VLBI Techniques
Bob Campbell, JIVE

- VLBI Arrays: a brief tour
- Model / delay constituents
- Getting the most out of VLBI phases
  - Observing tactics / propagation mitigation
- Wide-field mapping
- Concepts for the VLBI Tutorial
The EVN

[Image of a globe with various locations marked, including Arecibo, Cambridge, Effelsberg, and others. A red circle highlights the word EVN on a bar code.]
The EVN (European VLBI Network)

- Composed of existing antennas
  - generally larger (32m - 100m): more sensitive
  - baselines up to 10k km (8k km from Ef to Shanghai, S.Africa)
  - down to 17 km (with Jb-Da baseline from eMERLIN)
  - heterogeneous, generally slower slewing

- Frequency coverage [GHz]:
  - workhorses: 1.4/1.6, 5, 6.0/6.7, 2.3/8.4, 22
  - niches: 0.329, UHF (~0.6-1.1), 43
  - frequency coverage/agility not universal across all stations

- Real-time e-VLBI experiments

- Observing sessions
  - Three ~3-week sessions per year
  - ~10 scheduled e-VLBI days per year
  - Target of Opportunity observations
EVN Links

- **Main EVN web page:**  [www.evlbi.org](http://www.evlbi.org)
  - **EVN Users’ Guide:** Proposing, Scheduling, Analysis, Status Table
  - **EVN Archive**

- **Proposals:** due 1 Feb., 1 June, 1 Oct. (23:59:59 UTC)
  - via NorthStar web-tool:  [proposal.jive.eu](http://proposal.jive.eu) [.nl]

- **User Support via JIVE (Joint Institute for VLBI ERIC)**
  - [www.jive.eu](http://www.jive.eu)
  - RadioNet trans-national access

- **Links to proceedings of the biennial EVN Symposia:**
  - [www.evlbi.org/meetings](http://www.evlbi.org/meetings)
  - History of the EVN in *Porcas, 2010, EVN Symposium #10*
Real-time e-VLBI with the EVN

- Data transmitted from stations to correlator over fiber
- **Correlation proceeds in real-time**
  - Improved possibilities for feedback to stations during obs.
  - Much faster turn-around time from observations → FITS; permits EVN results to inform other observations
  - Denser time-sampling (beyond the 3 sessions per year)
  - EVN antenna availability at arbitrary epochs remains a limitation
- Disk-recorded vs. e-VLBI: different vulnerabilities
  - e-shipping approaching best of both worlds
The VLBA (Very Long Baseline Array)

- Homogeneous array (10x 25m)
  - planned locations, dedicated array
  - Bslns ~8600-250 km (~50 w/ JVLA)
  - faster slewing
  - HSA (+ Ef + Ar + GBT + JVLA)

- Frequency agile
  - down to 0.329, up to 86 GHz

- Extremely large proposals
  - Up towards 1000 hr per year

- Globals: EVN + VLBA (+ GBT + JVLA)
  - proposed at EVN proposal deadlines (1Feb, 1Jun, 1Oct)
  - VLBA-only proposals: 1Feb, 1Aug

- VLBA URL: science.nrao.edu/facilities/vlba
**East Asian VLBI Networks**

- **Chinese (CVN):** 4 ants., primarily satellite tracking
- **Korean (KVN):** 3 ants., simultaneous 22, 43, 86, 129 GHz
- **VERA:** 4 dual-beam ants., maser astrometry 22-49 GHz
  - KaVA == KVN + VERA
- **Japanese:** various astronomical & geodetic stations
Other Astronomical VLBI Arrays

- **Long Baseline Array**
  - Only fully southern hemisphere array
  - Can now propose joint EVN+LBA obs
    - growing number of east-Asian EVN stations provide lots of N-S baselines
    - LBA—western EVN ~12k km (< 1 hr)

- **Global mm VLBI Network (GMVA)**
  - Effelsberg, Onsala, Metsahövi, Pico Veleta, NOEMA, KVN, (most) VLBAs, Green Bank

- **86 GHz**
- **~2 weeks of observing per year**
- **Coordinated from MPIfR Bonn**
IVS (International VLBI Service)

- **VLBI** as space geodesy
  - cf: GPS, SLR/LLR, Doris
- **Frequency**: 2.3 & 8-9
  - some at 8-9 & 27-34
- **Geodetic VLBI tactics**:
  - many short scans
  - fast slews
  - uniform distribution of stations over globe

- **VGOS**: wide-band geodetic system (4x 2GHz over 2-14 GHz)
  - future: unmatched time-series of geodetic-source images
- **IVS web page**: ivscc.gsfc.nasa.gov
- **History of geodetic VLBI (pre-IVS)**:
Some rule-of-thumb VLBI scales

- Representative angular scales: 0.1 — 100 mas

- Physical scales of interest:
  - Angular-diameter distance \( D_A(z) \)
  - Proper-motion distance \( D_M(z) \) \( \rightarrow \) \( \mu \) to \( \beta_{\text{app}} \) conversion
  - \( D_A \) turns over with \( z \) (max \( z \sim 1.6 \)), \( D_M \) doesn’t

- Brief table (using Planck 2015 cosmology parameters, from J.P. Rachen colloquium, Dwingeloo 11jun2015):

<table>
<thead>
<tr>
<th>( z )</th>
<th>( D_A ) (for 1 mas)</th>
<th>( \beta_{\text{app}} ) (for 0.1 mas/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>6.4 pc</td>
<td>3.1 c</td>
</tr>
<tr>
<td>1</td>
<td>8.3 pc</td>
<td>5.4 c</td>
</tr>
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<td>1.6</td>
<td>8.4 pc</td>
<td>7.4 c</td>
</tr>
<tr>
<td>3</td>
<td>8.0 pc</td>
<td>10.3 c</td>
</tr>
</tbody>
</table>
VLBI vs. shorter-BI

- **Sparser u-v coverage**
- More stringent requirements on correlator model to avoid de-correlating during coherent averaging
- No truly point-like primary flux calibrators in sky
- Independent clocks & equipment at the various stations

\[ \tau = B \cdot s / c \]

- Max \( \tau \) = 21 ms
- Max \( \dot{\tau} \) = 1.55 us/s

at C-band:

(106\( \lambda \))

(7700 cyc/s)
VLBI *a priori* Model Constituents

- Station / Source positions: different frames (ITRF, ICRF), motions
- Times: UTC, TAI, TT, UT1, TDB/TCB/TCG
- Orientation: Precession (50″/yr), Nutation (9.6″, 18yr), Polar Motion (0.6″, 1yr)
- Diurnal Spin: Oceanic friction (2ms/cy), CMB (5ms, dcds), AAM (2ms, yrs)
- Tides: Solid-earth (30cm), Pole (2cm)
- Loading: Ocean (2cm), Hydrologic (8mm), Atmospheric (2cm), PGR (mm's/yr)
- Antennas: Axis offset, Tilt, Thermal expansion
- Propagation: Troposphere (dry [7ns], wet [0.3ns]), Ionosphere
- Relativistic τ(t) calculation: Gravitational delay, Frame choice/consistency
VLBI \textit{a priori} Model: References

- IERS Tech. Note #36, 2010: \textit{IERS Conventions 2010}
  - \url{www.iers.org} link via Publications // Technical Notes
- Urban & Seidelmann (Eds.) 2013, \textit{Explanatory Supplement to the Astronomical Almanac} (3\textsuperscript{rd} Ed.)
- IAU Division A (Fundamental Astronomy; \textit{was} Div. I)
  - \url{www.iau.org/science/scientific_bodies/divisions/A/info}
- SOFA (software): \url{www.iausofa.org}
- Global Geophysical Fluids center: \url{geophy.uni.lu}
- Older (pre-IAU 2000 resolutions):
  - \textit{Explanatory Supplement to the Astronomical Almanac} 1992
  - Seidelmann & Fukushima 1992, \textit{A&A}, 265, 833 \textit{(time-scales)}
VLBI Delay (Phase) Constituents

Conceptual components:

\[ \tau_{\text{obs}} = \tau_{\text{geom}} + \tau_{\text{str}} + \tau_{\text{trop}} + \tau_{\text{iono}} + \tau_{\text{instr}} + \varepsilon_{\text{noise}} \]

Instrumental Effects
Source Structure
Source/Station/Earth orientation

\[ \tau_{\text{geom}} = -\left[ \cos \delta \left\{ b_x \cos H(t) - b_y \sin H(t) \right\} + b_z \sin \delta \right] / c \]

where: \( H(t) = \text{GAST} - \text{R.A} \)

and of course: \( \varphi = 2\pi \omega \tau_p \) for \( \varphi_{\text{obs}} : \pm N_{\text{lobes}} \)
Closure Phase

- $\phi_{\text{cls}} = \phi_{AB} + \phi_{BC} + \phi_{CA}$
- Independent of station-based $\Delta\phi$
  - propagation
  - instrumental
- But loses absolute position info
  - degenerate to $\Delta\phi_{\text{geom}}$ added to a given station

- However, $\phi_{\text{str}}$ is baseline-based: it does not cancel
  - Closure phase can be used to constrain source structure
  - Point source $\rightarrow$ closure phase $= 0$
  - Global fringe-fitting / Elliptical-Gaussian modelling

Difference Phase

- Another differential $\varphi$ measure
  - pairs of sources from a given bsln
- (Near) cancellations:
  - propagation (time & angle between sources)
  - instrumental (time between scans)
- There remains differential:
  - $\varphi_{str}$ (ideally, reference source is point-like)
  - $\varphi_{geom}$ (contains the position offset between the reference and target)

- Differential astrometry on sub-mas scales:
  $\Rightarrow$ Phase Referencing $\Leftarrow$
Phase-Referencing Tactics

- Extragalactic reference source(s) (i.e., tied to ICRF2)
  - Target motion on the plane of the sky in an inertial frame

- Close reference source(s)
  - Tends towards needing to use fainter ref-sources

- Shorter cycle times between/among the sources
  - Shorter slews (close ref-sources, smaller antennas)
  - Shorter scans (bright ref-sources, big antennas)

- High SNR (longer scans, brighter ref-sources, bigger antennas)

- Ref.src structure (best=none; if not, then not a function of ν or t)

- In-beam reference source(s) – no need to “nod” antennas
  - Best astrometry (e.g., Bailes et al. 1990, Nature, 319, 733)
  - Requires a population of (candidate) ref-sources
  - VERA multi-beam technique / Sites with twin telescopes
Where to Get Phs-Ref Sources

- RFC Calibrator search tool (L. Petrov)
- VLBA Calibrator search tool
  - Links to both via www.evlbi.org
    - under: VLBI links // VLBI Surveys, Sources, & Calibrators
  - List of reference sources close to specified position
  - FD's (var. ν's) on short & long |B|: Images, Amp(|u-ν|)

- Multiple reference sources per target
  - Estimate gradients in “phase-correction field”
  - AIPS memo #111 (task ATMCA)

- Finding your own reference sources (e-EVN obs)
  - Sensitive wide-field mapping around your target
  - Go deeper than “parent” surveys (e.g., FIRST, NVSS)
Celestial Reference Frame

- Reference System vs. Reference Frame
  - RS: concepts/procedures to determine coordinates from obs
  - RF: coordinates of sources in catalog; triad of defining axes

- Pre-1997: FK5
  - “Dynamic” definition: moving ecliptic & equinox
  - Rotational terms / accelerations in equations of motions

- ICRS: kinematic \(\rightarrow\) axes fixed wrt extra-galactic sources
  - Independent of solar-system dynamics (incl. precession/nutation)

- ICRF2: most recent realization of the ICRS
  - IERS Tech.Note #35, 2009: 2\textsuperscript{nd} Realization of ICRF by VLBI
  - 295 defining sources (axes constraint); 3414 sources overall
  - Median \(\sigma_{\text{pos}}\)~ 100-175 \(\mu\text{as}\) (floor ~40 \(\mu\text{as}\)); axis stability ~10 \(\mu\text{as}\)
  - More emphasis put on source stability & structure

- Process to create ICRF3 underway
Faint-Source Mapping

- Phase-referencing to establish Dly, Rt, Phs corrections at positions/scan-times of targets too faint to self-cal

  Phase for ev018c.ms (C-band phase-referencing: Ef,Wb,Mc,Sv,Ze)

- Increasing coherent integration time to whole observation
  - Beasley & Conway 1995, *VLBI and the VLBA*, Ch 17, p.327
Differential Astrometry

- Motion of target with respect to a reference source
  - Extragalactic ref.src. → tied to inertial space (FK5 vs. ICRF)
  - Shapiro et al. 1979, *AJ*, 84, 1459 (3C345 & NRAO 512: '71-'74)

- Masers in SFR as tracers of Galactic arms
  - BeSSeL: bessel.vlbi-astrometry.org

- Pulsar astrometry (birthplaces, frame ties, $n_e$)
  - PSRPI: safe.nrao.edu/vlba/psrpi

- Stellar systems: magnetically active binaries, exo-planets
  - RIPL: astro.berkeley.edu/~gbower/RIPL


- IAU Symp #248: *From mas to μas Astrometry*
Phs-Ref Limitations: Troposphere

- Saastamoinen Zenith Delay [m] \((\text{catmm}.\text{f})\)
  
  \[
  \text{Dry: } \frac{0.0022768P_{\text{mbar}}}{1 - 0.00266 \cos 2\phi - 0.00028h_{\text{km}}}
  \]
  
  \[
  \text{Wet: } 0.00277 \left( \frac{1255}{T_{c} + 273.16} + 0.05 \right) \times RH 
  \times 6.11 \exp \left( \frac{17.269T_{c}}{T_{c} + 237.3} \right)
  \]
  
  thus:
  
  \[
  ZD_{\text{dry}} = ZD_d(P, \phi, h)
  \]
  
  \[
  ZD_{\text{wet}} = ZD_w(T, RH)
  \]

- Station \(\Delta ZD\) \(\rightarrow\) elevation-dependent \(\Delta \phi\)
  
  - Dry \(ZD\) \(~7.5\text{ns} \(~37.5\text{ cycles of phase at } \text{C-band})\)
  
  - Wet \(ZD\) \(~0.3\text{ns} \,(0.1–1\text{ns})\) but high spatial/temporal variability

- Water-vapor radiometers to measure precipitable water along the antenna’s pointing direction
Troposphere Mitigation

- Computing “own” tropo corrections from correlated data
- Scheduling: insert “Geodetic” blocks in schedule
  - sched: GEOSEG as scan-based parameter
  - other control parameters
  - egdelzn.key in examples
- AIPS
  - DELZN & CLCOR(opcode=atmo)
  - AIPS memo #110


- Numerical weather models & ray-tracing
Phs-Ref Limitations: Ionosphere

1 TECU = 1.34/ν[GHz] cycles of φ

TEC color-map scaling:
30  75  135  180 TECU
Phs-Ref Limitations: Ionosphere

Electron Density Profiles at WSRT: Summer/Winter

0200 LT

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<th>med</th>
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<td>10.09, 35.02</td>
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0800 LT

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<th>med</th>
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<td>2.97, 7.93</td>
<td>5.0, 16.35</td>
<td>10.9, 31.64</td>
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1400 LT

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<td>17.09, 18.17</td>
<td>34.69, 35.21</td>
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2000 LT

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<th>TEC</th>
<th>min</th>
<th>med</th>
<th>max</th>
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<tr>
<td>3.35, 10.59</td>
<td>7.47, 22.90</td>
<td>17.2, 48.21</td>
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</table>
Ionosphere Mitigation

- Dispersive delay $\rightarrow$ inverse quadratic dependence $\tau$ vs. $\nu$
  - Dual-frequency (e.g., 2.3, 8.4 GHz)

- IGS IONEX maps (gridded vTEC)
  igscb.jpl.nasa.gov/components/prods.html
  - 5° long. x 2.5° lat., every 2 hr
  - $h = 450$km // $\sigma \sim 2$-8 TECU
  - Based on $\geq 150$ GPS stations
  - Various analysis centers’ solutions

- AIPS: TECOR
  - VLBI science memo #23

- From raw GPS data:

- Incorporation of profile info?
  - Ionosondes, GPS/LEO occultations
Ionosphere: Climatology

The past few solar cycles: solar 10.7cm flux density

Prediction for solar cycle: peak ≤ solar-“medium” still 4+ yr to solar-minimum
Ionosphere: Equations

Collision-free Appleton-Hartree index of refraction through a cold plasma:

\[ \mu_p^2 = 1 - \frac{2X(1 - X)}{2(1 - X) - Y^2 \sin^2 \theta \pm \left[ Y^4 \sin^4 \theta + 4(1 - X)^2 Y^2 \cos^2 \theta \right]^\frac{1}{2}} \]

where \( \theta \) is the angle between \( \mathbf{B}_0 \) and the direction of propagation, and \( X \) and \( Y \) relate to the plasma & cyclotron frequencies:

\[ X \equiv \frac{\nu_p^2}{\nu^2}, \quad \text{with} \quad \nu_p^2 = \frac{e^2}{4\pi^2 \varepsilon_0 m_e} n_e \equiv K_p^2 n_e, \]

\[ Y \equiv \frac{\nu_b}{\nu}, \quad \text{with} \quad \nu_b = \frac{e}{2\pi m_e} B \equiv K_b B. \]

Values of these new \( K \)'s are: \( K_p^2 = 80.616 \, \text{m}^3 \, \text{s}^{-2} \) and \( K_b = 2.799 \times 10^{10} \, \text{s}^{-1} \, \text{T}^{-1} \).

Expanding Appleton-Hartree and dropping terms \(< 10^{-12}\) for L-band yields:

\[ \mu_p \simeq 1 - \frac{X}{2} - \frac{X^2}{8} \pm \frac{XY \cos \theta}{2} - \frac{XY^2}{2} \left( 1 - \frac{\sin^2 \theta}{2} \right) + \frac{X^2 Y \cos \theta}{4}, \]

where the "+" and "−" of the "±" correspond to two propagation modes. Terms of order \( X, X^2, Y, Y^2, Y^3, XY, X^2Y \), and \( XY^2 \) were kept in intermediate steps.

\[ \tau_p = \left( \int \mu_p \, dl \right) / c \]

\[ \mu_g = d \left( \nu \mu_p \right) / d\nu \]
Ionosphere: References

- Davies, K.E. 1990, *Ionospheric Radio*
  - from a more practical view-point; all frequency ranges
  - ~senior undergrad science in larger context
- Kelly, M.C. 1989, *Earth’s Ionosphere*
  - ~grad science, more detail in transport processes
  - same as above, plus attention to other planets
- Budden, K.G., 1988, *Propagation of Radio Waves*
  - frightening math(s) for people way smarter than I...
Troposphere vs. Ionosphere

- Cross-over frequency below which typical ionospheric delay exceeds typical tropospheric delay (at zenith)
  - Troposphere: ~7.8 ns (at sea level, STP)
  - Ionosphere: \(-1.34 \frac{TEC_{[TECU]}}{v^2_{[GHz]}}\) ns

\[ v_{\text{cross-over}} \sim \sqrt{\frac{TEC}{5.82}} \text{ GHz} \]

- can expect different tropo, iono vertical \rightarrow slant mapping functions

- for some representative TECs:

<table>
<thead>
<tr>
<th>TEC  [TECU]</th>
<th>Cross-over V [GHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>~1.3</td>
</tr>
<tr>
<td>50</td>
<td>~2.9</td>
</tr>
<tr>
<td>100</td>
<td>~4.1</td>
</tr>
</tbody>
</table>
Wide-field Mapping: FoV limits

- Residual delay, rate $\rightarrow$ slopes in phase vs. freq, time
  - Delay $= \frac{\partial \phi}{\partial \omega}$ i.e., via Fourier transform shift theorem;
  - Rate $= \frac{\partial \phi}{\partial t}$ 1 wrap of $\phi$ across band $= 1$/BW [s] of delay)
- Delay (& rate) = function of correlated position:
  $$\tau_0 = -[\cos \delta_0 \{b_x \cos(t_{sid} - \alpha_0) - b_y \sin(t_{sid} - \alpha_0)\} + b_z \sin \delta_0] / c$$
- As one moves away from correlation center, can make a Taylor-expansion of delay (& rate):
  $$\tau(\alpha, \delta) = \tau(\alpha_0, \delta_0) + \Delta \alpha \left( \frac{\partial \tau}{\partial \alpha} \right) + \Delta \delta \left( \frac{\partial \tau}{\partial \delta} \right)$$
- $\rightarrow$ leads to residual delays & rates across the field, increasing away from the phase center.
- $\rightarrow$ leads to de-correlations in coherent averaging over frequency (finite BW) and time (finite integrations).
Wide-field Mapping: Scalings

- To maintain ≤10% reduction in response to point-source:

\[ FoV_{BW} \lesssim \frac{49''5\ N_{frq}}{B_{1000km} \cdot BW_{SB\text{MHz}}} \]

\[ FoV_{time} \lesssim \frac{18''5\ \lambda_{cm}}{B_{1000km} \cdot t_{int}} \]

- Wrobel 1995, in "VLBI & the VLBA", Ch. 21.7.5

- Scaling: BW-smearing: inversely with channel-width
  time-smearing: inversely with \( t_{int} \), obs. Frequency

- Data size would scale as \( N_{frq} \times N_{int} \) (e.g., \( \propto \) area)

- Record for single experiment correlated at JIVE = 5.32 TB
- Expected record for an on-going multi-epoch exp. = 14.71 TB
WFM: Software Correlation

- Software correlators can use almost unlimited $N_{\text{freq}}$ & $t_{\text{int}}$
  - PIs can get a much larger single FoV in a huge data-set

- Multiple phase-centers: using the extremely wide FoV correlation “internally”, and steering a delay/rate beam to different positions on the sky to integrate on smaller sub-fields within the “internal” wide field:
  - Look at a set of specific sources in the field (in-beam phs-refs)
  - Chop the full field up into easier-to-eat chunks

- As FoV grows, need looms for primary-beam corrections
  - EVN has stations ranging from 20 to 100 m
Space VLBI: Orbiting Antennas

- (Much) longer baselines, no atmosphere in the way

- HALCA: Feb’97 — Nov’05
  - Orbit: $r = 12k – 27k$ km; $P = 6.3$ hr; $i = 31^\circ$

- RadioAstron: launched 18 July 2011
  - Orbit: $r = 10-70k$ km — 310-390k km; $P \sim 9.5$ d; $i = 51.6^\circ$
  - 329 MHz, 1.6, 5, 22 GHz
  - [www.asc.rssi.ru/radioastron](http://www.asc.rssi.ru/radioastron)

- Model/correlation issues:
  - Satellite position/velocity; proper vs. coordinate time

- Planned future mission: Millimetron (0.02-17 mm; ≥ 2019)
Space VLBI: Solar System Targets

- Model variations
  - Near field / curved wavefront; may bypass some outer planets
  - *e.g.*, Duev et al. 2012, *A&A*, 541, 43
  - Sekido & Fukushima 2006, *J. Geodesy*, 80, 137

- Science applications
  - Planetary probes (atmospheres, mass distribution, solar wind)
    - Huygens (2005 descent onto Titan), Venus/Mars explorers, MEX fly-by of Phobos, BepiColombo (Mercury)
  - Tests of GR (PPN γ, ∂G/∂t, deviations from inverse-square law)
    - IAU Symp #261: *Relativity in Fundamental Astronomy*
  - Frame ties (ecliptic within ICRS)
Future

- Digital back-ends / wider IFs / faster sampling
  - Higher total bit-rates (higher sensitivity)
  - More flexible frequency configurations
  - More linear phase response across base-band channels

- Developments in software correlation
  - More special-purpose correlation modes / features

- More stations: better sensitivity, $u$-$v$ coverage
  - Additional African VLBI stations for N-S baselines

- Continuing maturation of real-time e-VLBI
  - Better responsiveness (e.g., automatic overrides)
  - Better coordination into multi-{$\lambda$} campaigns
Concepts for the VLBI Tutorial

- **Review of VLBI- (EVN-) specific quirks**
  - |B| so long, no truly point-like primary calibrators
  - Each station has independent maser time/ν control; different feeds, IF chains, & back-ends.

- **Processing steps**
  - Data inspection
  - Amplitude calibration (relying on EVN pipeline...)
  - Delay / rate / phase calibration (fringing)
  - Bandpass calibration
  - Imaging / self-cal

- **ParselTongue wiki:**
Pipeline Outputs (downloads)

- Plots up through (rough) images
- Prepared ANTAB file (amplitude calibration input)
- A priori Flagging file(s) (by time-range, by channel)
- AIPS tables
  - CL1 = “unity”, typically 15s sampling
  - SN1 = TY ⊕ GC; CL2 = CL1 ⊗ SN1 (& parallactic angles)
  - FG1 (sums over all input flagging files)
  - SN2 = FG1 ⊕ CL2 ⊕ fring; CL3 = CL2 ⊗ SN2
  - BP1 = computed after CL3 ⊕ FG1
- Pipeline-calibrated UVFITS (per source)
Data Familiarization

- FITLD — to load data
- LISTR — scan-based summary of observations
- PRTAB, PRTAN (TBOUT)
  - Looking into contents of “tables”
- POSSM, VPLOT, UVPLT
  - Plots: vs. frequency, vs. time, u-v based
- SNPLT
  - Plot solution/calibration tables (various y-axes)
Amplitude Calibration (I)

- **VLBI:** no truly point-like primary calibrator
  - Structure- and/or time-variability at smallest scales
- Stations measure power levels on/off load
  - Convertible to $T_{sys}$ [K] via calibrated loads
- Sensitivities, gain curves measured at station
- **SEFD** = $T_{sys}(t) / \{DPFU \times g(z)\}$
  - $\sqrt{SEFD_1 \times SEFD_2}$ as basis to convert from unitless correlation coefficients to flux densities [Jy]
- EVN Pipeline provides JIVE-processed TY table
Amplitude Calibration (II)

- UVPLT: plot Amp(|uv|)
  - Calibrators with simple structure: smooth drop-off e.g., $A(\rho) \propto J_1(\pi a \rho)$ for a uniform disk, diameter=a

- Poorly calibrated stations appear discrepant

- Self-calibration iterations can help bring things into alignment
Delay/Rate Calibration

- Each antenna has its own “clock” (H-maser)
- Each antenna has its own IF-chains, BBCs
  - Differing delays (& rates?) per station/pol/subband
- Delay $\rightarrow \frac{\partial \varphi}{\partial \omega}$ (phase-slope across band)
- Rate $\rightarrow \frac{\partial \varphi}{\partial t}$ (phase-slope vs. time)
- Point-source = flat $\varphi(\omega, t)$
  - Regular variations: clocks, source-structure, etc.
  - Irregular variations: propagation, instrumental noise
  - $\varphi_{\text{str}}$ doesn’t necessarily close (not station-based)
Fringe-fitting

- Over short intervals (**SOLINT**), estimate delay and rate at each station (wrt reference sta.)
  - above = “global fringe-fit” (cf. “baseline fringe-fit”)

- “Goldilocks” problem for setting SOLINT:
  - too short: low SNR
  - too long: > atmospheric coherence time \[ = f(\omega) \]

- After fringing, phases should be flat in the individual subbands, and subbands aligned

- **BPASS**: solve for station bandpass (amp/phase)
  - removes phase-curvature across individual subbands
VLBI (EVN) obs:
What you may have thought before ERIS: artifacts from the dim mists of a Jungian collective unconscious?
More detailed Monte Carlo simulations reveal an altogether different post-ERIS paradigm: