. 2016

GROUND

SPACE

FWHM 200 µas

FWHM 100 µas

FWHM 31 µas

x10 improvement
Brightness temperature exceeding the limit

- Intrinsic brightness temperature $T_{b,int} > 2.9 \times 10^{12}$ K, suggesting departure from equipartition.

- Supported by estimates from the visibilities amplitudes and their errors (Lobanov 2015).
Evidence of helical magnetic fields

- Point symmetric structure in RM and EVPA.
- The polarization structure is consistent with the existence of a helical magnetic field threading the jet.
- In agreement with RMHD simulations of jets with a helical magnetic field by Porth et al. (2011).

Gómez et al. 2016
Strong-AGN KSP results
Beam:
- Ground: 0.39 x 0.28 mas at -6°
- Space: 0.04 x 0.02 mas at -59.3°
- Dynamic range:
  Ground: 770:1
  Space: 95:1

0836+710 at 22 GHz

Vega Garcia et al. 2018
RA images provide exceptional probes of internal structure

Vega Garcia et al. 2018
Nearby-AGN KSP results
3C84 at 22 GHz

- Slightly super-resolved in one direction
- Core resolved in direction transverse to the jet – the brightest feature in the middle of the flow
- Very wide opening angle at first, then rapid collimation to almost cylindrical jet
- Edge-brightened emission upstream of the core

Giovannini et al. 2018
3C84 at 22 GHz

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Giovannini et al. 2018
Summary

• **Effelsberg** has a crucial role in Space-VLBI observations with RadioAstron, being capable of detecting fringes at the longest space-baselines.

• Fringes delay and rates are used to constrain the correlation window at even longer baselines, allowing further fringe-search in AIPS.

• After 5 years from the start of the three AGN KSPs, the combination of global arrays with RadioAstron has collected a number of significant results, both from the technical and scientific point of view, achieving unprecedented details in jets structure.

• Record brightness temperature, record angular resolution in the first year of observations, promising results for the analysis of further KSP data.