Very long baseline interferometry

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10 mas

Image credit: Y. Y. Kovalev
Outline

• What is Very Long Baseline Interferometry?
• Science with VLBI – what can it do for you?
• VLBI signal path
• Differences to conventional radio interferometry
• VLBI arrays
Radically increase the baseline length: Very Long Baseline Interferometry

• There is no fundamental restriction to increasing the baseline length – same interferometry principles apply
• Give up the centrally distributed LO signals and allow each telescope to have its own electronics → can radically increase the baseline length → VLBI
• A global array with baseline lengths up to 10 000 km gives an angular resolution of 4 mas @ 21cm and <0.1 mas @ 3.5mm
Not even the sky is a limit …

- Earth’s size limits the baseline lengths below 12000km
- Still higher resolutions can be obtained by sending an antenna to space!

Apogee height: 21 400km
Observing bands: 1.6, 5 GHz
Max angular res.: 0.6 mas
Not even the sky is a limit …

- Earth’s size limits the baseline lengths below 12000km
- Still higher resolutions can be obtained by sending an antenna to space!

Russian RadioAstron mission (2011-)
Apogee height: 360 000km
Observing bands: 0.3, 1.6, 5, 22 GHz
Max nominal angular res.: 7 µas
…but source brightness temperature is!

Brightness temperature \( T_b = \frac{\lambda^2 S}{2k \Omega} = 1.36 \lambda_{cm}^2 \theta_{\text{arcsec}}^{-2} S_{\text{mJy}} \, [K] \)

…while interferometer’s HPBW is \( \theta_{\text{arcsec}} = 2.063 \frac{\lambda_{cm}}{B_{\text{max, km}}} \)

Therefore, \( T_b = 2.5 \times 10^7 \left( \frac{S}{1 \text{ mJy}} \right) \left( \frac{B_{\text{max}}}{8612 \text{ km}} \right)^2 \, [K] \)

VLBA baseline sensitivity is \( \approx 1 \, \text{mJy} \) at centimetre wavelengths

\( \Rightarrow T_{b,\text{min}} \sim 10^6 - 10^7 \, K \)

High resolution has a price tag in terms of surface brightness sensitivity

Targets (currently): compact non-thermal emitters
Science with VLBI
Science targets for VLBI

- Pulsars
- Masers
- Supernova shock waves
- Magnetically active stars
- Jets from accreting black holes
- Spacecraft
Science motivation for VLBI: Microarcsecond astrometry

Distance measurement using parallax

>100 parallax distances to masers around high-mass star forming regions:

- Spiral arm structure
- Distance to Galactic Center
- Galactic rotation curve

Image credit: Adam Deller

VLBI lecture 7.10.2015
Science motivation for VLBI: Microarcsecond astrometry

Black hole masses and $H_0$ from the motion of extragalactic H$_2$O masers in accretion disks around supermassive black holes.

- NGC 4258 – Warped Keplerian disk, diameter $\sim 0.5$ pc, edge-on, BH mass $\sim 3.6\times 10^7$ Solar masses (Miyoshi et al. 1995; Argon et al. 2007)
Science motivation for VLBI: Geodesy

Use astronomical sources as test sources for modeling either the propagation effects of the signal (ISM, ionosphere, atmosphere) or the positions of the antennas.

- Earth Orientation Parameters
- Coordinate system alignment
- Daily observations of UT1-UTC with VLBA (U.S. Naval Observatory)

Length of day variations (UT1-UTC)

BKG Sonderheft “Earth Rotation” (1998)
Science motivation for VLBI: Spacecraft navigation

Descent trajectory of Huygens probe on Titan
Cimo et al. (2010)
Science motivation for VLBI: Imaging at ultra-high resolution

Resolution is so high that changes in astronomical sources can be seen in time scales <<human life time \( \rightarrow \) movies

- Masers in young stellar objects, star-forming regions and circumstellar envelopes around Asymptotic Giant Branch stars.

VLBI movie of SiO masers around Mira variable TX Cam (Gonidakis et al. 2010)
Science motivation for VLBI: Imaging at ultra-high resolution

Resolution is so high that changes in astronomical sources can be seen in time scales << human life time → movies

- Expansion of supernova shock fronts

Expansion of the shock front of supernova SN1993J in M81 (Marcaide et al.)
Science motivation for VLBI: Relativistic jets from AGN

Outflows of magnetized plasma ejected by accreting supermassive black holes in AGN

- Excellent targets for VLBI: very bright, very compact, non-thermal emission + fast motion
- Monitoring of jets with VLBI – measure kinematics in a scale of light years in sources that are billions of light years away
- Apparent superluminal motion is observed → direct evidence for the relativistic speeds
Science motivation for VLBI: Relativistic jets from AGN

Inner 2pc of M87 with VLBA at 43 GHz

(Craig Walker et al.)

- Movie of 11 observations separated by three weeks
- Beam size 0.4x0.2 mas
Science motivation for VLBI: Jets from X-ray binaries

SS433
VLBA

Amy Mioduszewski
Michael Rupen
Craig Walker
Greg Taylor
VLBI technicalities
Telescopes are controlled autonomously, each executing a pre-distributed observing schedule to synchronize the array.
Each site has its own frequency standard ("clock"), a hydrogen maser with phase stability of $\sim 10^{-15}$ over 1000s.
Voltage signals are locally sampled, time-stamped, and recorded on disks (or in some cases transferred over fast internet connections).

Mark 5A recorder with 2 disk modules
Signals are replayed, synchronized, and correlated offline using fast computer clusters. The correlator does not care that signals are not in real time!
How does VLBI differ from connected-element interferometry?
How does VLBI differ from connected-element interferometry?

No fundamental difference. In practice, things get a bit more difficult when the antennas are not at the same physical site:

• Advert consequences of the high angular resolution
• Independent station clocks have independent clock off-sets and rates that need to be corrected. These also fluctuate and cause phase noise. Used to be a big problem.
• Stations have uncorrelated atmospheric path length fluctuations that cannot be modelled. Wet troposphere is the main source of phase noise in modern VLBI (Allan deviation of $10^{-13}$ while H-maser clocks have $<10^{-14}$)
• Earth’s curvature becomes a significant factor that has to be taken into account (as well as other “geophysical” effects)
• Recording the signals on disks (or historically, on tapes) has traditionally limited available bandwidth and, therefore, sensitivity. Not such a big problem anymore (2Gbps recording rates normal).
Advert consequences of the high angular resolution – I

- Almost all sources are resolved – one cannot rely on point-source gain calibrators
- VLBI requires sources with high $T_b$, but these are usually variable – one cannot rely on standard candles in flux calibration
- Therefore, calibration of gain amplitudes and setting the flux scale need to be done by radiometry of individual antennas. Works well!
- The longer baselines with ~10 antennas mean much more sparse sampling of the visibility function than with the VLA – more difficult to image very complex sources, missing flux on large angular scales.
Advert consequences of the high angular resolution - II

- Long baselines magnify the effect of small angular quantities – also small angle errors
- Need much more accurate source and antenna positions than with e.g., VLA
- Correlator model tries to predict these as well as Earth orientation parameters, clock off-sets and rates, and many “geophysical” effects
- Still, small errors in delay \( \frac{d\varphi}{dv} \) and rate \( \frac{d\varphi}{dt} \) remain
Dealing with residual delays and rates

• Significant residual delays and rates prevent us from averaging data in frequency and time.

• Solution: fringe-fitting, i.e. searching for delay and rate values that maximize the signal when averaged over time and frequency. (No implementation in CASA at the moment, need to use AIPS)

• For weak sources: phase-referencing. Frequently observe a nearby, strong calibrator and transfer its fringe-fit solutions to the weak target.

Image credit: ASC Lebedev
Dealing with station phase errors – self-calibration

Independent station clocks + atmospheric fluctuations $\rightarrow$ an unknown, variable phase term at every station

- Prevented imaging in the early days of VLBI
- Solution: phase self-calibration
  - For $N \geq 3$ antennas in the array, there are $(N - 1)N/2 \geq N$ independent measurements for every integration period
  - If we knew the source structure, we could solve for a set of $(N - 1)N/2$ equations and obtain $N$ unknown station phases. Well, we don’t.
  - Now the trick: make an initial guess of the source structure (e.g., point), solve the station phases, correct the data, make an image and use it as the source model in the next round of iteration… Hybrid mapping.
"Geophysics" of long baselines

- The Earth is round
- Source has different elevations at different antennas
- Parallactic angles are different for alt/az-mounted antennas at different sites – need to use circularly polarized signal to get correlation
- The Earth is surrounded with a layer of neutral and ionized gas
- Tropospheric path lengths are very different at different antennas (due to different elevations). Produces a relative delay, which has to be modelled
- The Earth is not entirely solid

<table>
<thead>
<tr>
<th>Item</th>
<th>Approx Max.</th>
<th>Time scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zero order geometry.</td>
<td>6000 km</td>
<td>1 day</td>
</tr>
<tr>
<td>Nutation</td>
<td>~ 20&quot;</td>
<td>&lt; 18.6 yr</td>
</tr>
<tr>
<td>Precession</td>
<td>~ 0.5 arcmin/yr</td>
<td>years</td>
</tr>
<tr>
<td>Annual aberration.</td>
<td>20&quot;</td>
<td>1 year</td>
</tr>
<tr>
<td>Retarded baseline.</td>
<td>20 m</td>
<td>1 day</td>
</tr>
<tr>
<td>Gravitational delay.</td>
<td>4 mas @ 90° from sun</td>
<td>1 year</td>
</tr>
<tr>
<td>Tectonic motion.</td>
<td>10 cm/yr</td>
<td>years</td>
</tr>
<tr>
<td>Solid Earth Tide</td>
<td>50 cm</td>
<td>12 hr</td>
</tr>
<tr>
<td>Pole Tide</td>
<td>2 cm</td>
<td>~1 yr</td>
</tr>
<tr>
<td>Ocean Loading</td>
<td>2 cm</td>
<td>12 hr</td>
</tr>
<tr>
<td>Atmospheric Loading</td>
<td>2 cm</td>
<td>weeks</td>
</tr>
<tr>
<td>Post-glacial Rebound</td>
<td>several mm/yr</td>
<td>years</td>
</tr>
<tr>
<td>Polar motion</td>
<td>0.5 arcsec</td>
<td>~ 1.2 years</td>
</tr>
<tr>
<td>UT1 (Earth rotation)</td>
<td>Several mas</td>
<td>Various</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>~ 2 m at 2 GHz</td>
<td>All</td>
</tr>
<tr>
<td>Dry Troposphere</td>
<td>2.3 m at zenith</td>
<td>hours to days</td>
</tr>
<tr>
<td>Wet Troposphere</td>
<td>0 – 30 cm at zenith</td>
<td>All</td>
</tr>
<tr>
<td>Antenna structure</td>
<td>&lt;10 m. 1 cm thermal</td>
<td>—</td>
</tr>
<tr>
<td>Parallactic angle</td>
<td>0.5 turn</td>
<td>hours</td>
</tr>
<tr>
<td>Station clocks</td>
<td>few microsec</td>
<td>hours</td>
</tr>
<tr>
<td>Source structure</td>
<td>5 cm</td>
<td>years</td>
</tr>
</tbody>
</table>

Effects taken into account in the VLBA correlator model
VLBI networks
Choose an array that fits your needs

Freq.

> 100 GHz

1 GHz

100 MHz

Angular resolution

arcmin

arcsec

milliarcsec!
VLBI networks - astronomical

European VLBI Network
• Coordinated VLBI operation of independent radio observatories
• Correlator in Dwingeloo, Netherlands
• Astronomical VLBI
• ~25 telescopes
• Max. baseline ~10000 km
• Freq. 0.3-43 GHz
• 3 sessions / year + eVLBI
VLBI networks - astronomical

Very Long Baseline Array (USA)
• A dedicated VLBI array – works all year round
• Correlator in Socorro, New Mexico
• Astronomical and geodetic VLBI
• 10 x 25m telescopes
• Max. baseline 8600 km
• Freq. 0.3-86 GHz
• Add Arecibo, VLA, GBT and Effelsberg for High Sensitivity Array
VLBI networks - astronomical

East Asian VLBI Network (China, Japan, Korea)

Long Baseline Array (Australia)
VLBI networks - geodetic

International VLBI Service for Geodesy & Astrometry

- Global network for geodetic VLBI
- Several correlators (e.g., MPIfR, Haystack and Washington)
Summary: VLBI

• Very Long Baseline Interferometry pushes the limits of (radio) astronomy in terms of angular resolution
• Only slightly more complicated than conventional radio interferometry
• Wide area of application (astrometry, geodesy, spacecraft navigation, astrophysics of black holes, neutron stars, supernovae…)
• Requires high brightness temperature targets (non-thermal emission)
Extra: space-VLBI and mm-VLBI
Space-VLBI

Earth’s size puts on upper limit on the baseline length. Further increase the resolution of VLBI possible by putting an antenna in space!

- First technology demonstration in the 1980s (TDRSS)
- First dedicated mission: Japanese HALCA satellite 1997-2003 (1.6 and 5 GHz; max baseline ~30000km)
- Currently operating: Russian Spektr-R satellite of the RadioAstron project
- Future: Two Chinese orbiting antennas?
Problems of space-VLBI

- Uncertainties in the orbit → residual acceleration term in the spacecraft clock rate
- Small antenna → poor baseline sensitivity → target sources must be very bright and compact
- Baseline changes quickly close to Earth → Source structure can also limit the integration time
Project originates from the 1980s and was significantly delayed due to the collapse of the Soviet Union

- Finally launched in 2011
- 10-m antenna
- Highly elliptical orbit: baselines from ~1000 km to ~350000 km
- Max. angular resolution: 7μas
- Two hydrogen masers onboard
Space-VLBI with RadioAstron

- Receivers onboard:
  - P (330 MHz)
  - L (1.6 GHz)
  - C (5 GHz)
  - K (18-25 GHz)
- 32 MHz bandwidth, dual-pol.
- 128 Mbps data rate
- Two-tracking stations (Puschino, Russia and Green Bank, USA) for receiving data
Space-VLBI with RadioAstron

First fringes (RadioAstron – Effelsberg; 18cm; 8000km baseline)

Angular resolution record: 27μas (RadioAstron –GBT; 1.3cm; 100000km baseline)
Nearby radio galaxy 3C84 observed with RadioAstron

3C84
Ground-only Image at 5 GHz

3C84
Space-VLBI image at 5GHz

Source: 0316+413, Epoch: 2013–09–21, 5 GHz, No shift
Peak: 3B44.5, Bands: 3.00, Stamps x √2, RMS: 0.30 mJy/beam
Beam: 1.93 x 0.97 mas at −2.2 deg. Nat.Wgt.(no toper)

Savolainen et al. in prep.
Nearby radio galaxy 3C84 observed with RadioAstron

“Hot spot” Mach disk / reverse shock?

Beam: 0.05x0.15 mas

0.3 mas 0.1 pc

3C84 22.2 GHz

Core

1 mas 0.35 pc

~2000 r_g

21-09-2013 uvw 2,0

Savolainen et al. in prep.
mm-VLBI and Event Horizon Telescope

One can also increase the angular resolution by decreasing the observing wavelength → mm-VLBI

- Global mm-VLBI Array operates at 3.5 mm
- VLBA + IRAM telescopes + Effelsberg + Yebes + GBT + Onsala + Metsähovi
- Correlator in Bonn
mm-VLBI and Event Horizon Telescope
How does a black hole look like?

Dark shadow inside a photon ring. Shadow size and shape encodes GR.

Bardeen 1973
Luminet 1979
Event Horizon Telescope Project develops VLBI capability at 1.3mm and aims to image the shadow of the black hole at the center of our Galaxy. It’s predicted size is ~40 microarcseconds.
mm-VLBI and Event Horizon Telescope

Two key development areas in the Event Horizon Telescope Project

Phasing up ALMA array – being commissioned

Mark 6 recorder (16 Gbps)
Data per session ~7 PetaBytes