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

OPTICON RadioNet Pilot

The OPTICON/Radionet Pilot has received funding from the European Commission's Horizon 2020 Research and Innovation Programme under grant agreement No, 101004719.

The EVN

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

0817 521217
BN 46
AVIAPTNR
TO
EVN
OS 641 / 18
VIA
OS 376 / 18
VIA
VIA
HOT

The EVN (European VLBI Network)

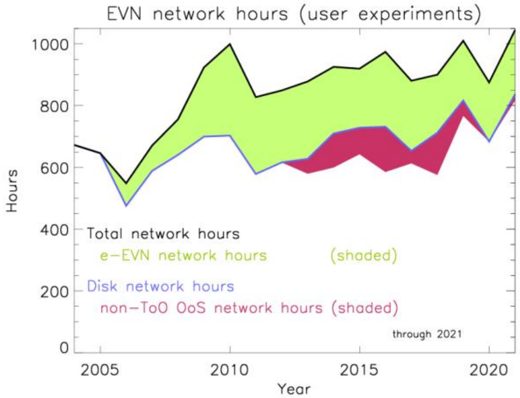
- Composed of existing antennas
  - generally larger (32m – 100m): more sensitive
  - baselines up to 10k km (8k km from Ef to TianMa, S.Africa)
  - down to 17 km (with Jb-Da baseline from eMERLIN)
  - heterogeneous, generally slower slewing
- Frequency coverage [GHz]:
  - workhorses: 1.4/1.6, 5, 6.0/6.7,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

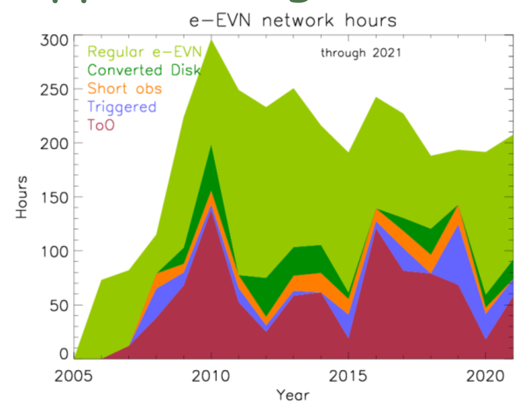
EVN Links

- 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. (16:00 UTC)
  - via NorthStar web-tool: **proposal.jive.eu**
- User Support via JIVE (Joint Institute for VLBI ERIC)
  - **www.jive.eu**
  - **usersupport@jive.eu**
  - ORP (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*

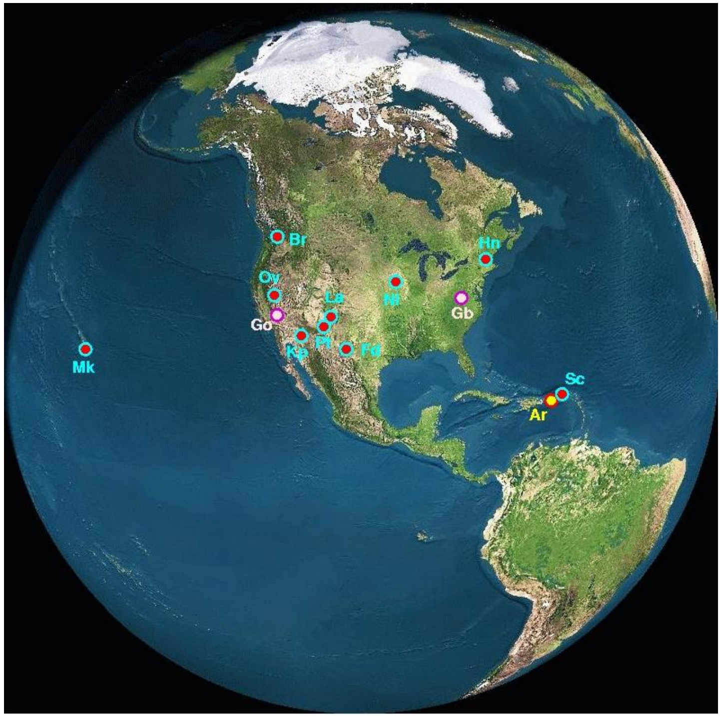
Real-time e-VLBI with the EVN

- 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)

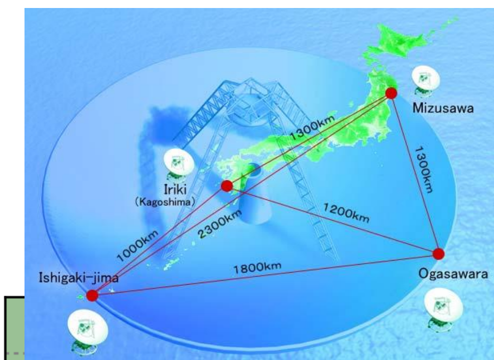


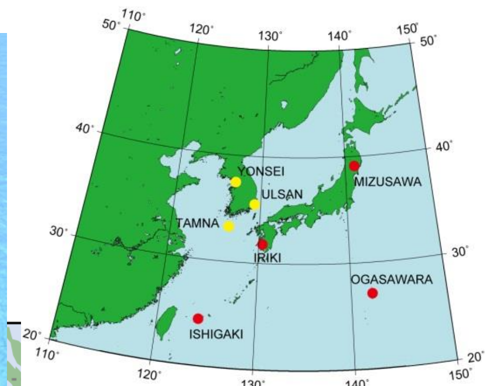
- Homogeneous array (10x 25m)
  - planned locations, dedicated array
  - Bslns ~8600-250 km (~50 w/ JVLA)
  - faster slewing
  - HSA (+ Ef + (Ar) + GBT + JVLA)
- Frequency agile
  - down to 0.329, up to 86 GHz
- Extremely large proposals
  - Up towards 1000 hr per year

- Globals: EVN + VLBA (+ GBT + JVLA)
  - proposed at EVN proposal deadlines (1 Feb., 1 Jun., 1 Oct.)
  - VLBA-only proposals: 1 Feb., 1 Aug.
- **www.nrao.edu/facilities/vlba**

Asian/Australian VLBI Networks

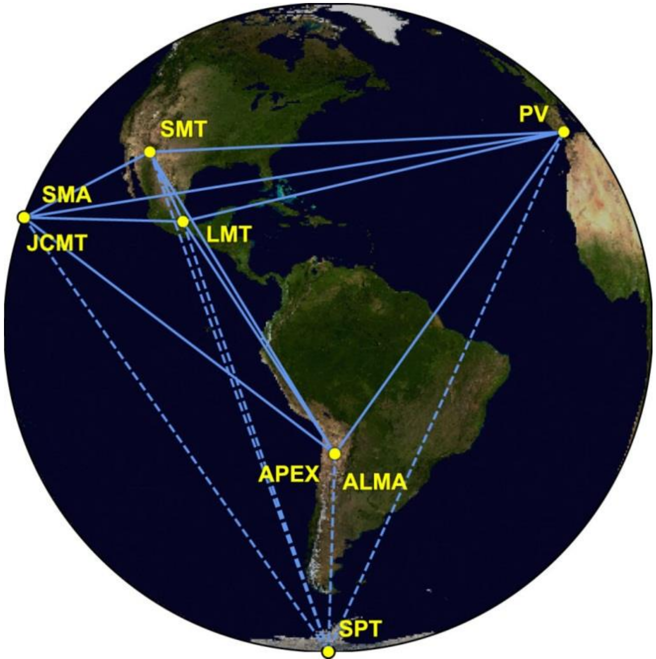
- East Asian VLBI Network (**radio.kasi.re.kr/eavn/main_eavn.php**)
- Korean (KVN): 3 ants., simultaneous 22, 43, 86, 129 GHz
- VERA: 4 dual-beam ants., maser astrometry 22-49 GHz
  - KaVA == KVN + VERA (issues separate KaVA Calls for Proposals)
- Australian LBA: can propose joint EVN+LBA observations
  - **www.atnf.csiro.eu/vlbi**





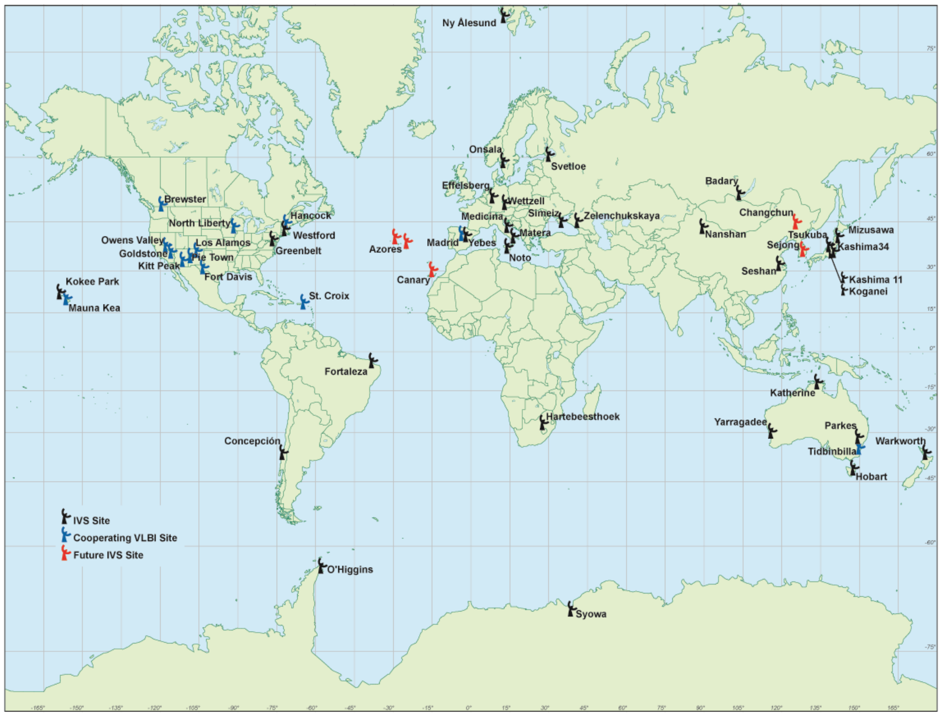
Higher-ν VLBI Arrays (+ ALMA)

- **Global mm VLBI Network (GMVA)**
  - Effelsberg, Onsala, Metsahövi, Pico Veleta, NOEMA, KVN, most VLBAs, Green Bank, ALMA (LMT, GLT)
- 86 GHz, ~2 weeks of observing per year
- Coordinated from MPIfR Bonn
- **www3.mpifr-bonn.mpg.de/div/vlbi/globalmm**
- **Event Horizon Telescope (EHT)**
  - NOEMA, IRAM 30m, JCMT, SMA, LMT, ARO/SMT, APEX, ALMA, SPT, GLT
- Proposing via ALMA calls
  - ALMA bands 6,7 (1.4, 0.88 mm)
- **www.eventhorizontelescope.org**



Global VLBI Alliance

IVS (International VLBI Service)



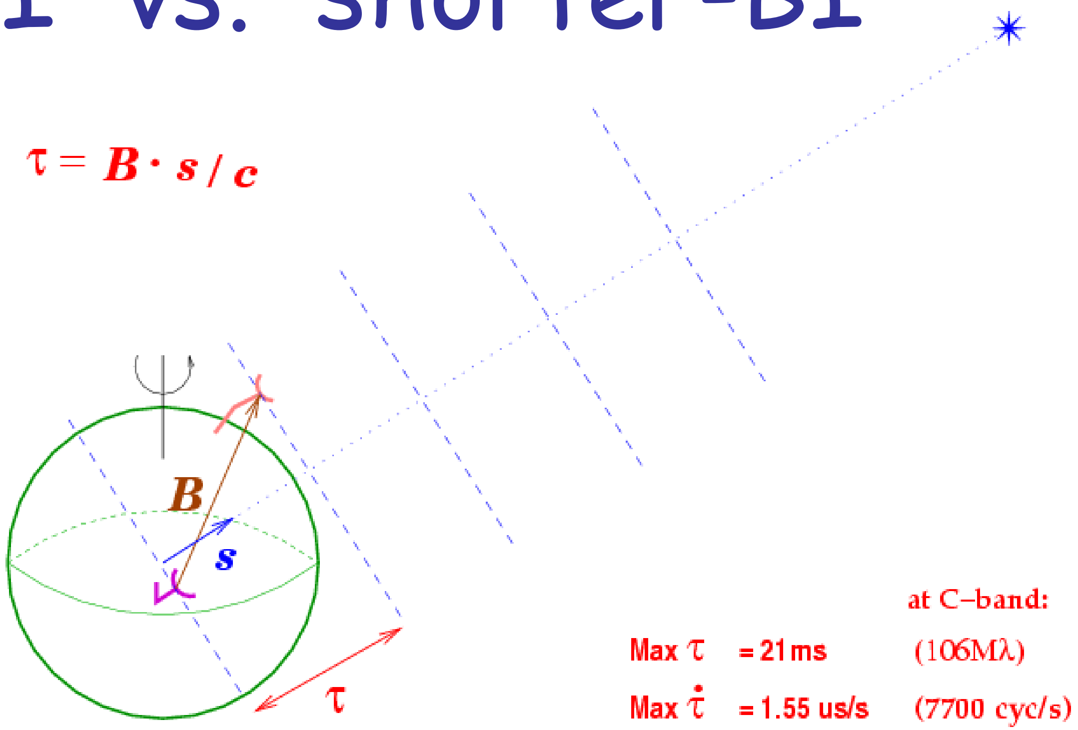
- VLBI as space geodesy
  - cf: GPS, SLR/LLR, Doris
- Frequency: 2.3 & 8-9
  some at 8-9 & 27-34
- Geodetic VLBI tactics:
  - many short scans
  - fast slews
  - uniform distribution of stations over globe
- VGOS: wide-band geodetic system (4x 2GHz over 2-14 GHz)
- IVS web page: **ivscc.gsfc.nasa.gov**
  - 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: 0.01 — 100 mas
- Physical scales of interest:
  - Angular-diameter distance $D_A(z)$
  - Proper-motion distance $D_M(z)$ → μ to β_{app} conversion
  - D_A turns over with z (max z~1.6), D_M doesn't
- Brief table, using Planck 2015 cosmology parameters

z	1 mas subtends (D_A)	β_{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

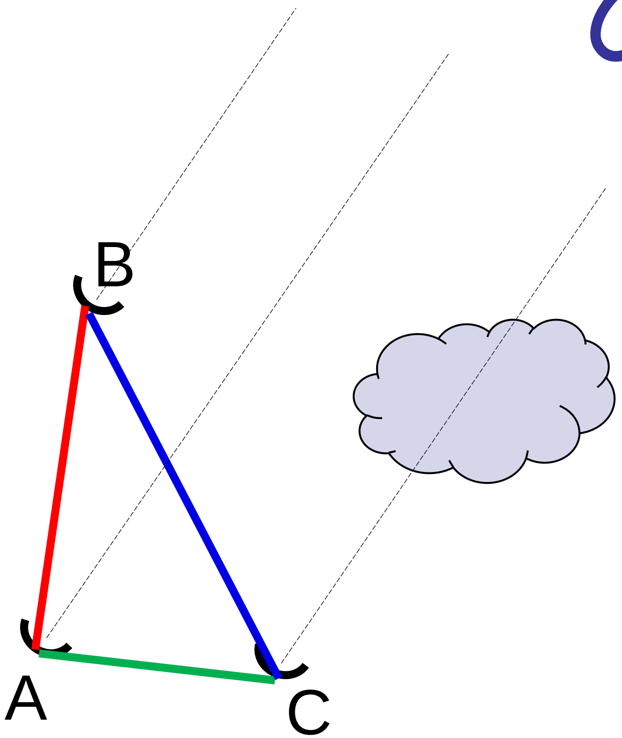
$$\tau_{geom} = -[\cos\delta \, \{b_x \cos H(t) - b_y \sin H(t)\} + b_z \sin\delta] / c$$

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

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

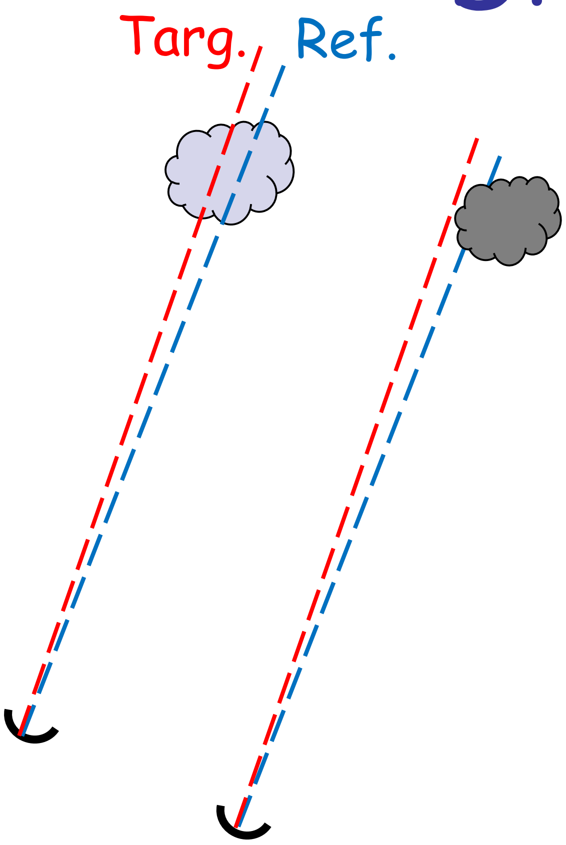
for φ_{obs}: $\pm\, N_{\text{lobes}}$

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, 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 / self-cal
- 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

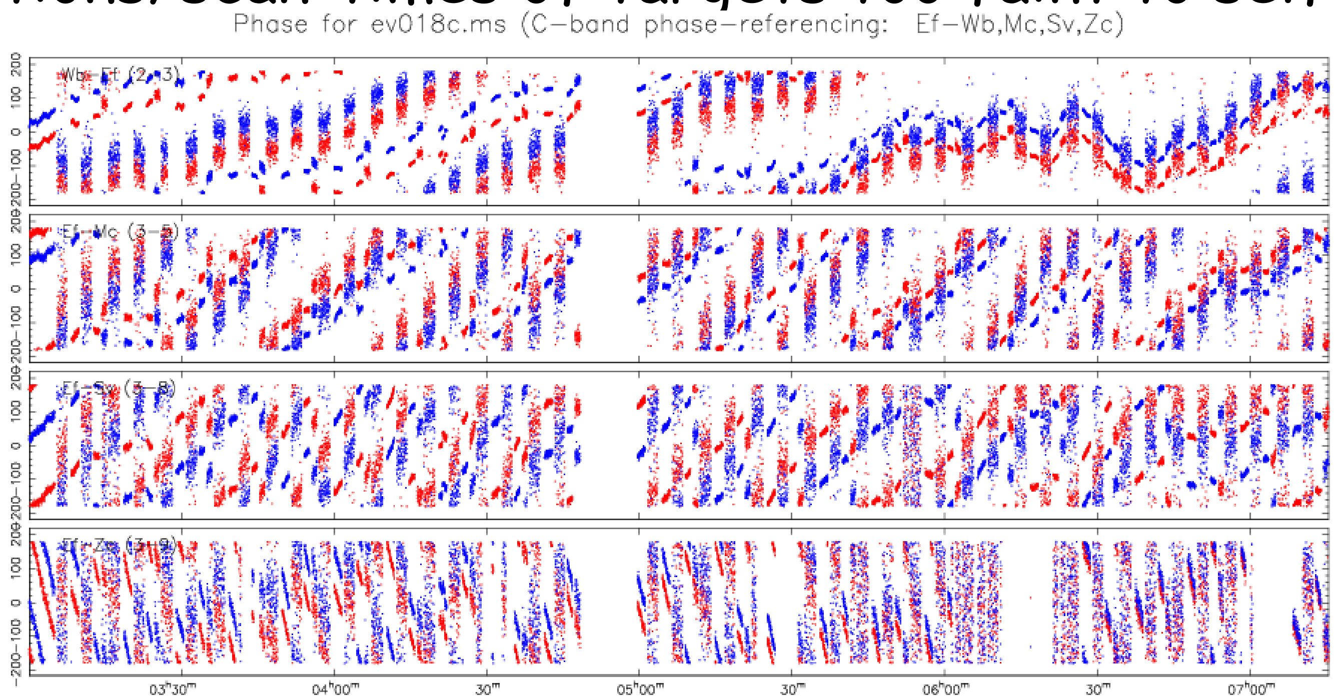
- Extragalactic reference source(s)   (*i.e.*, tied to an ICRF)
  - Target referenced to an inertial frame
- **Close reference source(s)**
  - Tends towards needing to use fainter ref-sources
- Shorter cycle times between/among the sources
  - Shorter slews   (close ref-sources, smaller antennas)
  - Shorter scans   (bright ref-sources, big antennas)
- High SNR   (longer scans, brighter ref-sources, bigger antennas)
- Ref.src structure [best=none; if some, preferably not f(t, ν)]
- **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/links**
    - under: VLBI Surveys, Sources, & Calibrators
  - List of reference sources close to specified position
  - FD (2 bands) on short & long |B|; Images, Amp(|*uv* |)
- >1 reference sources per target ("Multi-view")
  - Rioja et al., 2017, *AJ*, 153, 105
  - also, 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)

Faint-Source Mapping

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

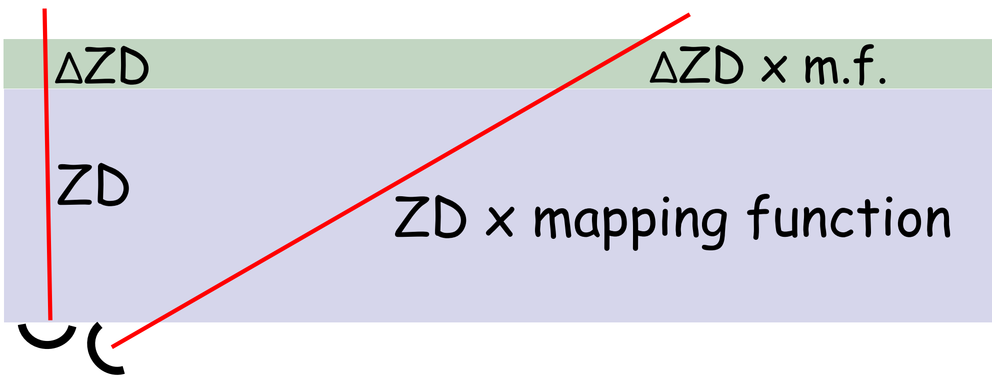


- Increasing coherent integration time to whole observation
  - Beasley & Conway 1995, *VLBI and the VLBA*, Ch 17, p.327
  - Alef 1989, *VLBI Techniques & Applications*, p.261

Differential Astrometry

- Motion of target with respect to a reference source
  - Extragalactic ref.src. → tie target to inertial frame
  - 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 γ 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:

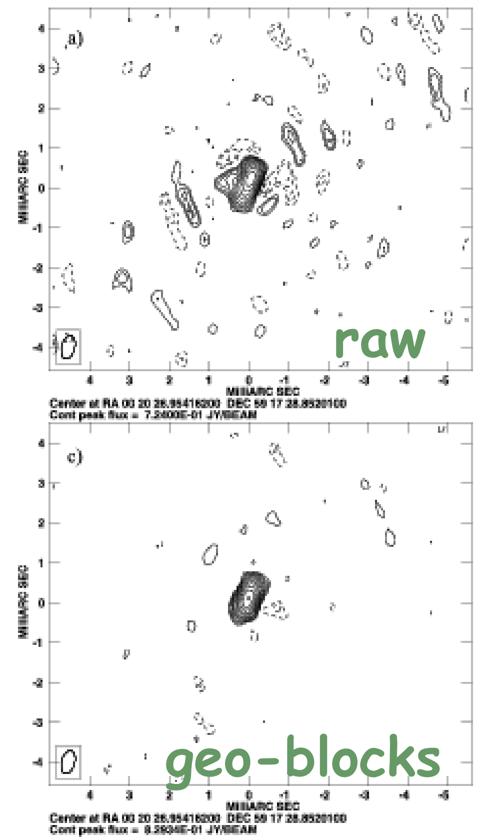
$$ZD_{\text{dry}} = ZD_d(P, \phi, h)$$
$$ZD_{\text{wet}} = ZD_w(T, RH)$$

- 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
  - **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
  - **astrogeo.org/spd**
  - **hg.geo.tuwien.ac.at/hg/projects/details/316713 & 1400848**

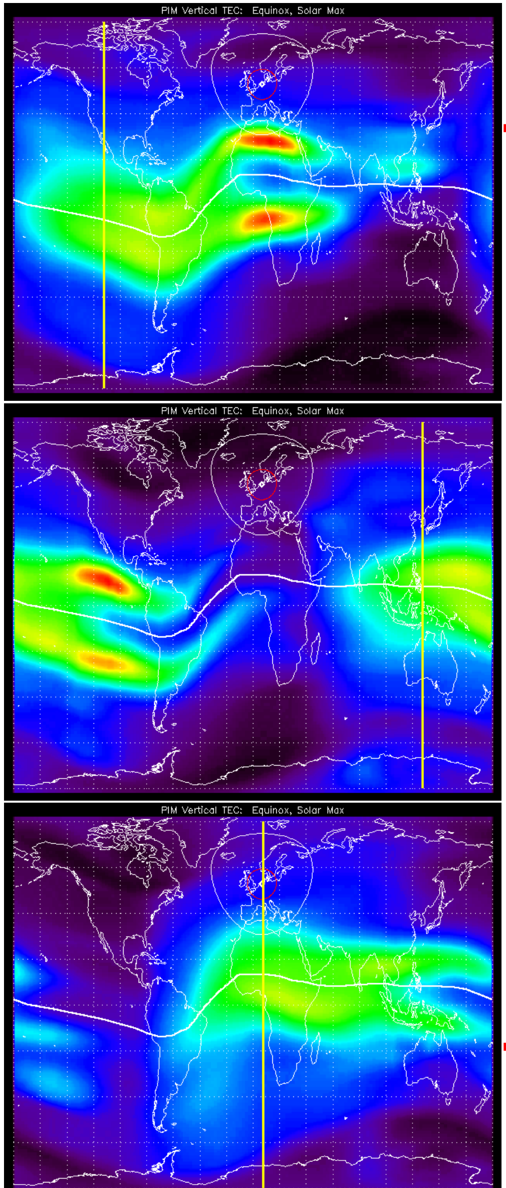
Animation removed: 1 of 2

Phs-Ref Limitations: Ionosphere

1930

0330

1130

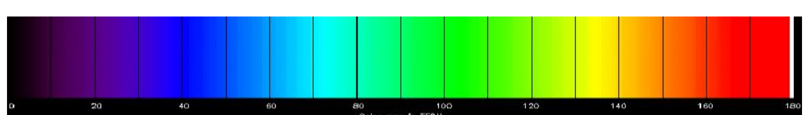


USAF
PIM model
run for
solar max

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

TEC color-map scaling:

30 75 135 180



Phs-Ref Limitations: Ionosphere

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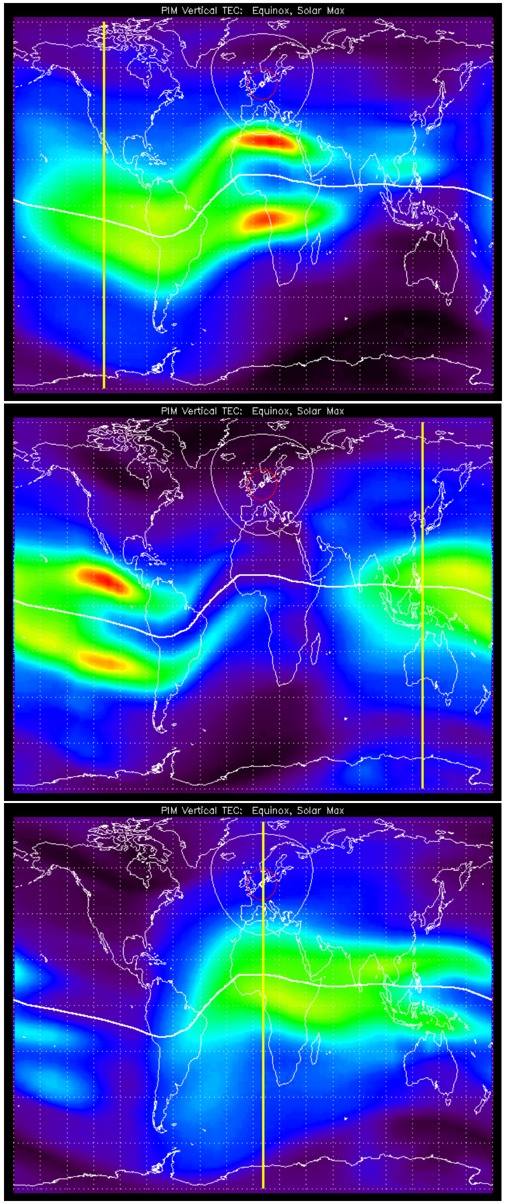
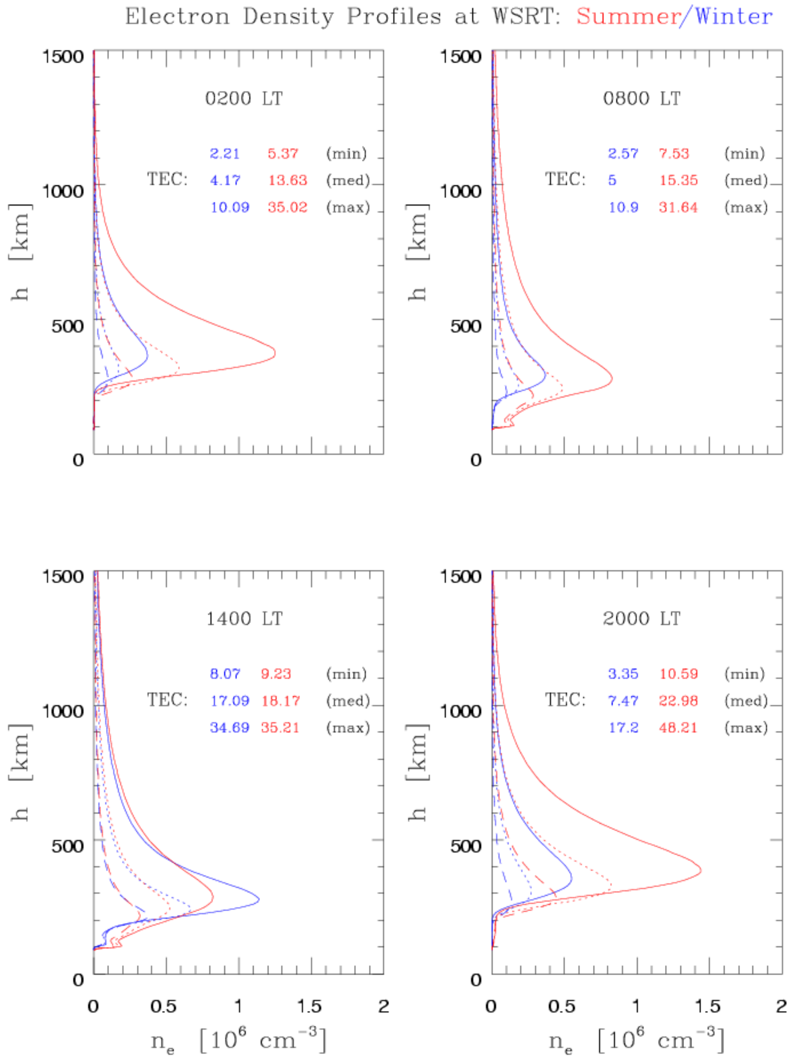
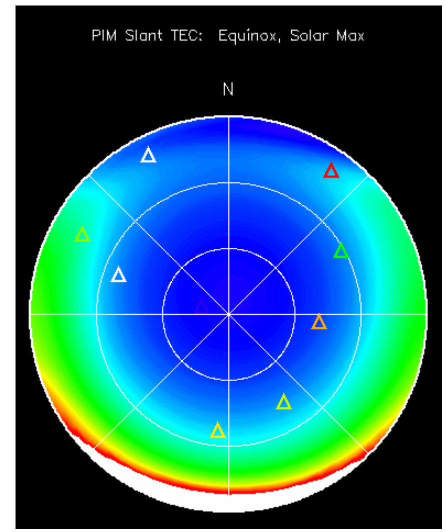
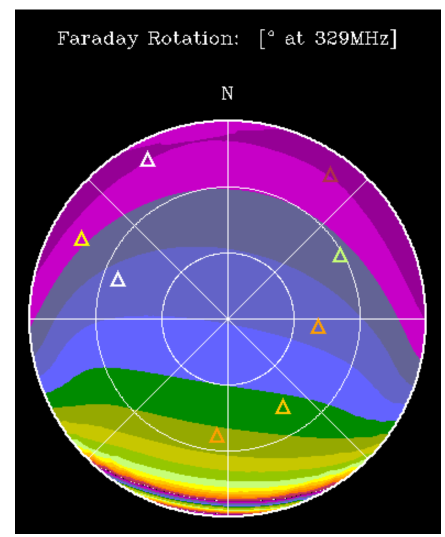
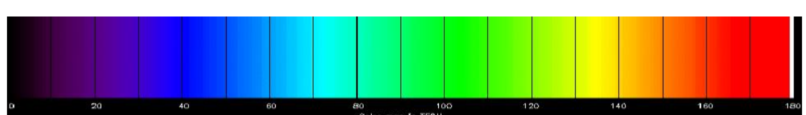




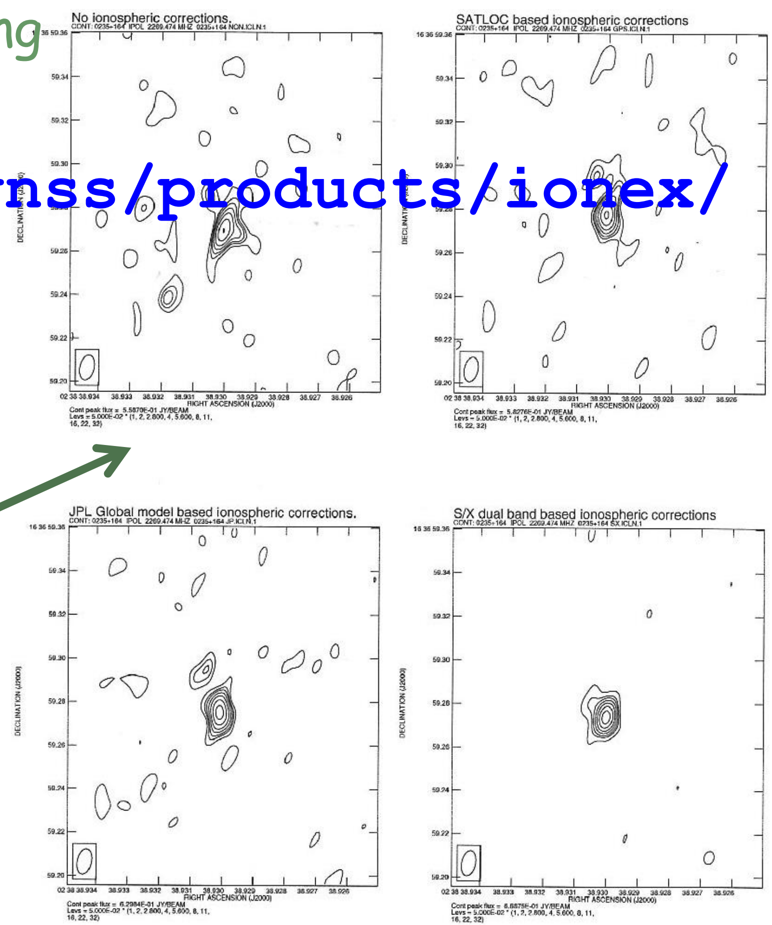




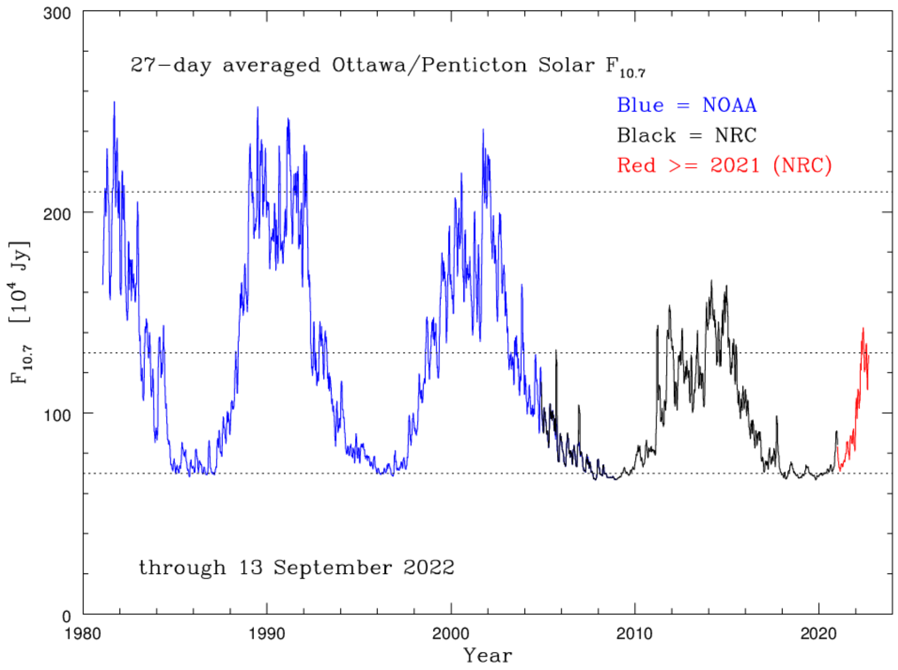


Ionosphere Mitigation

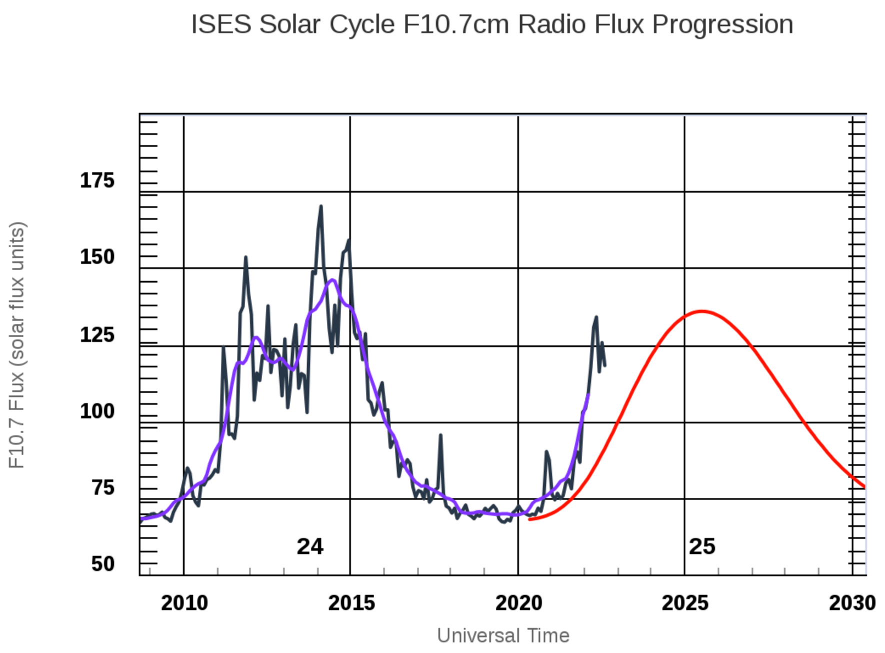
- Dispersive delay → inverse quadratic dependence τ vs. ν
  - Dual-frequency (e.g., 2.3, 8.4 GHz)
  - widely-separated sub-bands (receiver IF getting wider & wider…)
  - CASA: dispersive-delay fringe-fitting
- IGS IONEX maps (gridded vTEC)
  cddis.nasa.gov/archive/gnss/products/ionex/
  - 5° long. x 2.5° lat., every 2 hr
  - *h* = 450km // σ ~ 2-8 TECU
  - Based on ≥150 GPS stations
  - Various analysis centers' solutions
- TECOR (VLBA 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



Solar 10.7cm flux density over the past few solar cycles: last one ~"medium"



Prediction for upcoming solar cycle: also only up to ~"medium"

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 θ 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: $K_p^2 = 80.616\ \mathrm{m^3\,s^{-2}}$ and $K_b = 2.799 \times 10^{10}\ \mathrm{s^{-1}\,T^{-1}}$.

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 zenith delay exceeds typical tropospheric zenith delay
  - Troposphere: ~7.8 ns (at sea level, STP)
  - Ionosphere: $-1.34 TEC_{[TECU]} / \nu^2_{[GHz]}$ ns
- $\nu_{cross\text{-}over} \sim \sqrt{TEC / 5.82}$ GHz
  - tropo & iono vertical → slant mapping functions differ
  - Does not consider different spatial/temporal variation scales
- for some representative TECs:

TEC [TECU]	Cross-over ν [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
  - Bridle & Schwab, 1989, in "Synthesis Imaging in Rad.Astr.", Ch. 13

- 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 = 17.8 TB
  - Record for a multi-epoch exp. correlated at JIVE = 65.9 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, primary-beam corrections more important
  - EVN has stations ranging from 20 to 100 m (e.g., vs. FoV ~10′)

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

    Molera Calvés et al. 2021, *PASP*, 38, e065

- 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, $\partial G/\partial t$, deviations from inverse-square law)
  - Frame ties (ecliptic within ICRS)

Future

- Digital back-ends / wider IFs / multi-band Rx's
  - 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
  - e.g., GMRT, Thailand, Santa Maria, Africa,………
- Continuing maturation of real-time e-VLBI
  - Better responsiveness (e.g., automatic overrides)
  - 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.
- Processing steps
  - Data familiarization / inspection
  - Amplitude calibration (relying on EVN pipeline…)
  - Delay / rate / phase calibration (fringing)
  - Bandpass calibration
  - Imaging / self-cal

Pipeline Outputs (downloads)

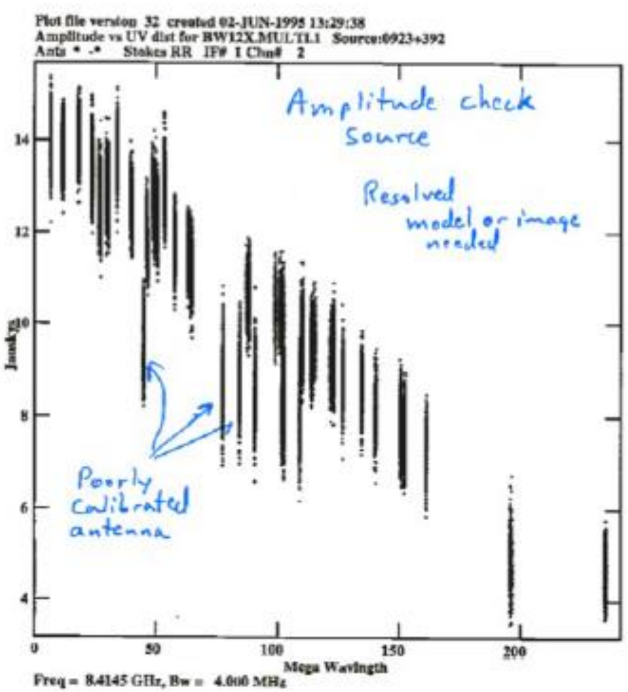
- Plots up through (rough) images
- **Prepared ANTAB file** (amplitude calibration input)
- **a priori Flagging file(s)** (by time-range, by channel)
- AIPS tables
  - CL1 = "unity", typically 15s sampling
  - SN1 = TY ⊕ GC; CL2 = CL1 ⊗ SN1 (& parallactic angles)
  - FG1 (sums over all input flagging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

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
  - Attached to IDI FITS files

Amplitude Calibration (II)

- amplitude(|uv|) plots
  - Calibrators with simple structure: smooth drop-off
    e.g., $A(\rho) = 2J_1(\pi a\rho)/(\pi a\rho)$ 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
  - φ_{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(ν)]
- After fringing, phases should be flat in the individual subbands, and subbands aligned

Animation removed: 1 of 2

VLBI (EVN) obs:

What you may have thought before ERIS: artifacts from the dim mists of a Jungian collective unconcious?

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