# VLBI Techniques

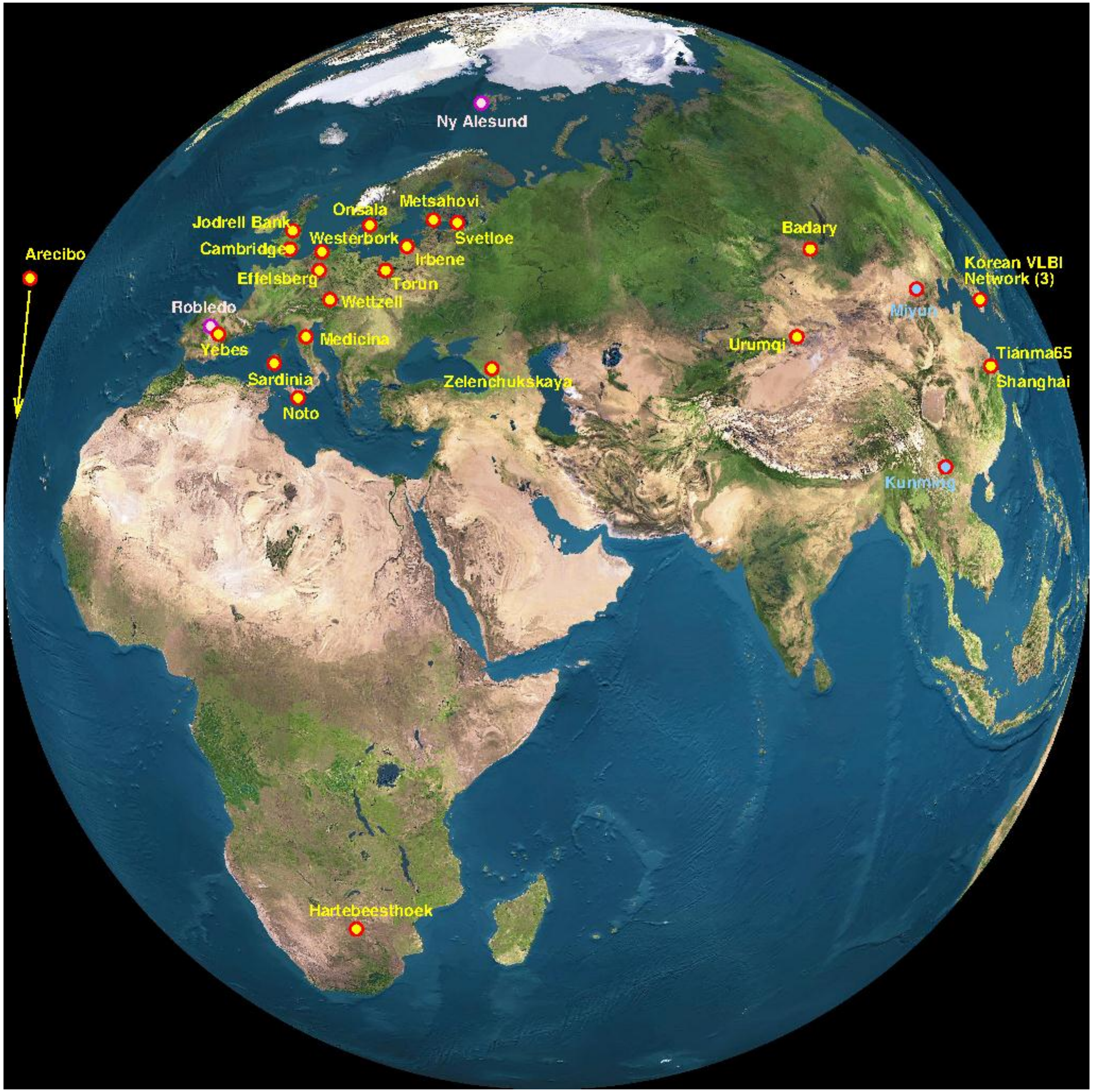
Bob Campbell, JIVE

- 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



RadioNet has received funding from the European Commission's Horizon 2020 Research and Innovation Programme under grant agreement No, 730562.

# The EVN



Ny Alesund
Jodrell Bank
Onsala
Metsahovi
Westerbork
Svetloe
Cambridge
Irbene
Effelsberg
Torun
Wettzell
Arecibo
Robledo
Yebes
Medicina
Sardinia
Noto
Zelenchukskaya
Badary
Korean VLBI Network (3)
Miyun
Urumqi
Tianma65
Shanghai
Kunming
Hartebeesthoek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# The EVN (European VLBI Network)

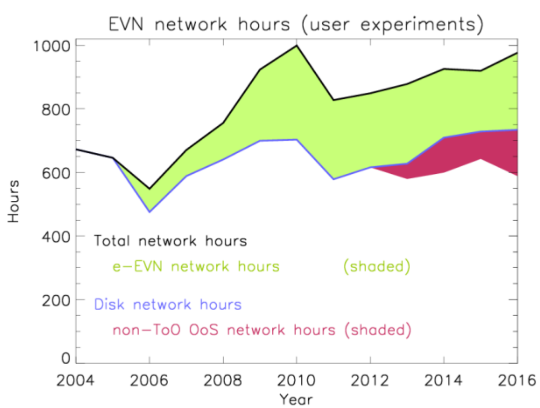
- Composed of existing antennas
  - generally larger (32m – 100m): more sensitive
  - baselines up to 10k km (8k km from Ef to Shanghai, S.Africa)
  - down to 17 km (with Jb-Da baseline from eMERLIN)
  - heterogeneous, generally slower slewing
- Frequency coverage [GHz]:
  - workhorses: 1.4/1.6, 5, 6.0/6.7,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

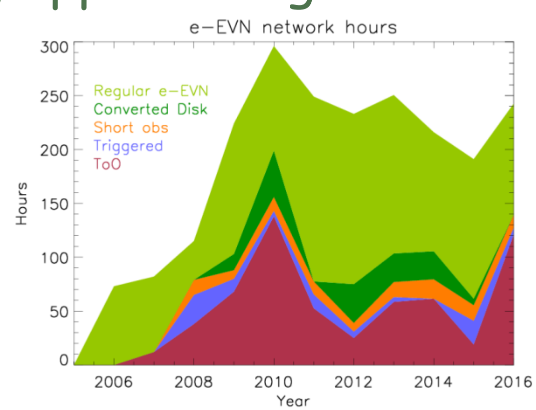
# EVN Links

- Main EVN web page: **www.evlbi.org**
  - **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**
- User Support via JIVE (Joint Institute for VLBI ERIC)
  - **www.jive.eu**
  - 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*

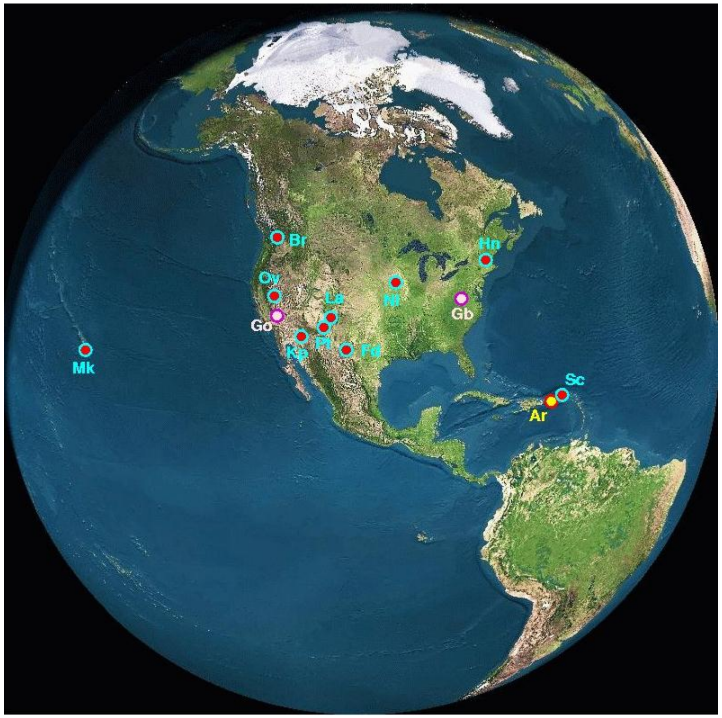
# Real-time e-VLBI with the EVN

- 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; 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
  - Recorded e- and/or e-shipping approaching best of both worlds



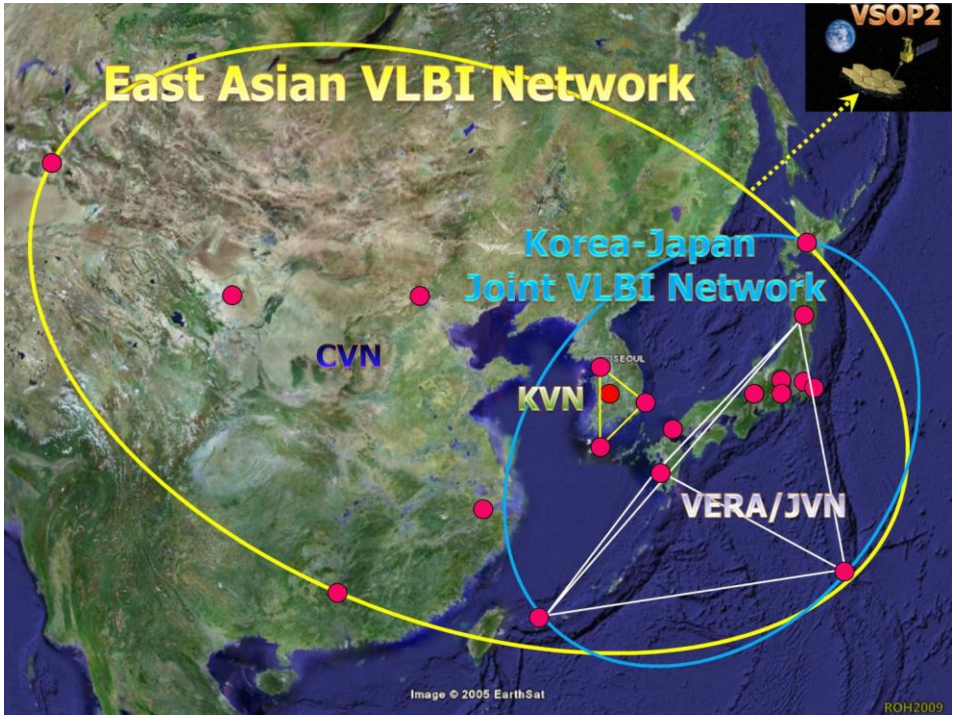
# The VLBA (Very Long Baseline Array)

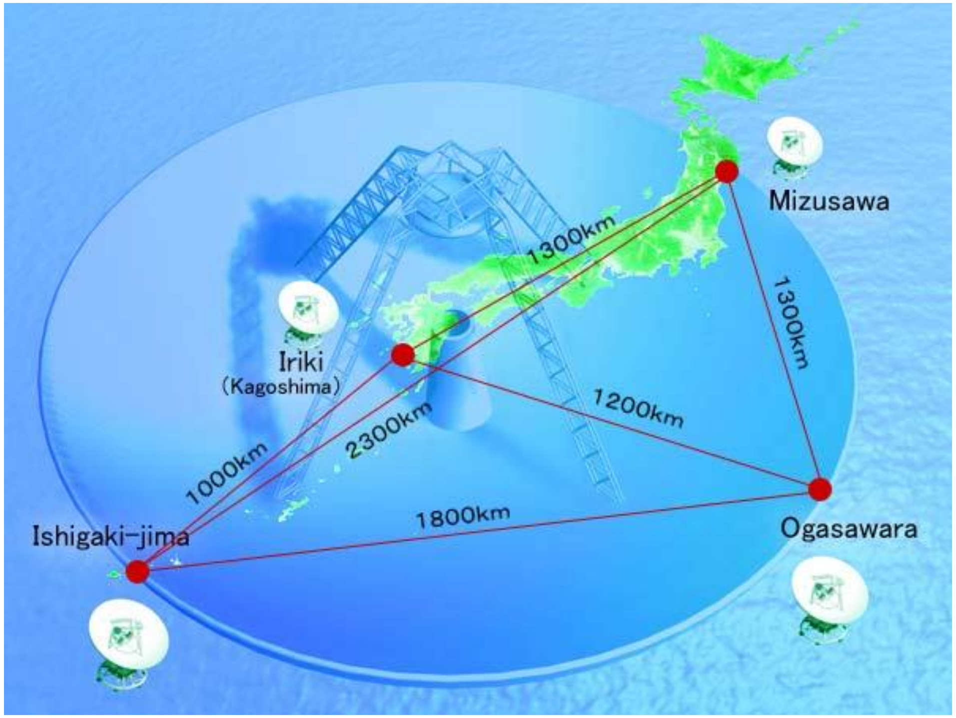



- Homogeneous array (10x 25m)
  - planned locations, dedicated array
  - Bslns ~8600-250 km (~50 w/ JVLA)
  - faster slewing
  - HSA (+ Ef + Ar + GBT + JVLA)
- Frequency agile
  - down to 0.329, up to 86 GHz
- Extremely large proposals
  - Up towards 1000 hr per year
- Globals: EVN + VLBA (+ GBT + JVLA)
  - proposed at EVN proposal deadlines (1Feb, 1Jun, 1Oct)
  - VLBA-only proposals: 1Feb, 1Aug
- VLBA URL: `science.lbo.us`

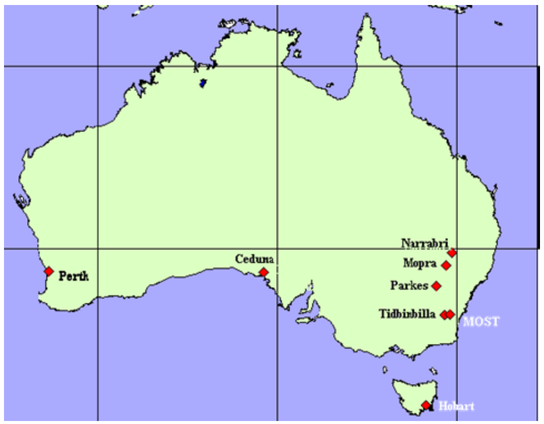
# East Asian VLBI Networks

- 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 (issues separate KaVA calls for proposals)
- Japanese: various astronomical & geodetic stations



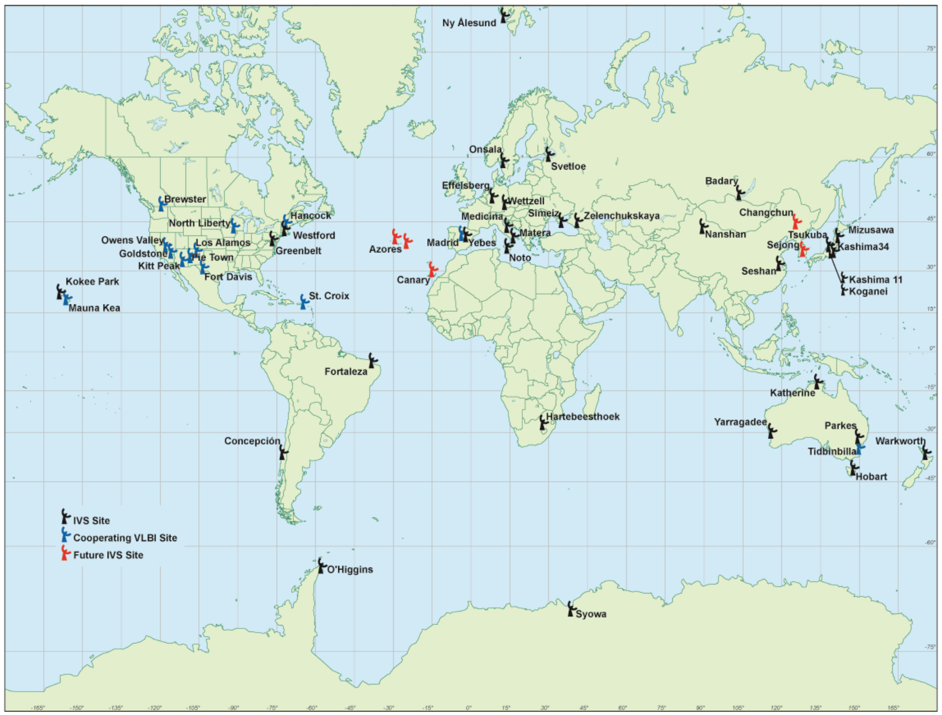
# Other Astronomical VLBI Arrays




- **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 (LMT, ALMA)
- 86 GHz
- ~2 weeks of observing per year
- Coordinated from MPIfR Bonn

# IVS (International VLBI Service)



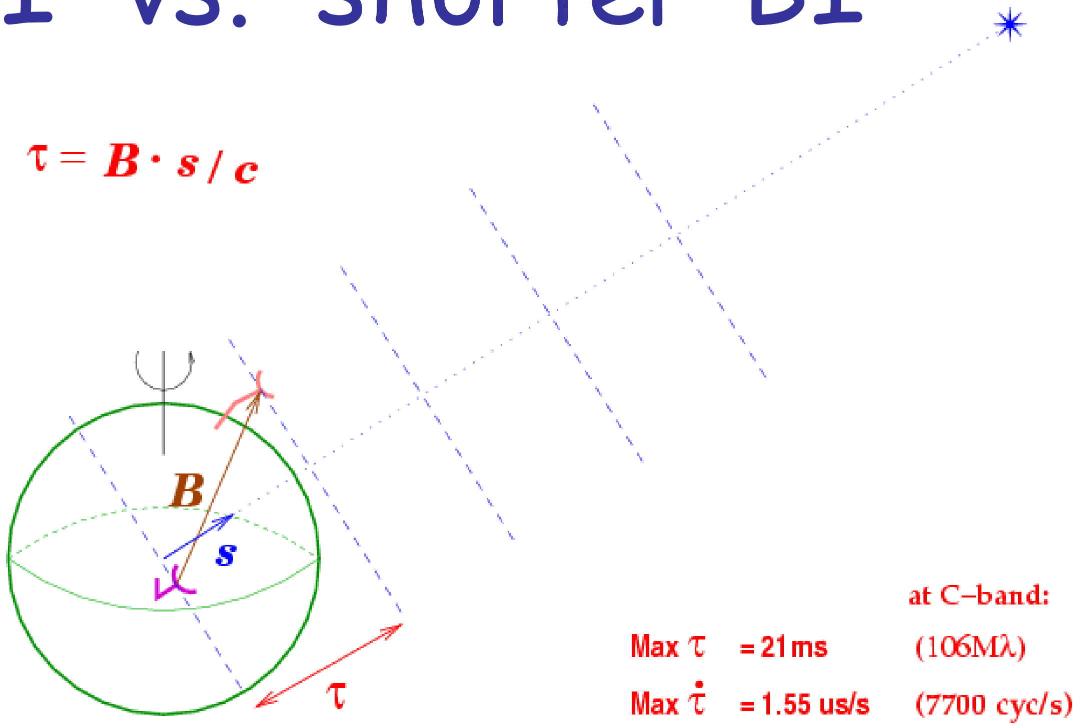

- VLBI as space geodesy
  - cf: GPS, SLR/LLR, Doris
- Frequency: 2.3 & 8-9
  some at 8-9 & 27-34
- Geodetic VLBI tactics:
  - many short scans
  - fast slews
  - uniform distribution of stations over globe
- VGOS: wide-band geodetic system (4x 2GHz over 2-14 GHz)
- IVS web page: **ivscc.gsfc.nasa.gov**
  - Mirror: **ivscc.bkg.bund.de**
- History of geodetic VLBI (pre-IVS):
  - Ryan & Ma 1998, *Phys. Chem. Earth*, 23, 1041

# 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 $D_M(z)$ → $\mu$ to $\beta_{app}$ conversion
  - $D_A$ turns over with z (max z~1.6), $D_M$ doesn't
- Brief table, using Planck 2015 cosmology parameters
  (from J.P. Rachen colloquium, Dwingeloo 11jun2015)

| z | 1 mas subtends $\{D_A\}$ | $\beta_{app}$ for 0.1 mas/yr $\{D_M\}$ |
|---|---|---|
| 0.1 | 1.8 pc | 0.66 c |
| 0.5 | 6.4 pc | 3.1 c |
| 1 | 8.3 pc | 5.4 c |
| 1.6 | 8.4 pc | 7.4 c |
| 3 | 8.0 pc | 10.3 c |

# 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

# 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** link via Publications // Technical Notes
- Urban & Seidelmann (Eds.) 2013, *Explanatory Supplement to the Astronomical Almanac (3rd Ed.)*
- IAU Division A (Fundamental Astronomy; was Div.I)
  - **www.iau.org/science/scientific_bodies/divisions/A/info**
- SOFA (software): **www.iausofa.org**
- Global Geophysical Fluids center: **geophy.uni.lu**
- Older (pre- IAU 2000 resolutions):
  - *Explanatory Supplement to the Astronomical Almanac* 1992
  - Seidelmann & Fukushima 1992, *A&A*, 265, 833 (time-scales)
  - Sovers, Fanselow, Jacobs 1998, *Rev Mod Phys*, 70, 1393

# VLBI Delay (Phase) 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

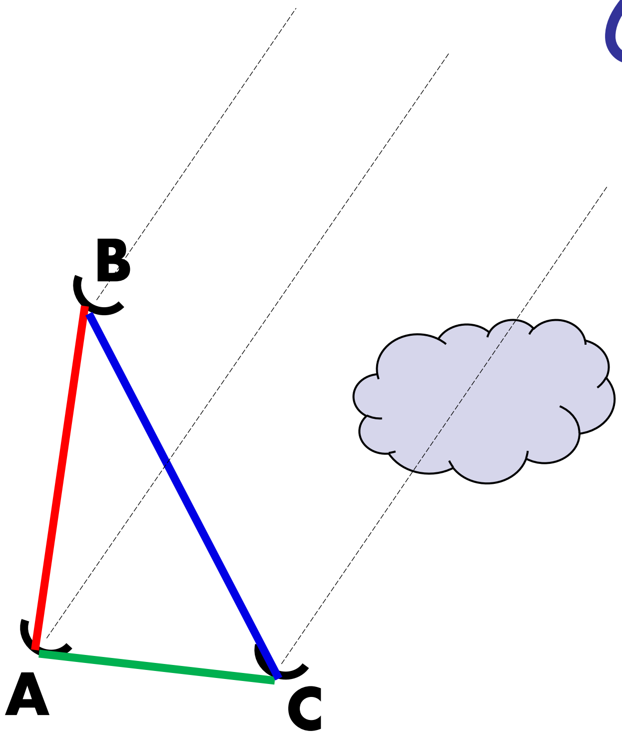
$$\tau_{geom} = -[\cos\delta\,\{b_x \cos H(t) - b_y \sin H(t)\} + b_z \sin\delta] / c$$

where: $H(t) = GAST - R.A.$

and of course: $\varphi = 2\pi\omega\tau_p$

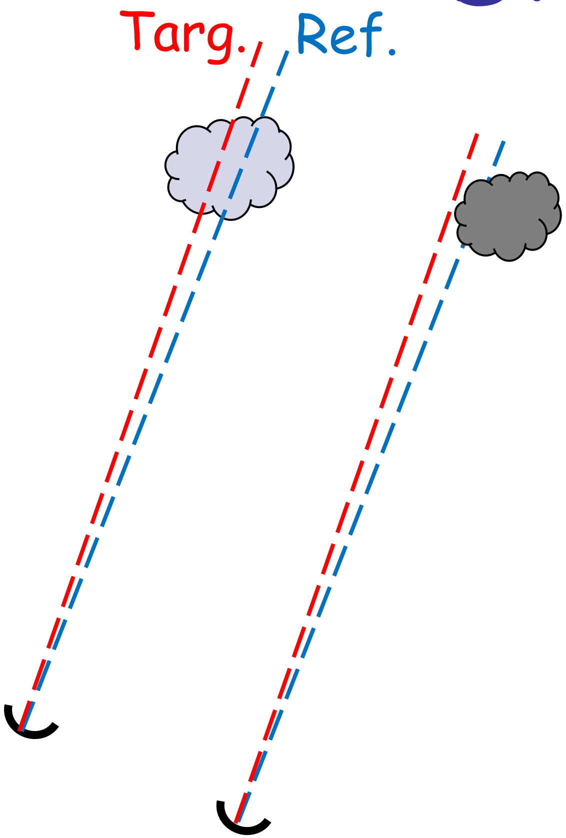
for $\varphi_{obs}$: $\pm N_{lobes}$

# 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 an arbitrary $\Delta\varphi_{geom}$ added to a given station
- However, $\varphi_{str}$ 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:
  - $\delta\varphi_{str}$ (ideally, reference source is point-like)
  - $\delta\varphi_{geom}$ (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 referenced to 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 $\nu$ 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

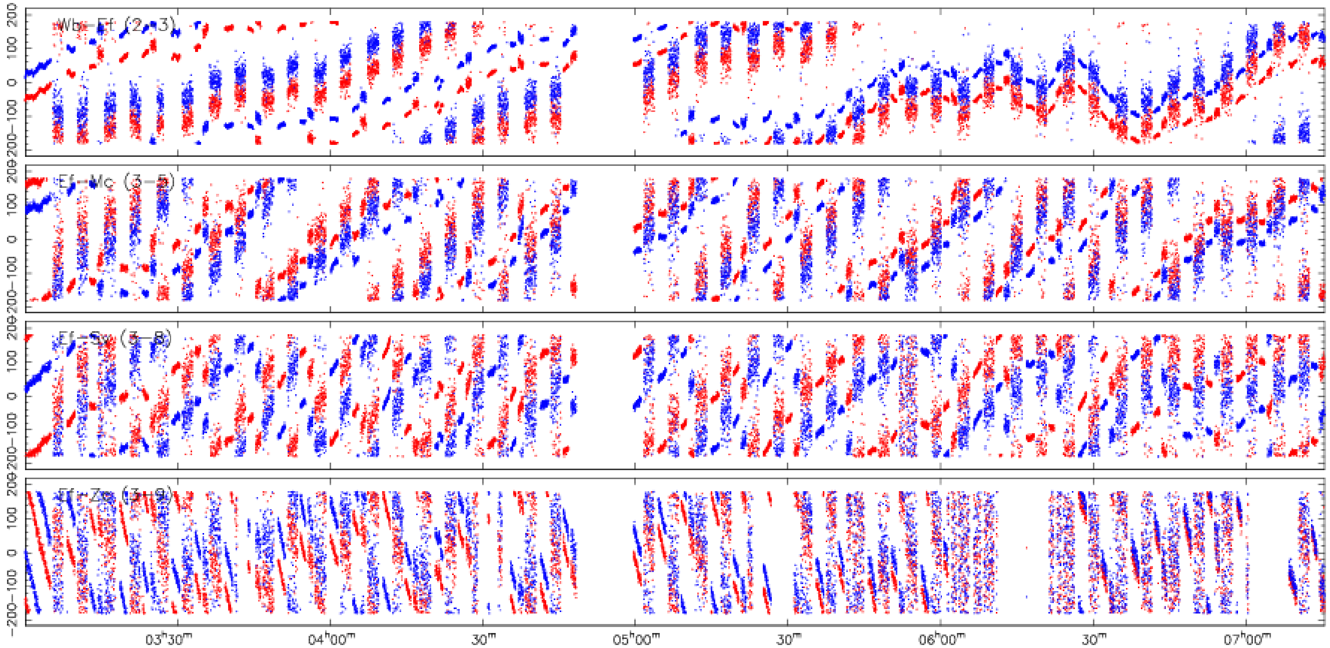
- RFC Calibrator search tool (L. Petrov)
- VLBA Calibrator search tool
  - Links to both via **www.evlbi.org**
    - under: VLBI links // VLBI Surveys, Sources, & Calibrators
  - List of reference sources close to specified position
  - FD (2 bands) on short & long |B|; Images, Amp(|*u-v*|)
- Multiple 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
  - 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 → 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 $\sigma_{pos}$ ~ 100-175 μas (floor ~40 μas); axis stability ~10 μas
  - 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

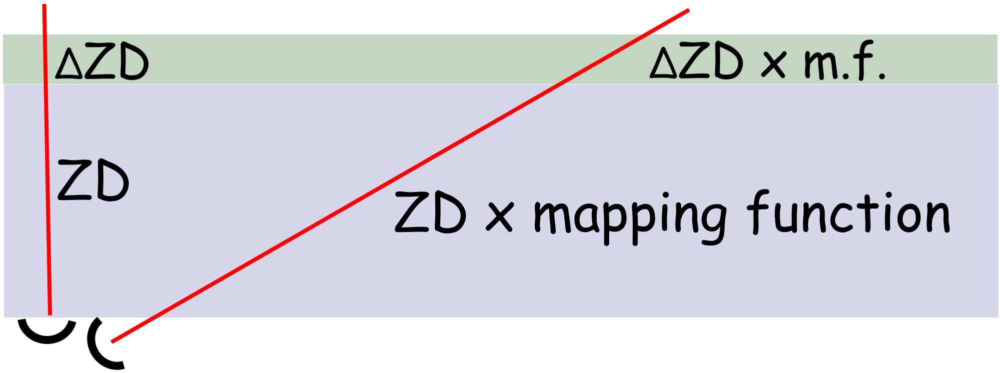



- Increasing coherent integration time to whole observation
  - Beasley & Conway 1995, *VLBI and the VLBA*, Ch 17, p.327
  - Alef 1989, *VLBI Techniques & Applications*, p.261

# 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, $n_e$)
  - PSRPI: **safe.nrao.edu/vlba/psrpi**
- Stellar systems: magnetically active binaries, exo-planets
- PPN $\gamma$ parameter: Lambert et al. 2009, *A&A*, 499, 331
- Frame dragging (GP-B): Lebach et al. 2012, *ApJS*, 201, 4
- IAU Symp #248: *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:

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

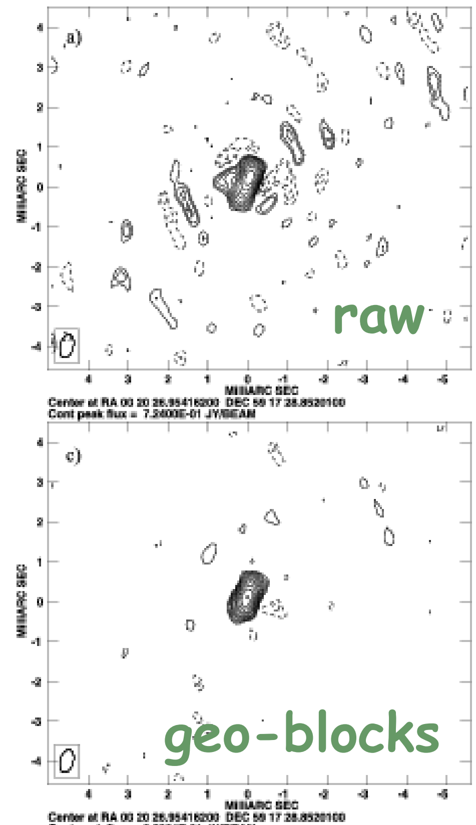
- Station ΔZD → elevation-dependent Δφ
  - Dry ZD ~ 7.5ns (~37.5 cycles of phase at C-band)
  - Wet ZD ~ 0.3ns (0.1—1ns) but high spatial/temporal variability
- Water-vapor radiometers to measure precipitable water along the antenna's pointing direction

# Troposphere Mitigation

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

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
  - **ggosatm.hg.tuwien.ac.at/proj-ggosatm.html**
  - **astrogeo.org/spd**



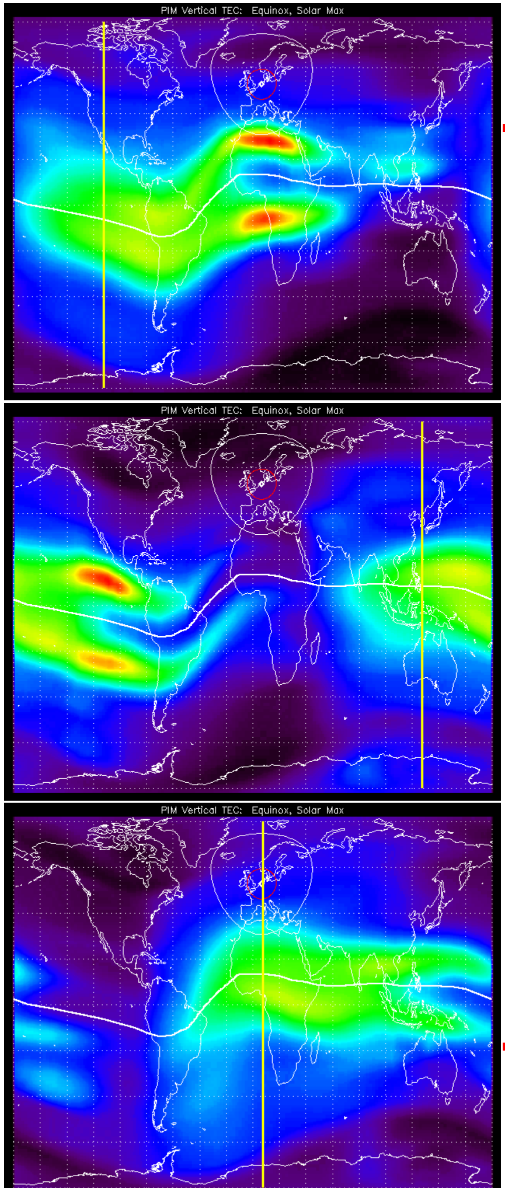
Animation removed: 1 of 2

# Phs-Ref Limitations: Ionosphere

1930

0330

1130

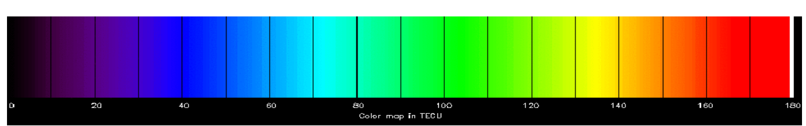



USAF
PIM model
run for
solar max

**1 TECU = 1.34/$\nu_{[GHz]}$ cycles of $\varphi$**

TEC color-map scaling:

30 75 135 180



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# Phs-Ref Limitations: Ionosphere

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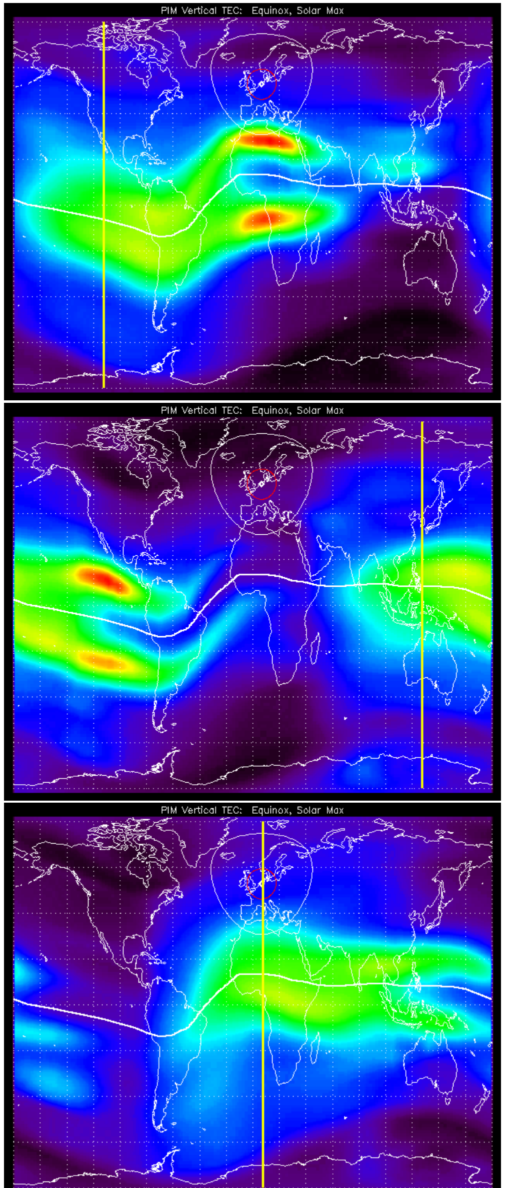
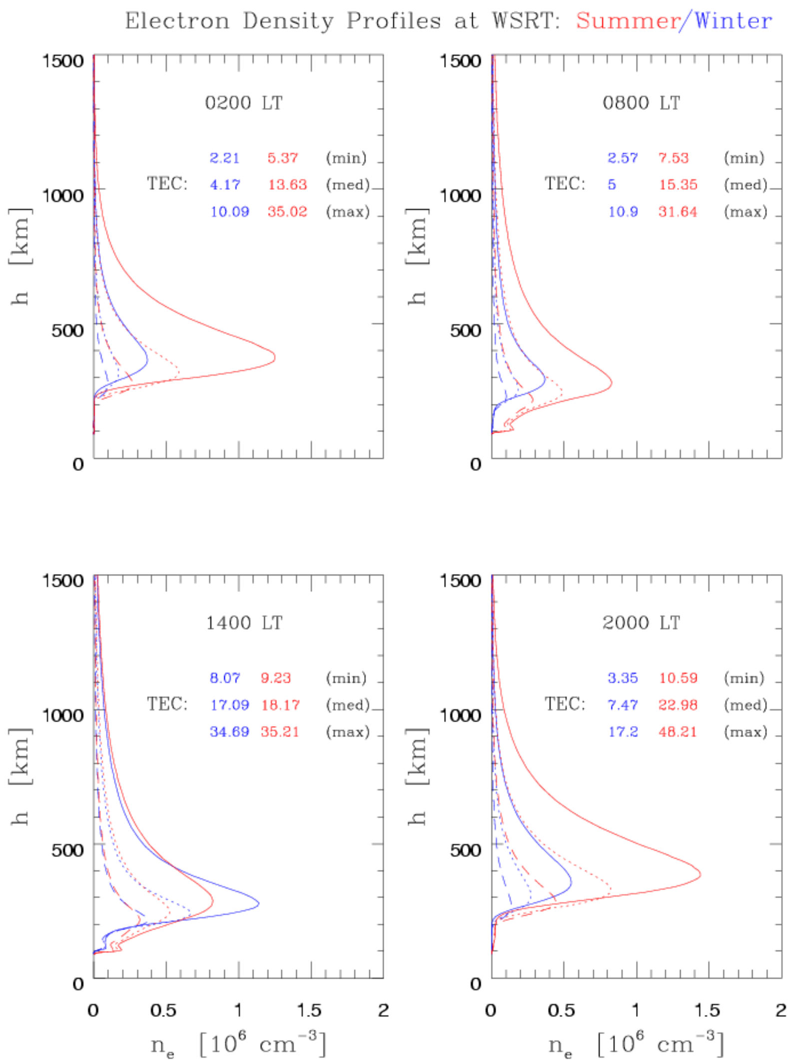
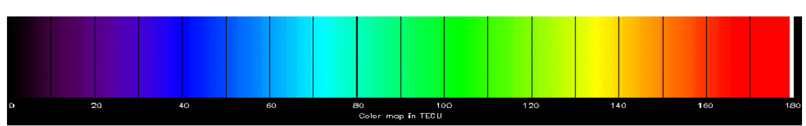
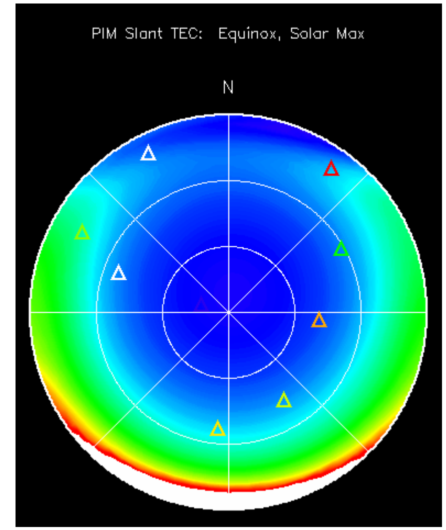
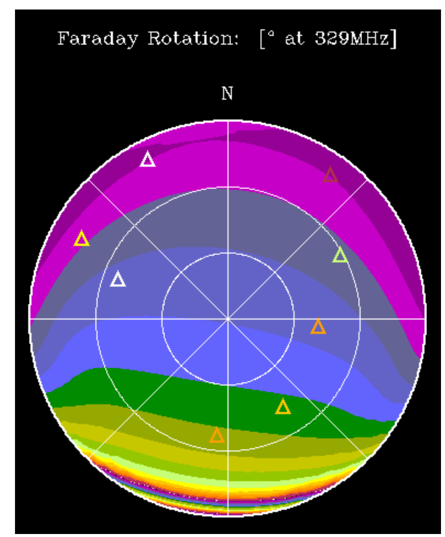


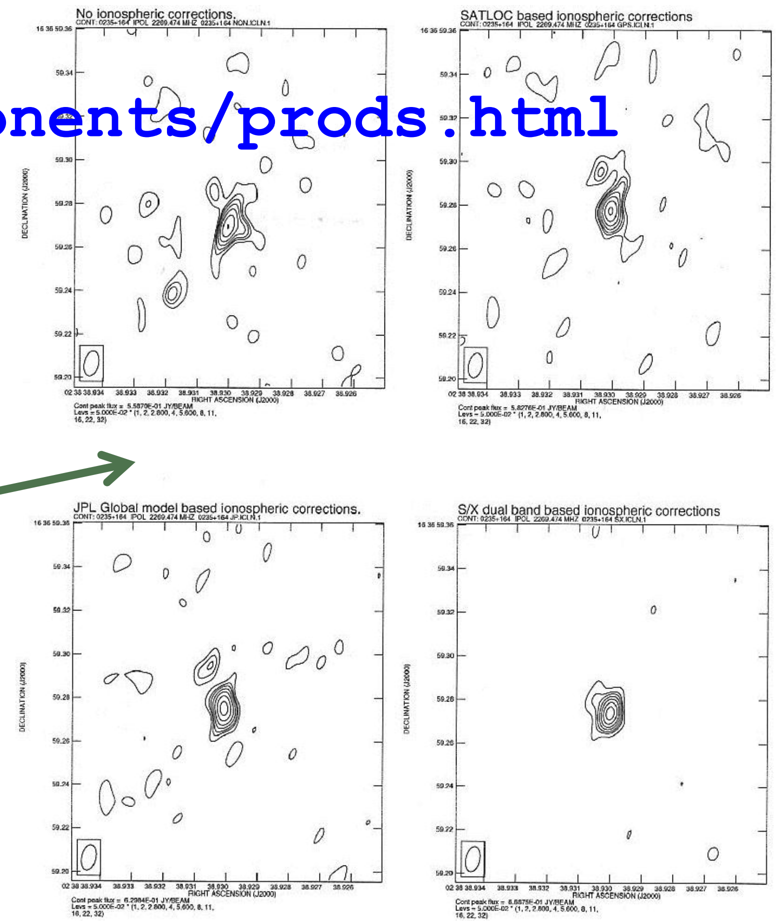





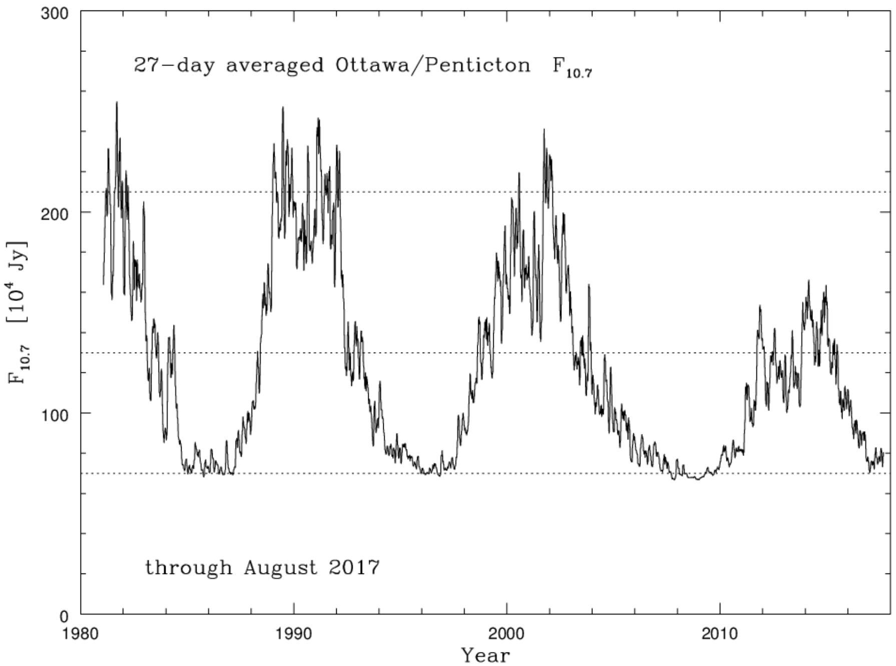



# Ionosphere Mitigation

- Dispersive delay → inverse quadratic dependence τ vs. ν
  - Dual-frequency (e.g., 2.3, 8.4 GHz)
  - widely-separated sub-bands (Brisken et al. 2002, *ApJ*, 571, 906)
- IGS IONEX maps (gridded vTEC)
  **igscb.jpl.nasa.gov/components/prods.html**
  - 5° long. x 2.5° lat., every 2 hr
  - *h* = 450km // σ ~ 2-8 TECU
  - Based on ≥150 GPS stations
  - Various analysis centers' solutions
- 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



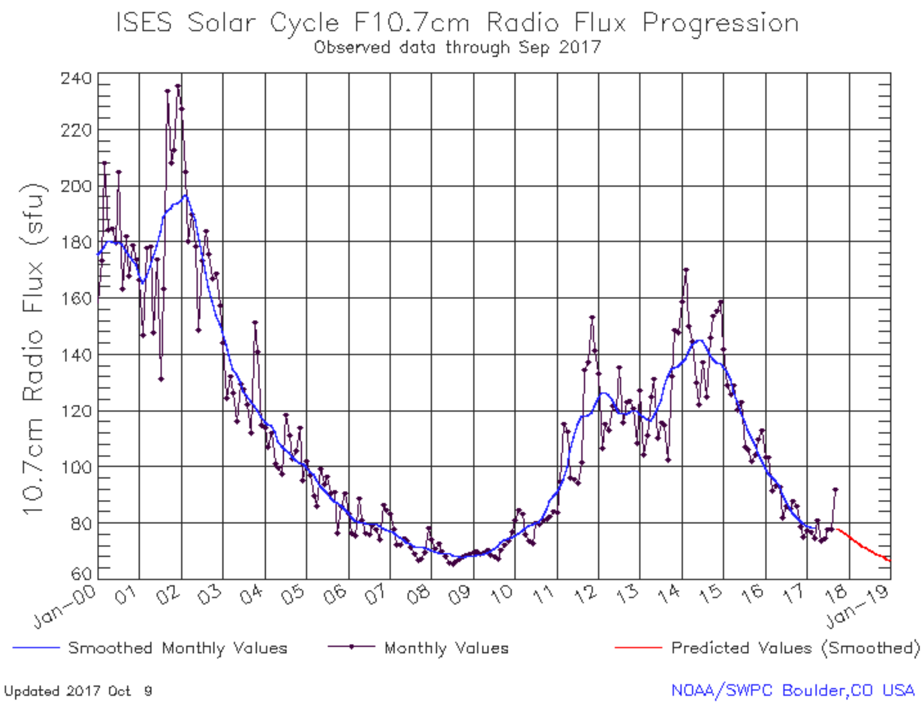
# Ionosphere: Climatology




The past few solar cycles: solar 10.7cm flux density

Past peak more akin to a solar "medium" condition

Prediction for current solar cycle: nearing solar "minimum"



# Ionosphere: Equations

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

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

N.B. $\mu_p < 1$

where $\theta$ is the angle between $\mathbf{B}_\oplus$ and the direction of propagation, and $X$ and $Y$ relate to the plasma & cyclrotron frequencies:

$$X \equiv \frac{\nu_p^2}{\nu^2}, \quad \text{with} \quad \nu_\mathrm{p}^2 = \frac{e^2}{4\pi^2\varepsilon_0 m_e}\, n_e \quad \equiv K_p^2 n_e,$$

$$Y \equiv \frac{\nu_b}{\nu}, \quad \text{with} \quad \nu_\mathrm{b} = \frac{e}{2\pi m_e}\, B \quad \equiv K_b B.$$

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

Expanding Appleton-Hartree and dropping terms $< 10^{-12}$ for L-band yeilds:

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

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.

$\tau_p = (\int \mu_p dl)/c$

$\mu_g = d(\nu\mu_p)/d\nu$

# Ionosphere: References

- Davies, K.E. 1990, *Ionospheric Radio*
  - from a more practical view-point; all frequency ranges
- Hargreaves, J.K. 1995, *Solar-Terrestrial Environment*
  - ~senior undergrad science in larger context
- Kelly, M.C. 1989, *Earth's Ionosphere*
  - ~grad science, more detail in transport processes
- Schunk, R. & Nagy, A. 2009, *Ionospheres*
  - 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: $-1.34\, TEC_{\text{[TECU]}} / \nu^2_{\text{[GHz]}}$ ns

- $\nu_{\text{cross-over}} \sim \sqrt{TEC / 5.82}$ GHz
  - can expect to encounter different tropospheric & ionospheric vertical → slant mapping functions

- for some representative TECs:

| TEC [TECU] | Cross-over $\nu$ [GHz] |
|---|---|
| 10 | ~1.3 |
| 50 | ~2.9 |
| 100 | ~4.1 |

# Wide-field Mapping: FoV limits

- Residual delay, rate → slopes in phase vs. freq, time
  - Delay = ∂φ/∂ω
  - Rate = ∂φ/∂t

  { i.e., via Fourier transform shift theorem; 1 wrap of φ 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):

  $$\tau(\alpha,\delta) = \tau(\alpha_0,\delta_0) + \Delta\alpha\,(\partial\tau/\partial\alpha) + \Delta\delta\,(\partial\tau/\partial\delta)$$
- → leads to residual delays & rates across the field, increasing away from the phase center.
- → 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:

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

  - 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 $N_{frq} \times N_{int}$ (e.g., ∝ 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 $N_{frq}$ & $t_{int}$
  - 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-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°
- RadioAstron:  launched 18 July 2011
  - Orbit:  $r$ = 10-70k km — 310-390k km;   $P$ ~ 9.5d;   $i$ = 51.6°
  - 329 MHz,   1.6,   5,   22  GHz
  - **www.asc.rssi.ru/radioastron**
- Model/correlation issues:
  - Satellite position/velocity;  proper vs. coordinate time

# 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 $\gamma$, $\partial G/\partial t$, deviations from inverse-square law)
    - IAU Symp #261: *Relavitivity in Fundamental Astronomy*
  - Frame ties (ecliptic within ICRS)

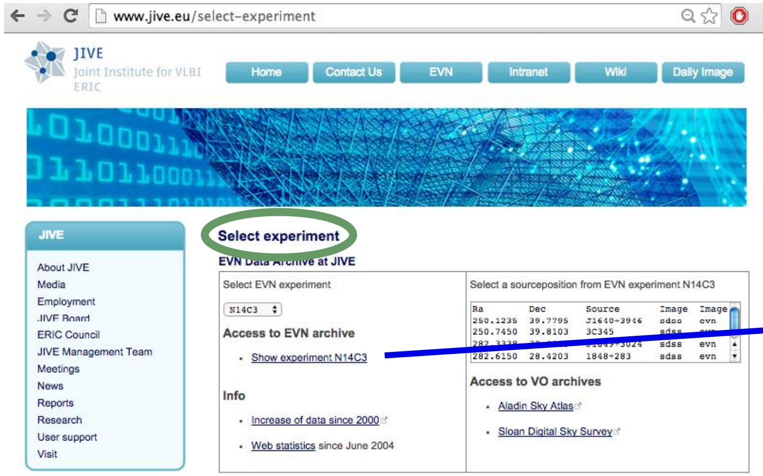
# Future

- 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/$\nu$ 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:
  - www.jive.eu/jivewiki/doku.php?id=parseltongue:parseltongue

# EVN Archive





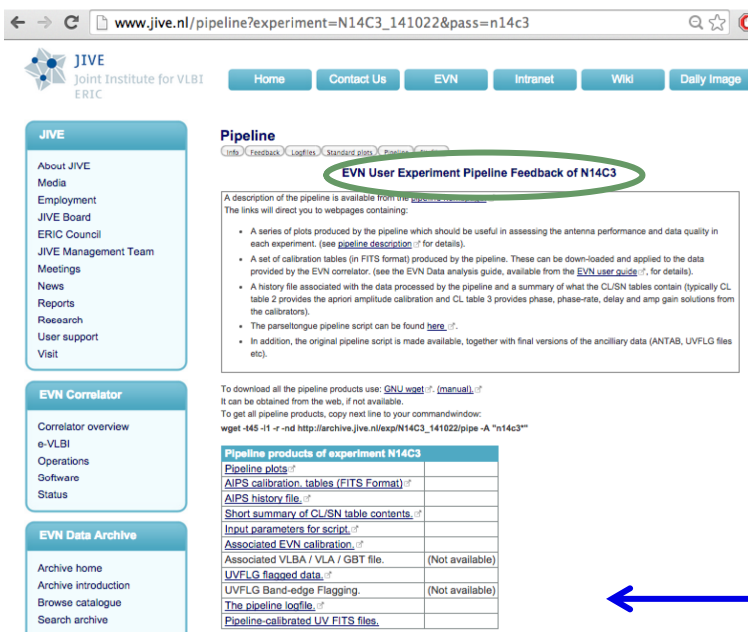
Feedback

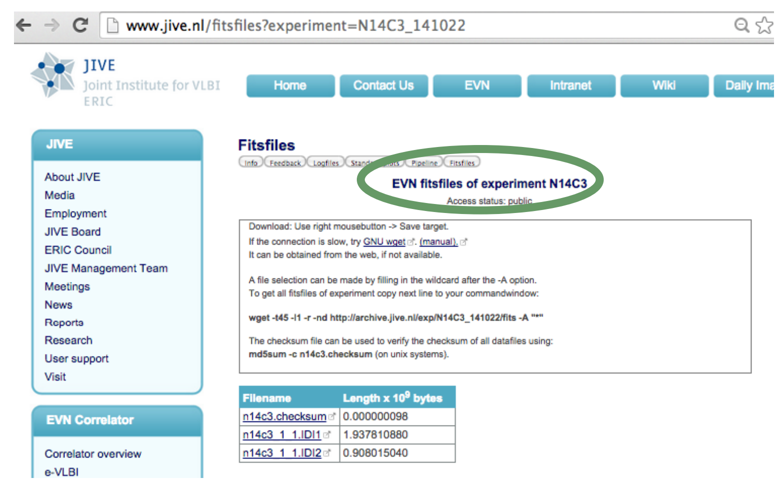
Logfiles

Plots

FITS

Pipeline



# 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
- Pipleline-calibrated UVFITS (per source)

# Data Familiarization

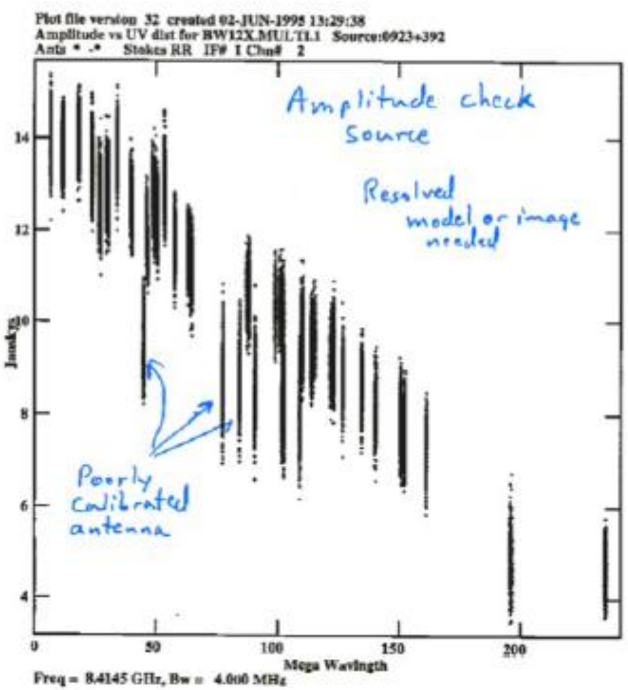
- FITLD — to load data
- LISTR — scan-based summary of observations
- PRTAB, TBOUT, PRTAN
  - Looking into contents of "tables"
- POSSM, VPLOT, UVPLT
  - Plots: vs. frequency, vs. time, u-v based
- SNPLT
  - Plot solution/calibration tables (various y-axes)

# 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 * g(z)}
  - $\sqrt{\{SEFD_1 * SEFD_2\}}$ 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 → $\partial\varphi/\partial\omega$ (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
  - $\varphi_{str}$ 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(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