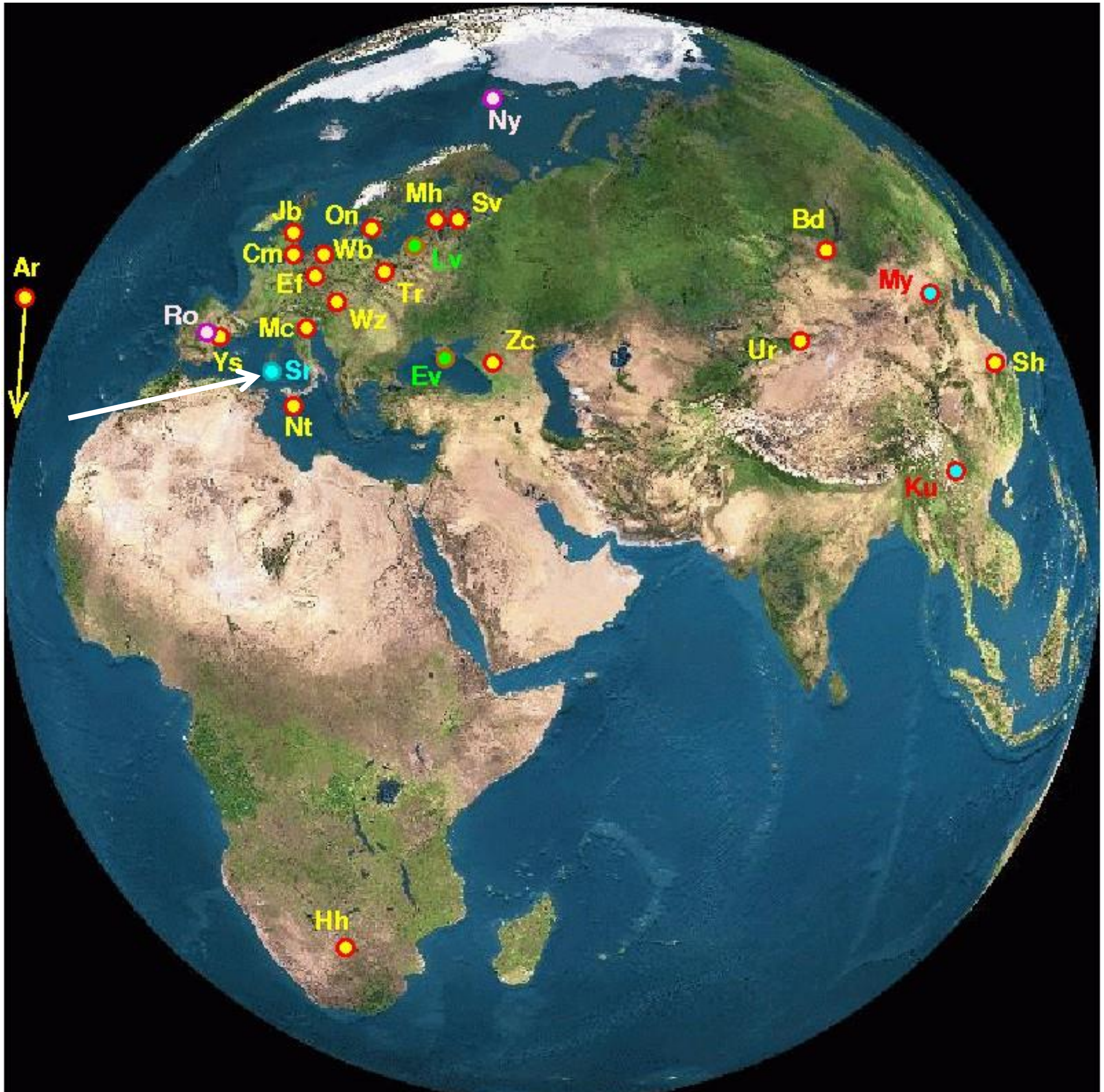
VLBI Techniques

Bob Campbell, JIVE

- 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

(viewgraphs with orange titles = for reference on web)

The EVN



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The EVN (European VLBI Network)

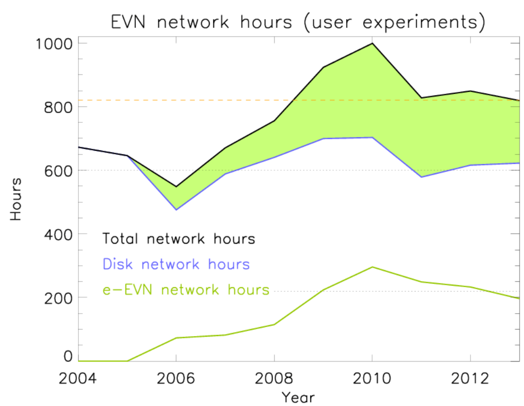
- Composed of existing antennas
  - generally larger (32m – 100m): more sensitive
  - baselines up to 10k km (8k km from Ef to Shanghai, S.Africa)
  - down to 17km (with Jb-Da baseline from eMERLIN)
  - heterogeneous, generally slower slewing
- Frequency coverage [GHz]:
  - workhorses: 1.4/1.6, 5, 6.0/6.7, 2.3/8.4, 22
  - niches: 0.329, UHF (~0.6—1.1), 49
  - 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

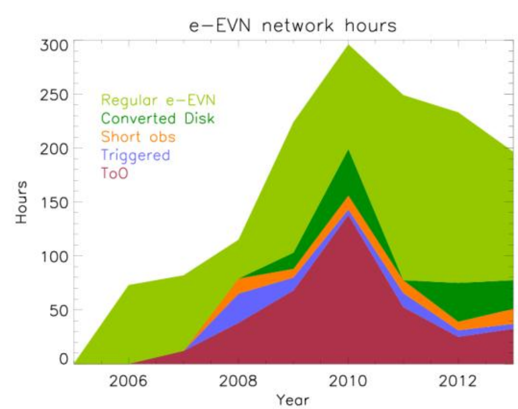
EVN Links

- Main EVN web page: **www.evlbi.org**
  - EVN Users' Guide: Proposing, Scheduling, Analysis
  - EVN Archive
- Proposals: due 1 February, 1 June, 1 October
  - via NorthStar web-tool: **proposal.jive.nl**
- User Support via JIVE (Joint Institute for VLBI in Europe)
  - **www.jive.nl**
  - RadioNet trans-national access
- Links to proceedings of the biennial EVN Symposia:
  - **www.evlbi.org/meetings**
  - History of the EVN in Porcas, 2010, *EVN Symposium #10*

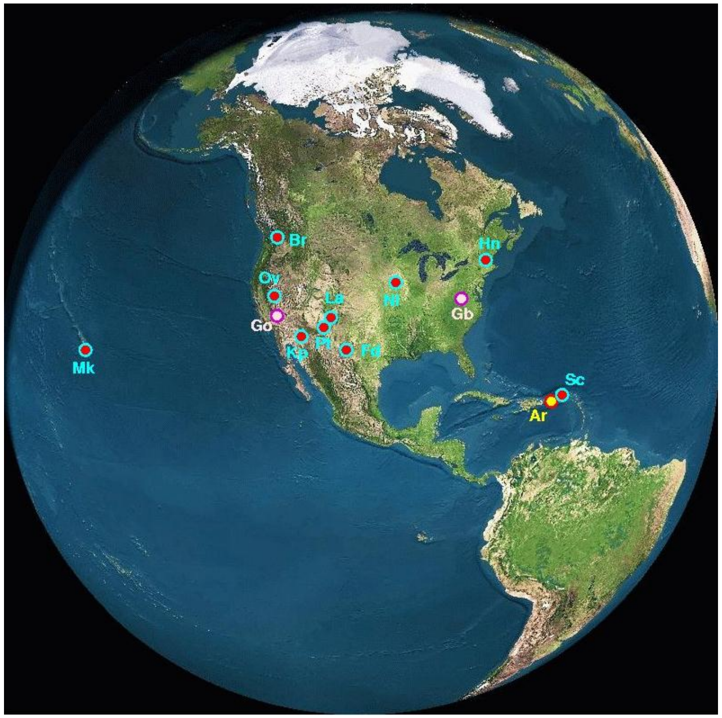
Real-time e-VLBI with the EVN

- 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 to let EVN results inform other observations
  - Denser time-sampling (>3 sessions per year)
  - EVN antenna availability at arbitrary epochs remains a limitation
- Disk-recorded vs. e-VLBI: different vulnerabilities
  - NEXPReS — EC project to approach best of both worlds





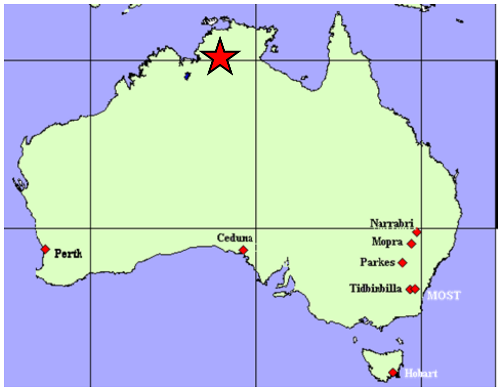
The VLBA (Very Long Baseline Array)



- Heterogeneous array (10x 25m)
  - planned locations, dedicated array
  - Bslns ~8600-250 km (~50 w/ VLA)
  - faster slewing
  - HSA (+ Ef + Ar + GBT + VLA)
- Frequency agile
  - down to 0.329, up to 86 GHz
- Extremely large proposals
  - Up towards 1000 hr per year

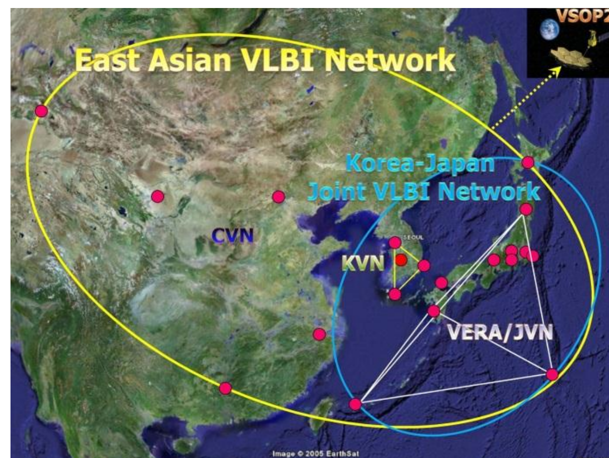
- Globals: EVN + VLBA (+ GBT + VLA)
  - proposed at EVN proposal deadlines (VLBA-only: 1Feb, 1Aug)
- VLBA web page: **www.vlba.nrao.edu**

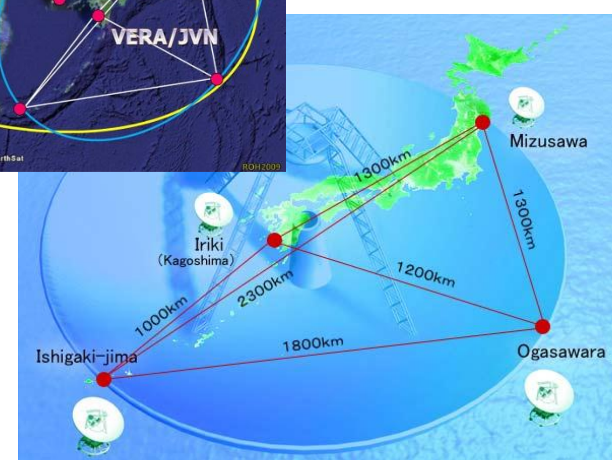
Other Astronomical VLBI Arrays



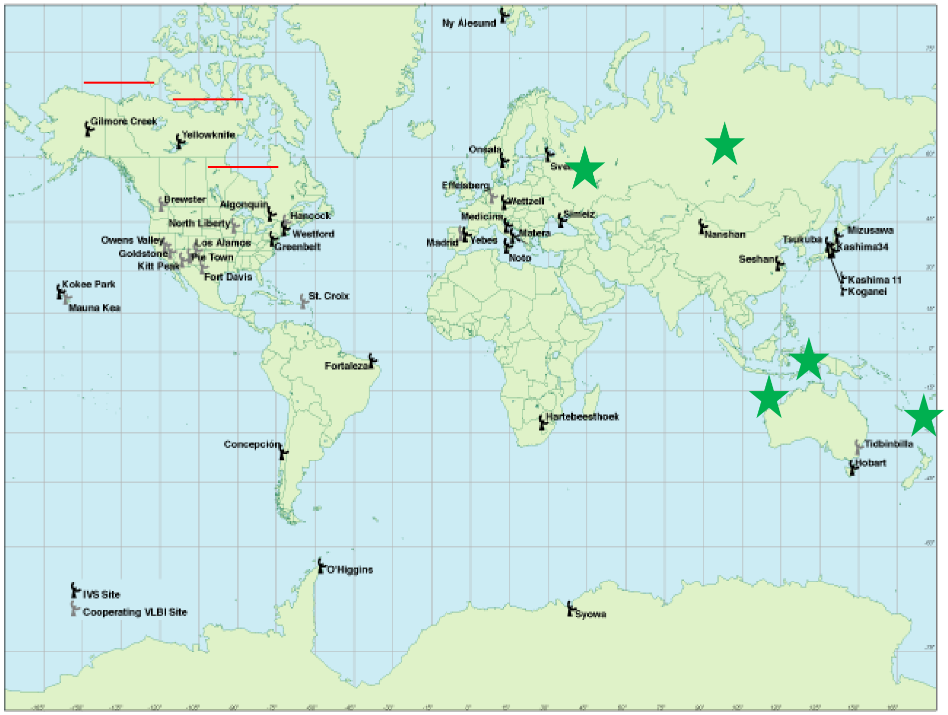
- **Long Baseline Array**
  - Only fully southern hemisphere array
- New stations:
  - 12m in N.T., Perth, Tasmania (AUscope)
  - 12m in New Zealand (north of Aukland)

- **East Asian VLBI Network**
- Chinese (CVN)
- Korean (KVN)
- Japanese (JVN)
- VERA
  - 4 dual-beam antennas optimized for maser astrometry 22—49 GHz





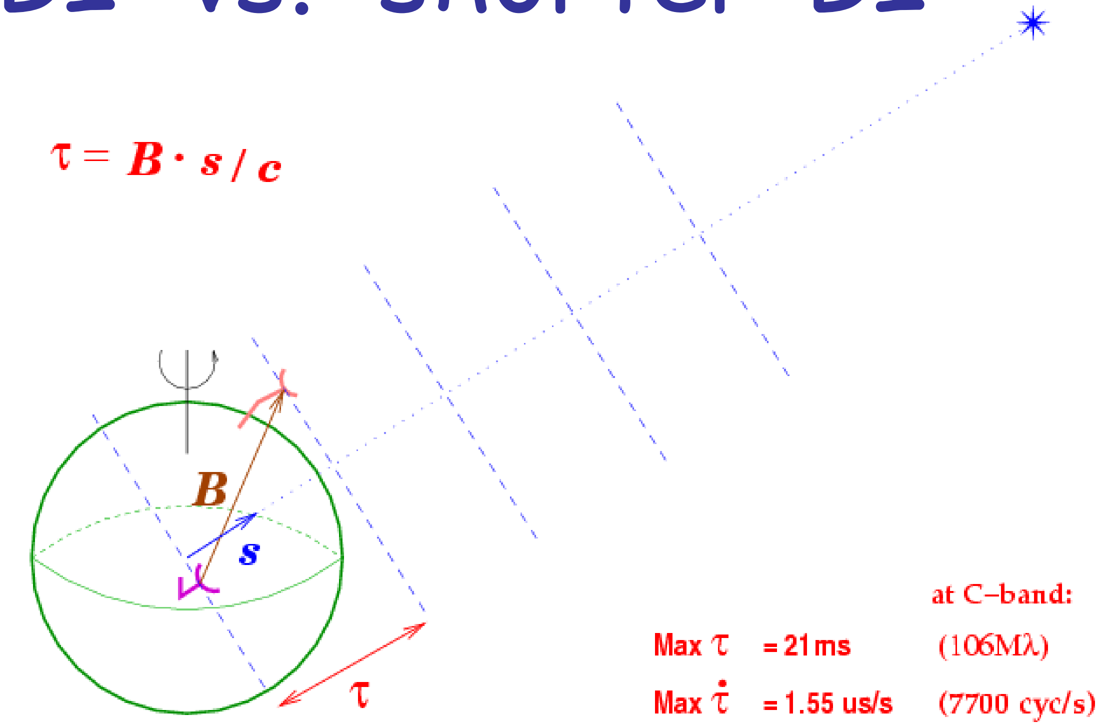
IVS (International VLBI Service)



- VLBI as space geodesy
  - cf: GPS, SLR/LLR, Doris
- Frequency: S/X
- Geodetic VLBI tactics:
  - many short scans
  - fast slews
  - uniform distribution of stations over globe

- VLBI2010: IVS plans for wide-band geodetic system
- IVS web page: **ivscc.gsfc.nasa.gov**
- History of geodetic VLBI (pre-IVS):
  - Ryan & Ma 1998, *Phys. Chem. Earth*, 23, 1041

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 at the various stations

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 $\tau(t)$ calculation: Gravitational delay, Frame choice/consistency

VLBI *a priori* Model: References

- IERS Tech.Note #36, 2010: "*IERS Conventions 2010*"
  - **www.iers.org** links thru Publications / Technical Notes
- Sovers, Fanselow, Jacobs 1998, *Rev Mod Phys*, 70, 1393
- Seidelmann & Fukushima 1992, *A&A*, 265, 833
  - Describes the various time-scales (pre- IAU 2000 resolutions)
- IAU Division A (Fundamental Astronomy; was Div.I)
  - www.iau.org/science/scientific_bodies/divisions/A/info
  - **maia.usno.navy.mil/iaudiv1/index.html**
- SOFA (software): **www.iausofa.org**
- Global Geophysical Fluids center: **geophy.uni.lu**
- Older (pre- IAU 2000 resolutions)
  - *Explanatory Supplement to the Astronomical Almanac* 1992

VLBI Delay Constituents

- Conceptual components:

$$\tau_{obs} = \tau_{geom} + \tau_{str} + \tau_{trop} + \tau_{iono} + \tau_{instr} + \varepsilon_{noise}$$

Propagation

Instrumental Effects

Source Structure

Source/Station/Earth orientation

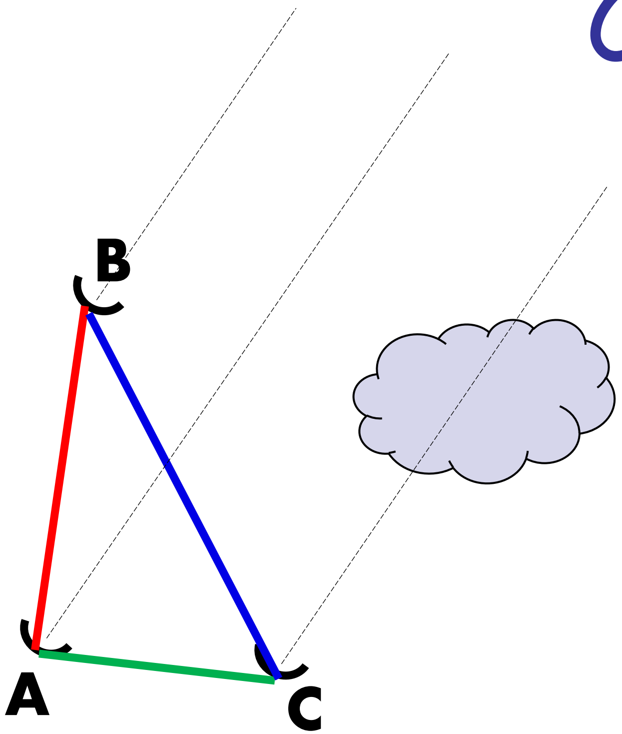
for φ: $\pm N_{lobes}$

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

where: $H(t) = GAST - \alpha$

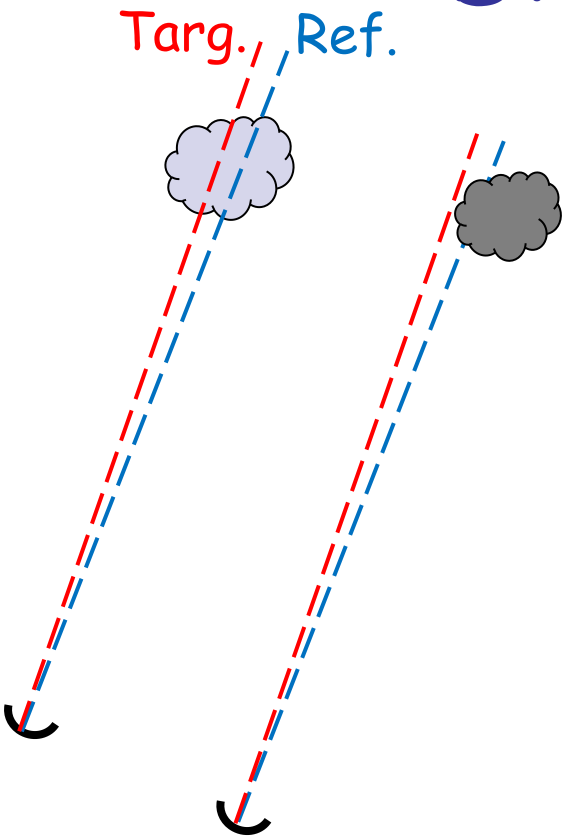
& $\vec{b}$ has been transformed into the CRF

Closure Phase



- $\varphi_{cls} = \varphi_{AB} + \varphi_{BC} + \varphi_{CA}$
- Independent of station-based $\Delta\varphi$
  - propagation
  - instrumental
- But loses absolute position info
  - degenerate to $\Delta\varphi_{geom}$ added to a given station
- However, φ_{str} is baseline-based: it does not cancel
  - Closure phase can be used to constrain source structure
  - Point source → closure phase = 0
  - Global fringe-fitting / Elliptical-Gaussian modelling
- Original ref: Rogers et al. 1974, *ApJ*, 193, 293

Difference Phase



- Another differential φ measure
  - pairs of sources from a given bsln
- (Near) cancellations:
  - propagation (time & angle between sources)
  - instrumental (time between scans)
- There remains differential:
  - φ_{str} (ideally, reference source is point-like)
  - φ_{geom} (contains the position offset between the reference and target)
- Differential astrometry on sub-mas scales:

→ Phase Referencing ←

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 ν or t)
- **In-beam reference source(s)** – no need to "nod" antennas
  - Best astrometry (e.g., Bailes et al. 1990, *Nature*, 319, 733)
  - Need for population of faint candidate ref-sources
  - VERA multi-beam technique

Where to Get Phs-Ref Sources

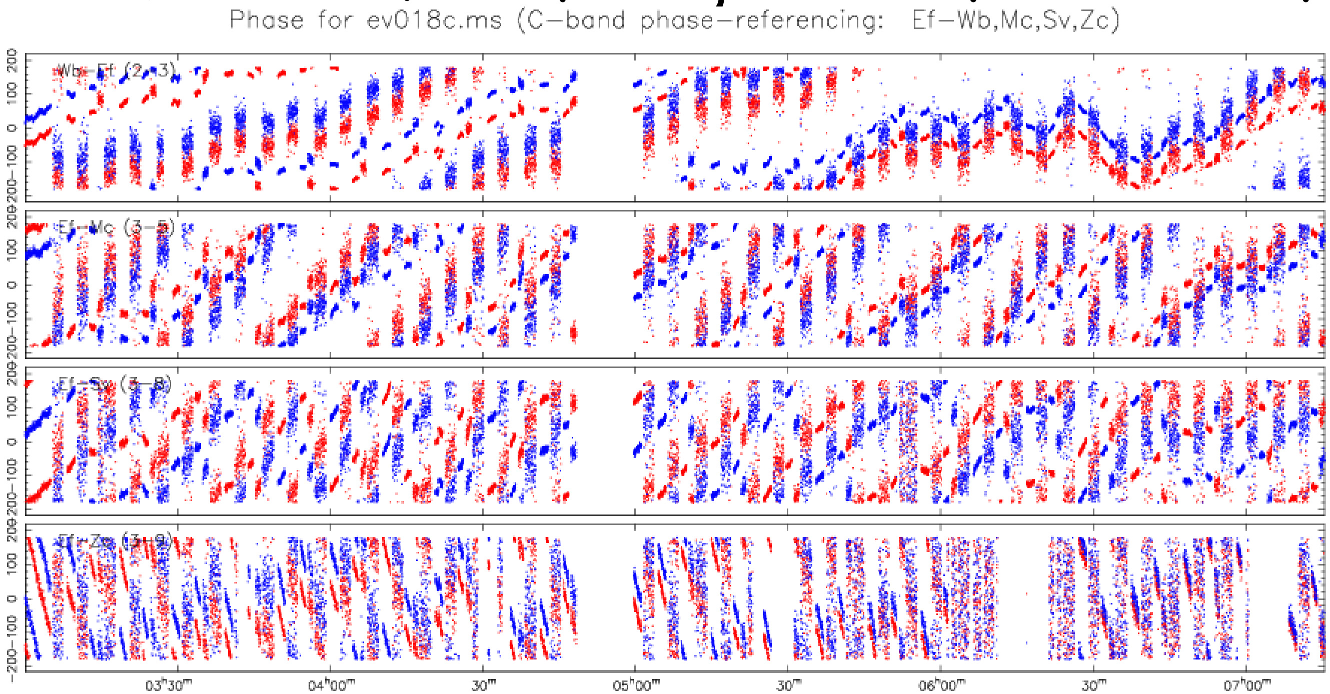
- RFC Calibrator search tool (L. Petrov)
- VLBA Calibrator search tool
  - Links to both via **www.evlbi.org**
    - VLBI links // VLBI Surveys, Sources, & Calibrators
  - List of reference sources close to specified position
  - Fluxes (S,X) on short/long bsln; Images, Amp(|*u-v*|)
- Multiple reference 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
  - 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 → 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: *"2nd Realization of ICRF by VLBI"*
  - 295 defining sources (axes constraint); 3414 sources overall
  - Median σ_{pos} ~ 100-175 μas (floor ~40 μas); axis stability ~10 μas
  - More emphasis put on source stability & structure

Faint-Source Mapping

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

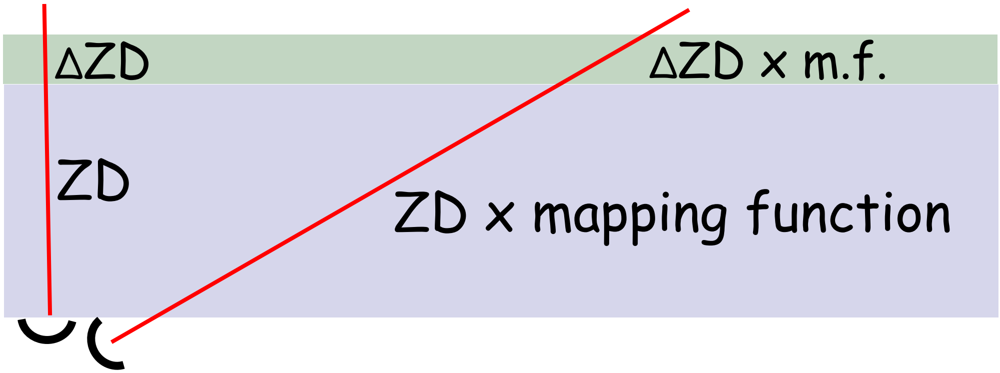


- Increasing useful coherent integration time to whole obs.
  - Beasley & Conway 1995, *VLBI and the VLBA*, Ch 17, p.327
  - Alef 1989, *VLBI Techniques & Applications*, p.261

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, η_e)
  - PSRPI: **safe.nrao.edu/vlba/psrpi**
- Stellar systems: magnetically active binaries, exo-planets
  - RIPL: **astro.berkeley.edu/~gbower/RIPL**
- PPN γ parameter: Lambert et al. 2009, *A&A*, 499, 331
- IAU Symp #248, 2007/8: *"From mas to μas Astrometry"*

Phs-Ref Limitations: Troposphere



- Saastamoinen Zenith Delay [m] (catmm.f)

$$\text{Dry}: \quad \frac{0.0022768 P_{\text{mbar}}}{1 - 0.00266 \cos 2\phi - 0.00028 h_{\text{km}}}$$

$$\text{Wet}: \quad 0.002277 \left(\frac{1255}{T_c + 273.16} + 0.05 \right) \times RH \times 6.11 \exp\left(\frac{17.269 T_c}{T_c + 237.3} \right)$$

thus:

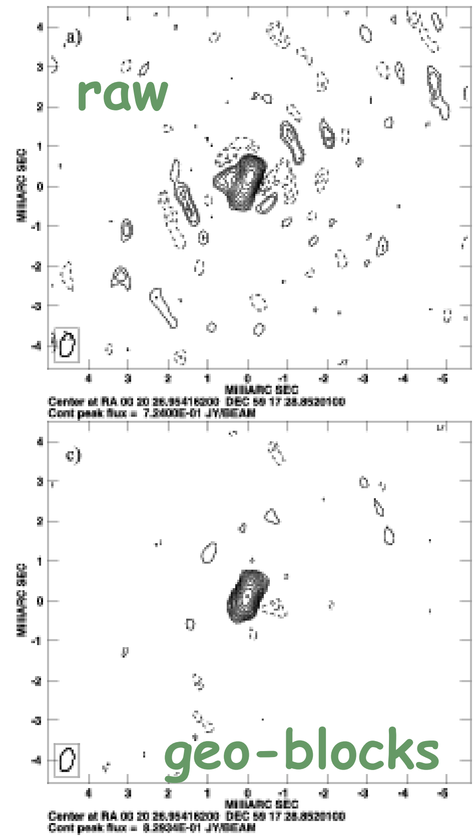
$$ZD_{\text{dry}} = ZD_d(P, \phi, h)$$
$$ZD_{\text{wet}} = ZD_w(T, RH)$$

- Station ΔZD → elevation-dependent Δφ
  - Dry ZD ~ 7.5ns (~37.5 cycles of phase at C-band)
  - Wet ZD ~ 0.3ns (0.1—1ns) 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 (v ≥ 9.4): GEOSEG as scan-based parameter
  - other control parameters
  - `egdelzn.key` in examples
- AIPS
  - DELZN & CLCOR/opcode=atmo
  - AIPS memo #110

Brunthaler, Reid, & Falcke 2005, in *Future Directions in High-Resolution Astronomy (VLBA 10th anniv.)*, p.455: "Atmosphere-corrected phase-referencing"



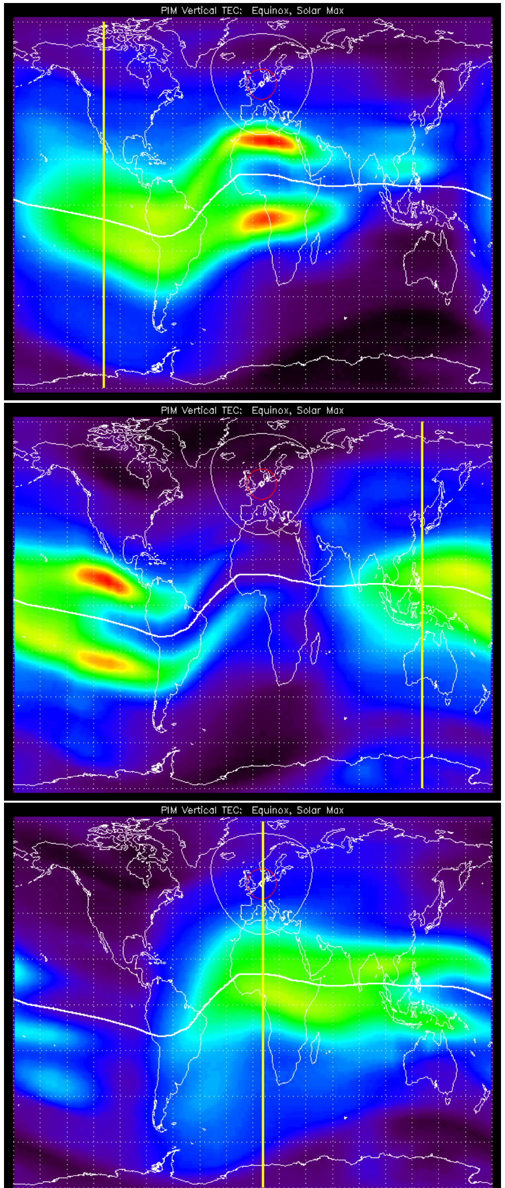
- Numerical weather models & ray-tracing

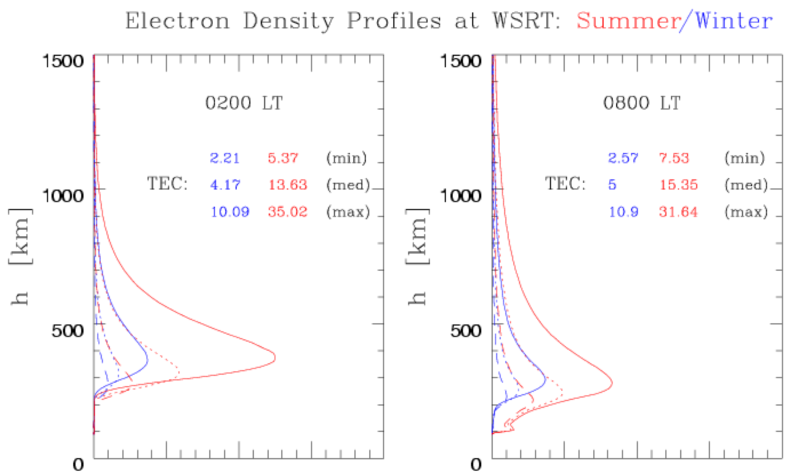
Phs-Ref Limitations: Ionosphere

1930

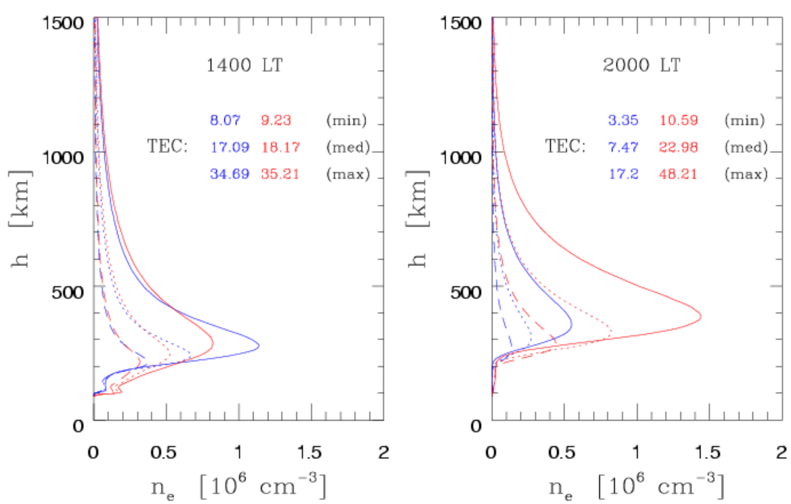
0330

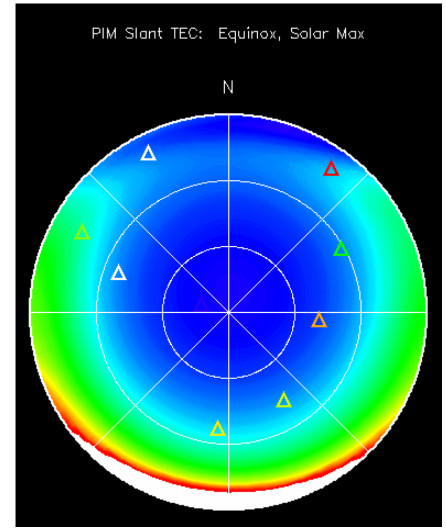
1130

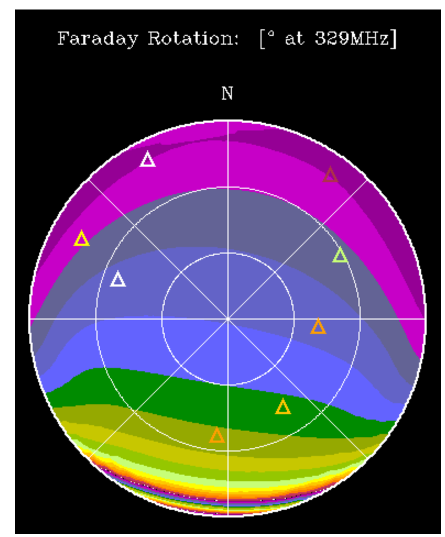


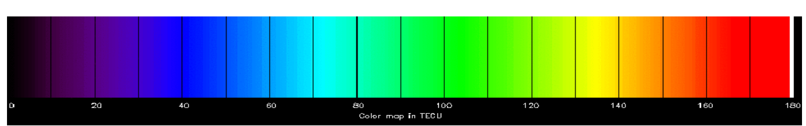


$$1\ \text{TECU} = 1.34/\nu_{[GHz]}\ \text{cycles}$$



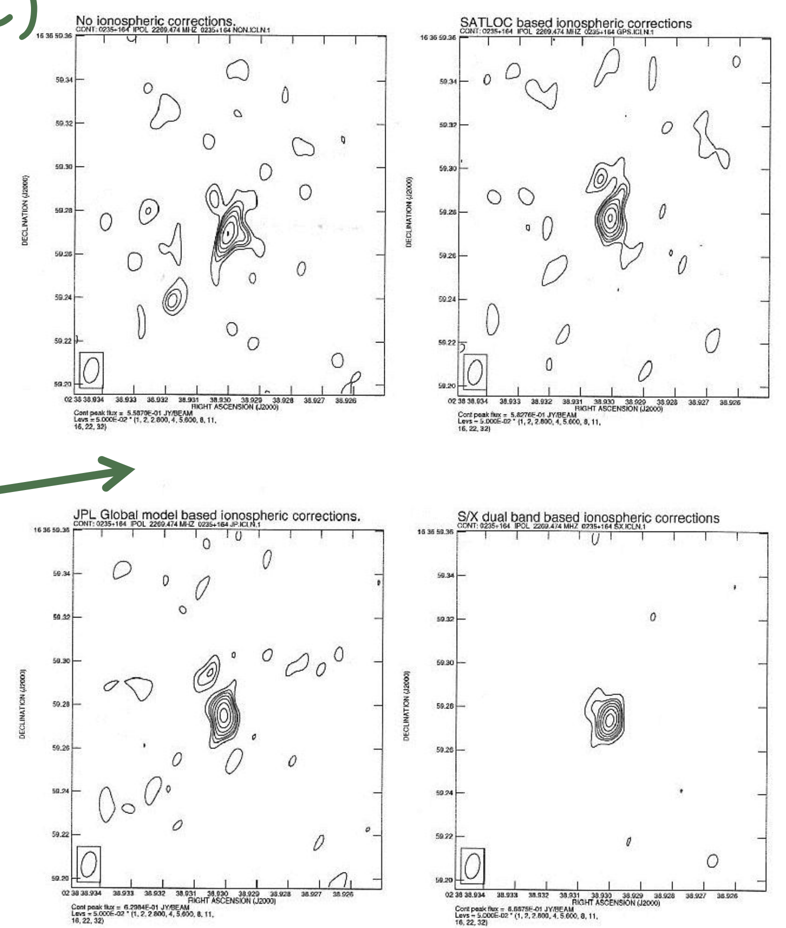




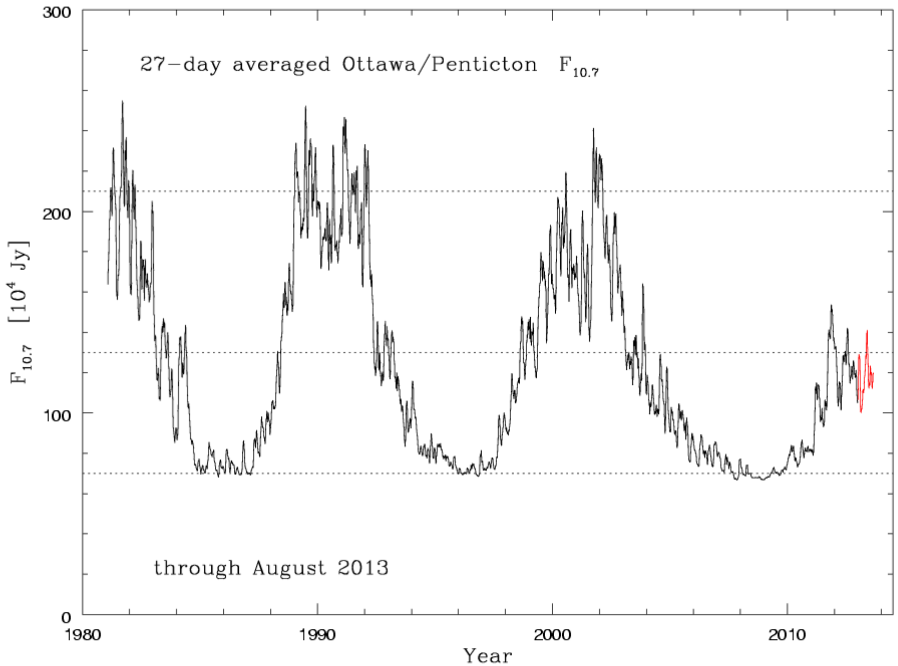


Ionosphere Mitigation

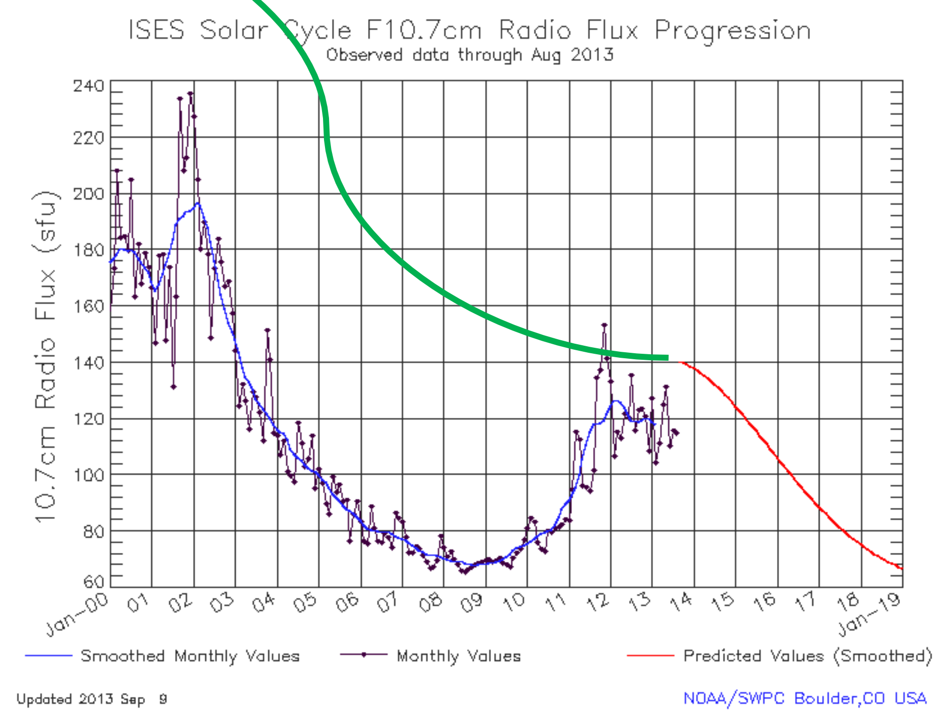
- Dispersive delay → inverse quadratic dependence τ vs. ν
  - Dual-frequency (S/X) or widely-separated SBs (W. Brisken thesis)
- IGS IONEX maps (gridded vTEC)
  - **igscb.jpl.nasa.gov**
  - 5° long. x 2.5° lat., every 2 hr
  - h = 450km // σ ~ 2-8TECU
  - Based on ≥150 GPS stations
  - 5 analysis centers + an IGS solution
- AIPS: TECOR
  - VLBI science memo #23
- From raw GPS data:
  - Ros et al. 2000, *A&A*, 356, 375
- Incorporation of profile info?
  - Ionosondes, GPS/LEO occultations



Ionosphere: Climatology



The past few solar cycles: solar 10.7cm flux density



Prediction for rest of solar cycle: ≤ solar-"medium"

Wide-field Mapping: FoV limits

- Residual delay, rate → slopes in phase vs. freq, time
  - Delay = ∂φ/∂ω (i.e., via Fourier transform shift theorem)
  - Rate = ∂φ/∂t
- Delay, rate = functions 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:
  - $\tau(\alpha,\delta) = \tau(\alpha_0,\delta_0) + \Delta\alpha\,(\partial\tau/\partial\alpha) + \Delta\delta\,(\partial\tau/\partial\delta)$
- Which leads to residual delays & rates across the field, increasing away from the phase center.
- Which lead 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:

$$FoV_{\rm BW} \lesssim \frac{49''\!.5\, N_{\rm frq}}{B_{\rm 1000km} \cdot BW_{\rm SB_{MHz}}} \qquad FoV_{\rm time} \lesssim \frac{18''\!.5\, \lambda_{\rm cm}}{B_{\rm 1000km} \cdot t_{\rm int}}$$

  - 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 $N_{frq} \times N_{int}$
  - Record for single observation correlated at JIVE = 1028.7 GB
  - Record for multi-epoch experiment corr. at JIVE = 2149.9 GB

WFM: Software Correlation

- Software correlators can use almost unlimited N_{frq} & t_{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-ref)
  - Tile the full field into easier-to-eat chunks
- As FoV grows, need looms for primary-beam corrections
  - EVN has stations ranging from 20 to 100 m

Space: Orbiting Antennas

- Longer baselines
  - Match resolutions from L-band (space) & C-band (earth)
- HALCA: Feb'97 — Nov'05
  - Orbit: r = 12k—27k km; P = 6.3 hr; i = 31°
- RadioAstron: launched 18 July
  - Orbit: r = 10-70k km — 310-390k km; P ~ 9.5d; i = 51.6°
  - **www.asc.rssi.ru/radioastron**
- Model/correlation issues:
  - Satellite position/velocity; proper vs. coordinate time

Space: Solar System Targets

- Model variations
  - Near field / curved wavefront; may bypass some outer planets
  - *e.g.*, Sekido & Fukushima 2006, *J. Geodesy*, 80, 137
    Duev *et al.* 2012, *A&A*, 541, 43
- Science applications
  - Planetary probes (atmospheres, mass distribution, *etc.*)
    - Huygens (2005 descent onto Titan), Venus/Mars explorers, BepiColombo (Mercury)
  - Tests of GR (PPN γ, $\dot{G}$, deviations from inverse-square law)
    - IAU Symp #261, 2009/10: *"Relavitivity in Fundamental Astronomy"*
  - Frame ties (ecliptic within ICRS)

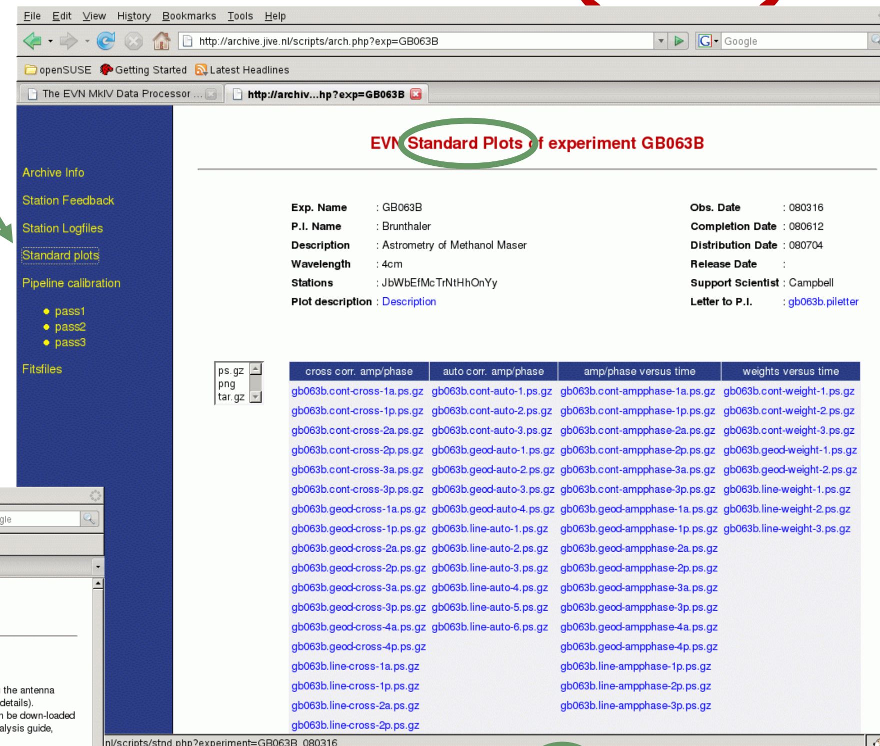
Future

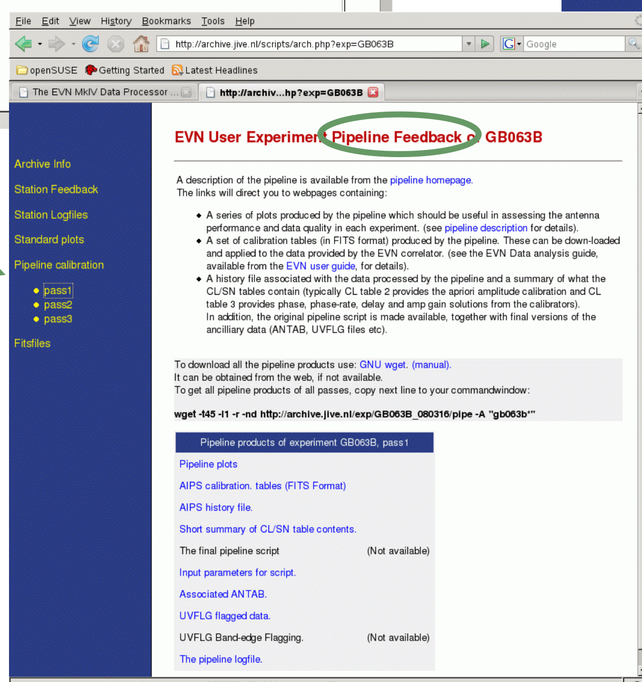
- Digital back-ends
  - Higher total bit-rates (higher sensitivity)
  - More flexible frequency configurations
  - Better *a priori* phase calibration across subbands
- Growing exploitation of software correlation
  - Much better temporal/spectral resolutions
  - More special-purpose correlation modes / features
- More stations: better sensitivity, *u-v* coverage
- Continuing maturation of real-time e-VLBI
  - Transparency and responsiveness from users' PoV
  - Better coordination into multi-λ campaigns

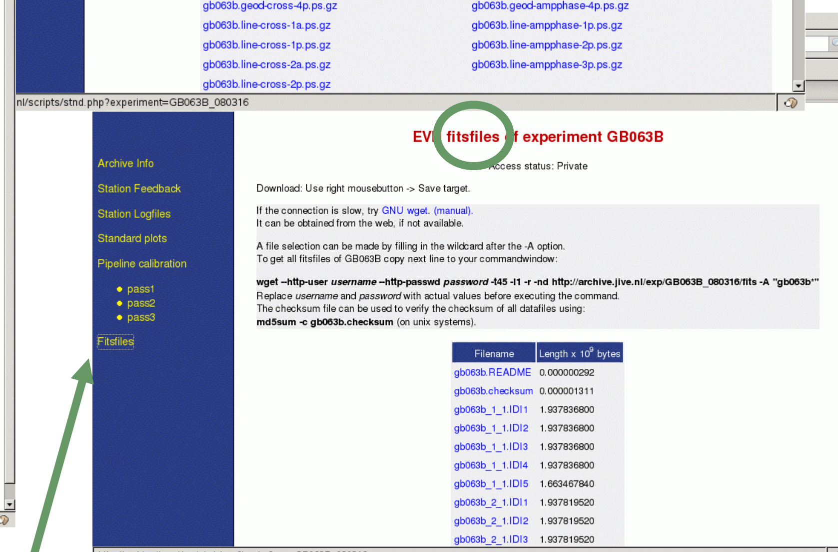
Concepts for the VLBI Tutorial

- 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.
- Pre-imaging processing steps
  - Data inspection
  - Amplitude calibration
  - Delay / rate / phase calibration
  - Bandpass calibration
- **ParselTongue wiki:**
  - www.jive.nl/jivewiki/doku.php?id=parseltongue:parseltongue

EVN Archive (old)







FITS,
Pypeline,
Plots,
Feedback

New Archive Pypeline Entry

www.jive.nl/pipeline?experiment=EJ010_120313&pass=ej010

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- e-VLBI
- Operations
- Software
- Status

EVN Data Archive
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- Archive introduction
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- JIVE projects
- RadioNet

Pipeline

Info | Feedback | Logfiles | Standard plots | Pipeline | Fitsfiles

EVN User Experiment Pipeline Feedback of EJ010

A description of the pipeline is available from the pipeline homepage.
The links will direct you to webpages containing:

- A series of plots produced by the pipeline which should be useful in assessing the antenna performance and data quality in each experiment. (see pipeline description for details).
- A set of calibration tables (in FITS format) produced by the pipeline. These can be down-loaded and applied to the data provided by the EVN correlator. (see the EVN Data analysis guide, available from the EVN user guide, for details).
- A history file associated with the data processed by the pipeline and a summary of what the CL/SN tables contain (typically CL table 2 provides the apriori amplitude calibration and CL table 3 provides phase, phase-rate, delay and amp gain solutions from the calibrators).
- The parseltongue pipeline script can be found here.
- In addition, the original pipeline script is made available, together with final versions of the ancilliary data (ANTAB, UVFLG files etc).

To download all the pipeline products use: GNU wget. (manual).
It can be obtained from the web, if not available.
To get all pipeline products, copy next line to your commandwindow:
wget --http-user *username* --http-passwd *password* -t45 -l2 -r -nd http://archive.jive.nl/exp/EJ010_120313/pipe -A "ej010*" -k
Replace *username* and *password* with actual values before executing the command.

Pipeline products of experiment EJ010	
Pipeline plots	
AIPS calibration tables (FITS Format)	
AIPS history file.	
Short summary of CL/SN table contents.	
Input parameters for script.	
Associated EVN calibration.	
Associated VLBA / VLA / GBT file.	(Not available)
UVFLG flagged data.	
UVFLG Band-edge Flagging.	
The pipeline logfile.	
Pipeline-calibrated UV FITS files.	

Pypeline Outputs (downloads)

- Plots; input run-control file; pypelog; AIPS history
- Prepared ANTAB file (amplitude calibration input)
- Flagging file(s) used (time-ranges, channels)
- AIPS tables
  - CL1 = "unity", 15s sampling
  - SN1 = TY ⊕ GC; CL2 = CL1 ⊗ SN1 (& parallactic angles)
  - FG1 (sums over all input flagging files)
  - SN2 = FG1 ⊕ fring; CL3 = CL2 ⊗ SN2
  - BP1 = computed after CL3 ⊕ FG1
- Pypleline-calibrated UVFITS (per source)

Data Familiarizaton

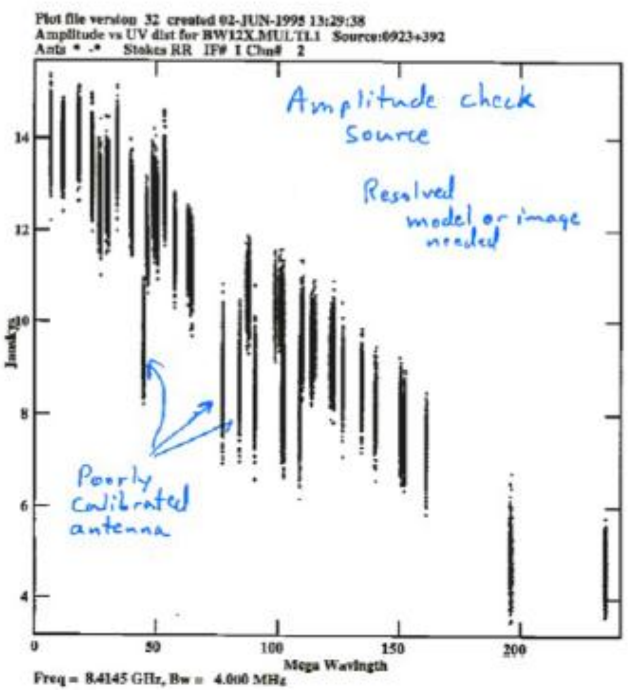
- FITLD, MSORT, INDXR
  - Loading data, sorting, prep calibration table
- LISTR — scan-based summary of observations
- PRTAB, PRTAN, TBOUT
  - Looking into table contents
- POSSM, VPLOT, UVPLT
  - Plots: vs. frequency, vs. time, u-v based
- SNPLT
  - Plot solution/calibration tables (various x-axes)

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 = Tsys(t) / {DPFU * g(z)}
  - $\sqrt{\{SEFD_1 * SEFD_2\}}$ as basis to convert from unitless correlation coefficients to flux-densities [Jy]
- Pypeline 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-chain, BBCs
  - Differing delays & rates per station/subband/pol
- Delay → $\partial\varphi/\partial\omega$ (phase-slope across band)
- Rate → $\partial\varphi/\partial t$ (phase-slope vs.time)
- Point-source = flat $\varphi(\omega,t)$
  - Regular variations: clocks, source-structure, etc.
  - Irregular variations: propagation, instrumental noise
  - φ_{str} doesn't necessarily close (not station-based)

Fringe-fitting

- Over short intervals (SOLINT), estimates 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(ω)]
- 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:

a view through the dim mists of a Jungian collective unconcious?

More careful Monte Carlo simulations reveal an altogether different post-ERIS paradigm: