(The basics of)

VLBI Basics

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With big thanks to many of you, here and “out there”
Some of the Points Will Cover Today

• Geodetic radio telescopes
• VLBI vs GPS concept
• Station requirements
• VLBI digitization
• Correlation
• Geodetic post-processing dynamic planet
VLBI Global Observing System (VGOS) Multi-technique Core Sites
Why VLBI?
Geo ... desy, physics

EOP

Time

Astro ... nomy, metry, physics

Space Navigation
What is VLB ... A/I?
What is VLB ... I?
Very Long Baseline Interferometry
VLBI Today
VGOS Today ... Tomorrow
Basic Elements of VLBI (Geodesy)

- Antennas
- Receivers
- Analog and digital stages
- Recorders and data transport
- Correlation, post-processing
- Imaging, geodesy
VLBI (VGOS) Station

Antenna

Feed

Calibrator

Positioner

Payload

Converters

Digitizers

Recorders

Correlator
VLBI

Geometric delay

$$\tau_g = \vec{B} \cdot \hat{s}/c$$

Relative phase

$$\phi_g = 2\pi v \tau_g$$
The Geodetic Measurement System

GPS

λ

Measured

GPS antenna

Carrier

Code

19 cm

293 m

000011101001101000111100110...

...
The Geodetic Measurement System

"Relative phase"

\[ \phi_g = 2\pi v \tau_g \]
High-precision Geodetic Science

Measured vs Modeled

\[ \tau = \tau_g + \tau_{clk} + \tau_{ion} + \tau_{trop} + \tau_{inst} + \tau_{rel} + \tau_{other} + \epsilon \]

**Signal** (geometry => position), rest is "noise"
(clocks, ionosphere, troposphere, electronics, etc)
Practical VLBI Observational Goals

High-precision Geodesy means observable with small uncertainty

• Sensitivity = ability to ”see” faint objects (interferometer, Jy)

\[ \Delta S = \frac{1}{\eta_s} \times \frac{SEFD}{\sqrt{2 \times \Delta \nu \times \tau_{acc}}} \]

• Resolution = ability to “see” details in distant objects
What determines sensitivity?

• Amount of energy collected (Ta, gain, efficiency)
  – Size and quality of the collecting area
    – but cost of bigger antennas tends to increase as D^{2.7} (i.e., doubling antenna diameter raises price by ~6!)
  – Bandwidth of the energy spectrum
    – sensitivity increases as square root of observed bandwidth, cost effective

• Quietness of the receiving detectors (Tsys)
  – many receivers are already approaching quantum noise limits, or are dominated by atmospheric noise
What determines resolution?

\[ \theta \sim \frac{\lambda}{D} \]
A Few Resolution Examples

100 m telescope at $\lambda=1\text{cm}$ → $\sim 20$ arcsec

VLA ($\sim 35 \text{ km}$) at $\lambda=1\text{cm} → \sim 0.1$ arcsec
($\sim 2 \text{ km on moon; } \sim 2 \text{ m at 5000 km}$)

10,000 km telescope at $\lambda=1\text{cm} → \sim 200$ micro-arcsec
($\sim 40 \text{ cm on moon; } \sim 5 \text{ mm at 5000 km}$)

5,000 km telescope at $\lambda=1\text{mm} → \sim 40$ micro-arcsec
($\sim 8 \text{ cm on moon; } \sim 0.1 \text{ mm at 1000 km}$)
Principle of Radio Interferometry

- As source moves, response changes as cos (projection)
- Projected baseline = $D \cdot \cos \theta$
- Fringe-pattern spacing on sky
  - = $\lambda / (\text{projected baseline})$
  - = $\lambda / (D \cdot \cos \theta)$
Fringe pattern

Fringe spacing
\( \lambda/(D \cdot \cos \theta) \)
Interferometric Response to Point Source
Extended radio source
Extended radio source (one fringe width)
Large radio source ("resolving out")
Geodetic VLBI Radio Sources

• VLBI geodesy requires sources that are bright, compact, and “stable” both in time and frequency; not easy

• The total number of available useful sources for current geodetic-VLBI capabilities is small; <~1000

• VGOS, with its improved sensitivity, should significantly improve the number of available sources
Principle of (Geodetic) VLBI

Measure time-of-arrival difference to accuracy of a few picoseconds (3 ps = 1 mm)
Scheduling for Mutual Visibilities
VLBI station requirements

• Observing “noise” from quasars (contaminated by various noise sources)

• Measuring a (group) delay (a time measurement) whose resolution is inverse of spanned bandwidth
  • Requires wideband feeds and receivers (VGOS 2-14 GHz)
  • Multi-band systems to correct for ionosphere delays
VGOS Broadband Delay

Frequency (GHz)

Phase (cycles)

S-Band: Serious RFI

X-Band

~ 2.2 – 14 GHz Spanned RF Bandwidth

~ 1 GHz Data Bandwidth

Group delay (slope)
VLBI station requirements

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  - Multi-band systems to correct for ionosphere delays
  - Low-noise receivers (low SEFD, antenna efficiency, cryogenics)
  - Antennas that are large, efficient, and fast (atmosphere)
  - High-speed recording for high SNR via large bandwidth (Nyquist)
**1967**
720 kbps
1st VLBI

**1971**
4 Mbps

**1977**
224 Mbps

**2006**
2 Gbps
1st mag disk

**2010**
4 Gbps

**2014**
16 Gbps

**1990**
512 Mbps
VLBI station requirements

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  • Hydrogen maser frequency standards
Stability of Various Frequency Standards

1 radian at 10 GHz for 1000 s
VLBI station requirements

• Observing “noise” from quasars (contaminated by various noise sources)

• Measuring a (group) delay (a time measurement) whose resolution is inverse of spanned bandwidth

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  • Multi-band systems to correct for ionosphere delays
  • Low-noise receivers (low SEFD, antenna efficiency, cryogenics)
  • Antennas that are large, efficient, and fast (atmosphere)
  • High-speed recording for high SNR via large bandwidth (Nyquist)
  • Hydrogen maser frequency standards
  • Accurate time synchronization (to ~300 nsec with GPS time)
  • Instrumental calibrations (cable delays and phase calibration)
# Legacy-VGOS Comparison

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>VGOS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Antenna Size</strong></td>
<td>5–100 m dish</td>
<td>~12 m dish</td>
</tr>
<tr>
<td><strong>Slew Speed</strong></td>
<td>~20–200 deg/min</td>
<td>≥ 720 deg/min</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
<td>200–15,000 SEFD</td>
<td>≤ 2,500 SEFD</td>
</tr>
<tr>
<td><strong>Frequency Range</strong></td>
<td>S/X band</td>
<td>~2–14 (18) GHz</td>
</tr>
<tr>
<td><strong>Recording Rate</strong></td>
<td>128, 256 Mbps</td>
<td>8–16 Gbps</td>
</tr>
<tr>
<td><strong>Data Transfer</strong></td>
<td>Usually ship disks, some e-transfer</td>
<td>e-transfer, e-VLBI, ship disks when required</td>
</tr>
</tbody>
</table>

What data are recorded?

Answer: precisely timed samples of noise, usually nearly pure white, Gaussian noise!

- Interesting fact: normally, the voltage signal is sampled with only 1 or 2 bits/sample

- Big consequence, it is near incompressible

- But also another important consequence, it is not a big deal to lose a small amount of data
Waveform sampled at 2 bits/sample

- The spectrum of a Gaussian-statistics bandwidth-limited signal may be completely reconstructed by measuring only the sign of the voltage at each Nyquist sampling point (Van Vleck 1960)

- Relative to infinite bit sampling, VLBI SNR at 1 and 2 bits/sample is only 63% and 87%, respectively, better compensated by increasing recording bandwidth
Build an Array from Individual Telescopes

- To summarize:
  - Incredibly faint noise sources are observed by systems that are 1000x noisier
  - Limited ability to expand the bandwidth (sampler/recorder limitations)
  - Short integration times (clock behavior, recorder limits, fast moving antennas in VLBI Geodesy)

Correlator

- Multiplies and accumulates noisy signals from the individual telescopes to pull the signal from the noise, thus forming a large Earth-size array
Cross-correlation of weak signal

Receiver 1 noise $n_1(t)$
Receiver 2 noise $n_2(t)$
Signal $s(t)$

Correlation is product and accumulation

$$(s + n_1) (s + n_2) = s^2 + n_1s + n_2s + n_1n_2$$

(Earth rotation adds complexity because causes time-of-arrival difference and Doppler shift to continually changes)
Correlators: Two Flavors of Processors

FX: First Fourier Transform
XF: First Correlation

Amplitude
Phase
Delay
Delay Rate
Correlator Channel

FX

Phase Generator

Complex FFT

Frac. dly correct

Accumulate

$S(\omega)$

XF

Phase Generator

Complex FFT

Frac. dly correct

Complex Correlator

Accumulators

$R(\tau)$
The goal is to measure the group delay, defined as $\frac{d\theta}{d\omega}$.

First, we must measure the observed fringe-phase difference for each of the observed frequency channels:

For a given delay, the higher the fringe frequency, the greater time-rate change in phase:

Combine Channels: Bandwidth Synthesis
Multiband Delay
Mk4/DiFX fourfit 3.14 rev 1564

0059+581.zietjm, 045-1400A, GE
GGAO12M - WESTFORD, fgroup X, pol XX

Fringe quality 9
SNR 177.1
Int time 29.988
Amp 8.363
Phase 151.7
PFD 0.0e+00
Delays (us)
SBD -0.000232
MBD -0.000131
Fringe rate (Hz)
0.002285
Ion TEC -0.116
Ref freq (MHz)
6000.0000
AP (sec) 1.000

Amp. and Phase vs. time for each freq., 6 segs, 5 APs / seg (5.00 sec / seg.), time ticks 5 sec

+58°24'11.137"

[Graph showing multiband delay (µs) and related parameters]
The Final Result: Fringes!

Observables for each baseline-scan:

- Correlation Amplitude
- Correlation Phase (generally $2\pi$ ambiguous)
- Total Group Delay
- Total Delay-Rate
- All tied to a precise UT epoch
High-precision Geodetic Science

Measured vs Modeled

$$\tau = \tau_g + \tau_{clk} + \tau_{ion} + \tau_{trop} + \tau_{inst} + \tau_{rel} + \tau_{other} + \epsilon$$

Signal (geometry => position), rest is “noise”
(clocks, ionosphere, troposphere, electronics, etc)
The ensemble of observables from an experiment are only useful if a detailed and highly sophisticated model of the Earth and its messy motions exists.
### Modeling the Dynamic Earth

<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°</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°</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>

Adapted from Sovers et al., 1998
VGOS Testbed Precision Assessment

WRMS 6.8 ps (~2 mm)

Day in year 2015

Postfit delay residuals (ps)

18 hours

4 cm
NASA Next Generation VLBI

Future Sites

McDonald Observatory, Texas

Tahiti

Kōkeʻe Park Geophysical Observatory, Hawaii
Terrestrial Reference Frames and EOP

VLBI

SLR

GNSS

DORIS
And that’s pretty much it for today

Have all a productive and jolly TOW!