Astrometric Interferometry

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Outline

- VLBI observables for astrometry
- VLBI modeling
- Reference frames and surveys (ICRF, VCS)
- Organisation for data acquisition and processing (IVS)
- Phase-referenced astrometry

Astrometric potential of VLBI

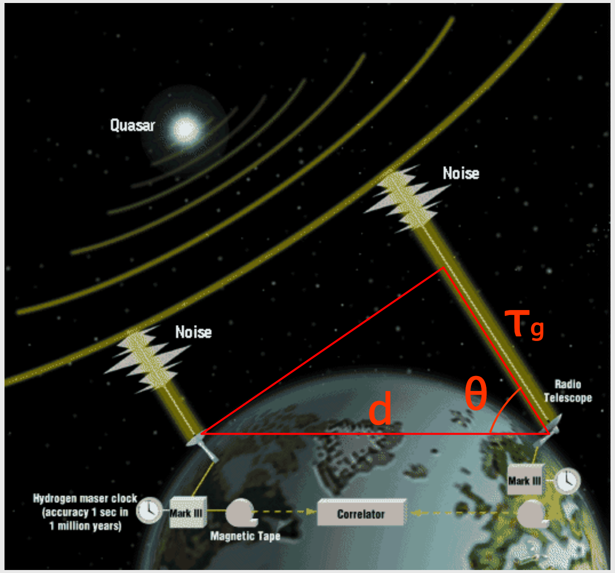
- Geometric time delay

$$c\,\tau_g = d \cos\theta$$

- Variation of time delay with source direction:

$$\Delta\tau_g = -(d/c)\sin\theta\,\Delta\theta$$

$$\Rightarrow \Delta\theta = -(c/d\sin\theta)\,\Delta\tau_g$$



- A change of 10% of a wavelength is easily detectable at correlation

$$\Delta\tau_g = 0.1\lambda / c$$

$$\Rightarrow \Delta\theta = -(0.1\lambda / d\sin\theta)$$

Assuming:

d=5000 km
λ= 3.6 cm

$\Delta\theta = 0.14$ mas/sinθ

➔ directions theoretically measurable by VLBI to ~ 0.2 mas

Astrometric VLBI observables (1)

- <u>Phase delay</u>

$$\tau_\phi = \phi/\omega$$

ϕ = fringe phase
$\omega = 2\pi\nu$
ν = frequency (e.g. 8 GHz)

- Φ only known modulo 360° → τ_ϕ ambiguous
- Interpretation of the phase requires resolving the inherent ambiguity (i.e. determining the number of phase cycles)
- Prediction of the number of cycles requires a very accurate geometric model (< 20 ps or 5 mm at 8 GHz)
- But, generally not the case… => τ_ϕ cannot be used directly

<u>Error in phase delay:</u>

$$\sigma_{\tau\phi} = (1/\omega)\,\sigma_\phi = (1/\omega)\cdot(1/SNR)$$

The phase delay VLBI observable is very accurate but ambiguous

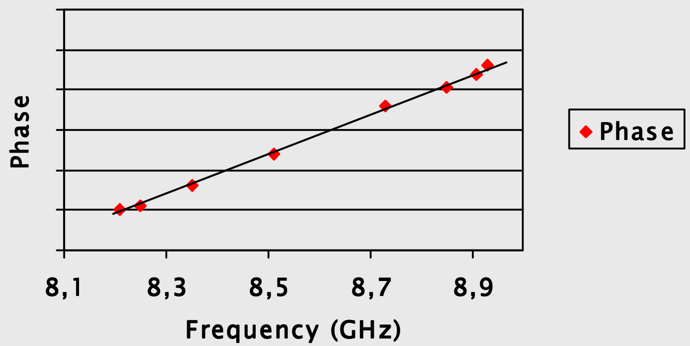
ν = 8.4 GHz, SNR =50
=> $\sigma_{\tau\phi}$ = 0.4 ps (0.1 mm)

Astrometric VLBI observables (2)

- <u>Group delay</u>

$$\tau_{group} = \partial\phi / \partial\omega$$

  - τ_{group} not ambiguous (unlike τ_{ϕ})
  - In practice, τ_{group} is determined by fitting a straight line to the sequence of phases measured at several "discrete" frequencies



  - <u>Error in group delay:</u>

$$\sigma_{\tau_{group}} = \sigma_{\phi} \,/\, (2\pi\, \Delta\nu_{rms}) = 1 \,/\, (2\pi\, \Delta\nu_{rms}\, SNR)$$

The group delay is less accurate than the phase delay but not ambiguous

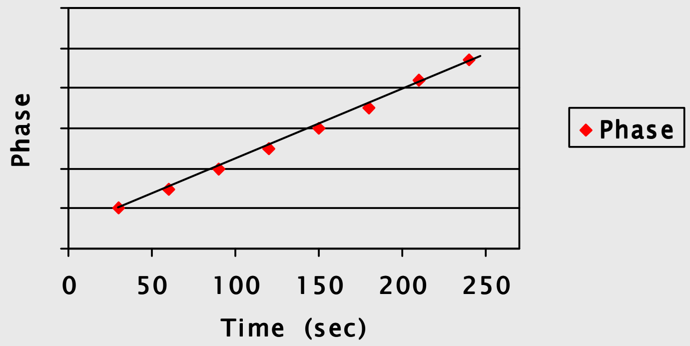
$\Delta\nu_{rms}$ = 0.3 GHz, SNR = 50
=> $\sigma_{\tau_{group}}$ = 10 ps (3 mm)

Astrometric VLBI observables (3)

- <u>Phase delay rate</u> (fringe frequency)

$$\dot{\tau}_\phi = \partial\tau_\phi/\partial t = (1/\omega)\ \partial\phi/\partial t$$

  - $\dot{\tau}_\phi$ not ambiguous
  - $\dot{\tau}_\phi$ is determined by fitting a straight line to the sequence of phases measured over time (a few minutes)



  - <u>Error in phase delay rate:</u>

$$\sigma_{\dot{\tau}_\phi} = (1/\omega)\ \sigma_\phi\ /\ \Delta t_{rms} = 1/\ (2\pi\nu\ \Delta t_{rms}\ SNR)$$

ν = 8.4 GHz, Δt_{rms} = 60 s, SNR = 50 => $\sigma_{\dot{\tau}_\phi}$ = 0.06 ps/s

Angular sensitivity of VLBI observables

Assuming: $d = 5000$ km, $\lambda = 3.6$ cm, SNR = 50, $\Delta\nu_{rms} = 0.3$ GHz, $\Delta t_{rms} = 60$ s

- Phase delay

  $\sin\theta \, \Delta\theta(\tau_\phi) = (1/2\pi) \cdot (\lambda/d) \cdot (1/SNR)$ => 0.005 mas

- Group delay

  $\sin\theta \, \Delta\theta(\tau_{group}) = (1/2\pi) \cdot (\lambda/d) \cdot (\nu/\Delta\nu_{rms}) \cdot (1/SNR)$ => 0.13 mas

- Phase delay rate

  $\cos\theta \, \Delta\theta(\dot{\tau}_\phi) = (1/2\pi) \cdot (\lambda/d) \cdot (1/\omega_e \, \Delta t_{rms}) \cdot (1/SNR)$ => 1.1 mas

  (ω_e = angular velocity of the Earth's rotation)

The primary astrometric VLBI observable is the group delay (also called « bandwidth synthesis » delay)

VLBI observing mode for astrometry

- Duration of experiments: 24 hours
- Dual-band observations to calibrate ionosphere (8.4/2.3 GHz)
- Bandwidth:
  - 8 frequencies at X band spead over 720 MHz (8.2-8.9 GHz)
  - 6 frequencies at S band spread over 125 MHz (2.22-2.35 GHz)
- 6-10 telescopes
- Observe ~ 50 different sources with a few scans on each source =>a few thousand delay observations
- For each measured quantity (τ_{group} or $\dot{\tau}_{\phi}$), calculate corresponding theoretical model

  => Form O-C (observed – calculated) and estimate parameters of interest (e.g. source coordinates,...)
- Software: CALC/SOLVE (NASA), MODEST (JPL), OCCAM (Europe)

VLBI modeling

- Observables:

$$\tau_{group} = \partial\phi/\partial\omega \,, \qquad \dot{\tau}_{\phi} = (1/\omega)\, \partial\phi/\partial t$$

- VLBI model (τ_{group} abbreviated as τ)

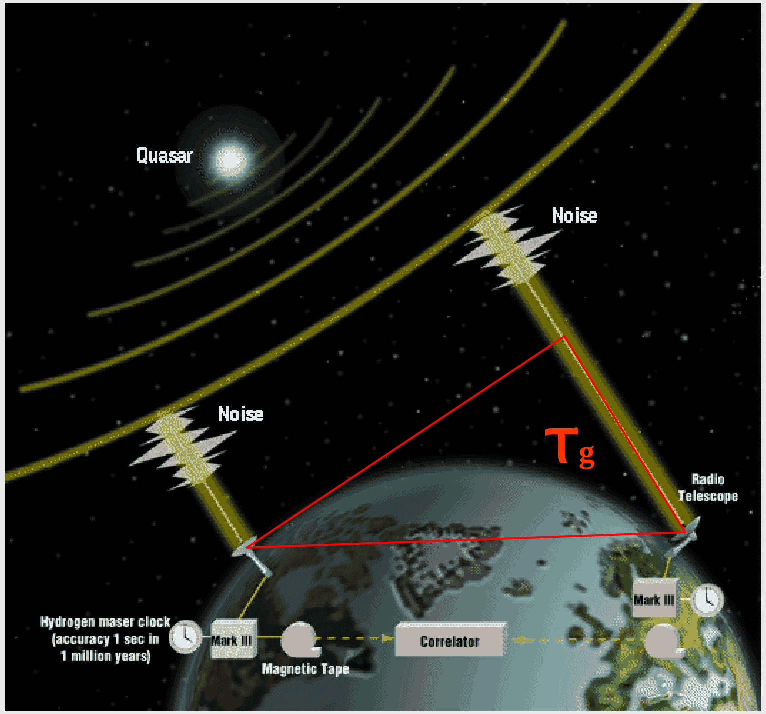
$$\tau = \tau_g + \tau_{inst} + \tau_{trop} + \tau_{ion} + \ldots$$

τ_g = geometric delay

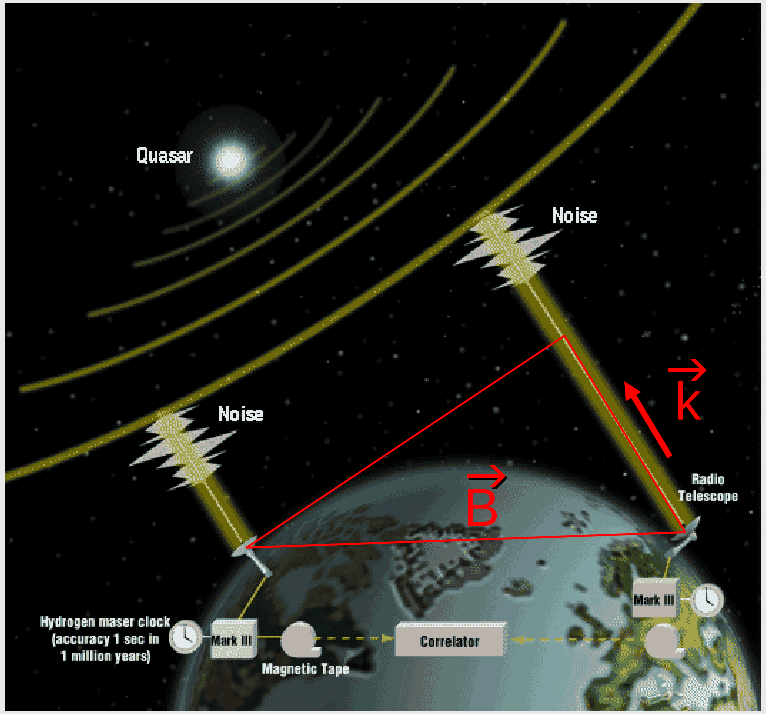
τ_{inst} = instrumental delay

τ_{trop} = tropospheric delay

τ_{ion} = ionospheric delay



VLBI modeling: geometric delay τ_g



τ_g max = 0,02 s

$$\tau_g = -(1/c)\,\vec{k}\,.\,\vec{B}\,[...]$$

- $\vec{B}_{cel} = Q\,(\vec{B}_{ter} + \vec{\Delta B}_{ter})$
- Relativistic effects at the level of 10^{-8} s
- $\vec{\Delta B}_{ter}$ depends on:
  - Tectonic motions
  - Solid Earth tides
  - Ocean loading
  - Atmospheric loading
  - ...

Q = rotational transformation of coordinates from the terrestrial frame to the celestial frame

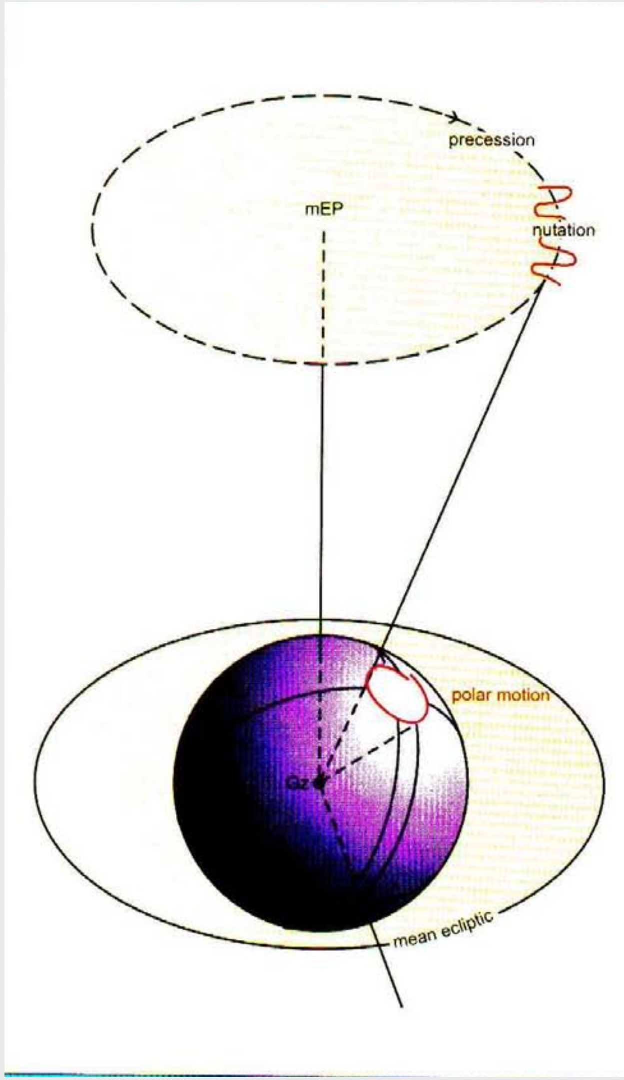
Q = PNUXY   X,Y = polar motion, U=Earth's rotation
N = nutation, P=precession

VLBI modeling: Earth's orientation

$$Q = PNUXY$$

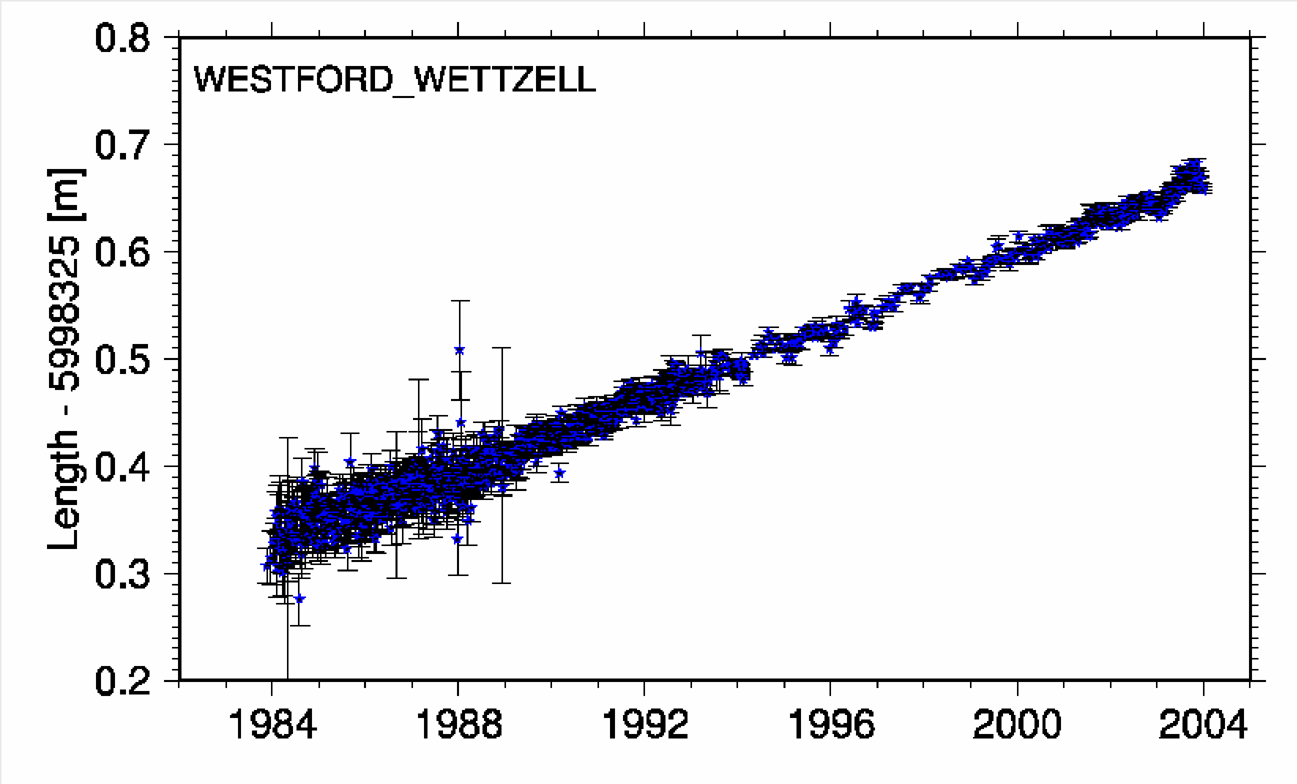
- X, Y: polar motion
- U: rotation of the Earth around its axis (UT1−UTC)
- N: nutation
  → consists of several hundreds of periodic terms
- P: precession

Q transforms a vector from the terrestrial frame to the celestial frame



VLBI modeling: plate tectonic motions

Evolution of the distance between Westford (USA) and Wettzell (Germany) between 1984 and 2004



VLBI modeling: instrumental delay τ_{inst}

- The instrumental delay comprises two terms:

  - The delay caused by the shift between the clocks at the two stations

$$\tau_{clock} = \tau_{clock2} - \tau_{clock1}$$

  - The delay caused by propagation time in cables and etectronics at each station

$$\tau_{prop} = \tau_{prop2} - \tau_{prop1}$$

- In practice, the instrumental delay $\tau_{inst} = \tau_{clock} + \tau_{prop}$ is modeled by a linear or quadradic function with the coefficients estimated from the VLBI observations.

VLBI modeling: tropospheric delay τ_{trop}

- τ_{trop} may be separated into two components
  - The dry component: ~ 7 ns at zenith (210 cm)
    -> may be predicted to ~ 1cm from meteorological data
  - The wet component: < 1 ns at zenith (30 cm)
    -> difficult to predict, quickly variable

- Modeling
  - For each station i: $\tau_{trop\ i} = \tau_{trpz\ i}\ R(H_i)$

    $\tau_{trpz\ i}$ = zenith tropospheric delay

    R = mapping function (H_i = elevation)
  - Differential effect

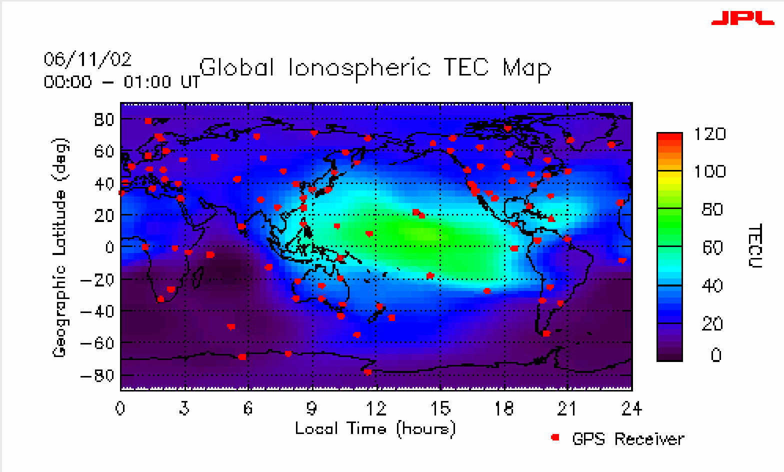
    $$\tau_{trop} = \tau_{trop\ 2} - \tau_{trop\ 1}$$

- In practice
  - $\tau_{trpz\ i}$ estimated from the VLBI data

VLBI modeling: ionospheric delay τ_{ion}

- Depends on the total electronic content (TEC) above telescopes
- Diurnal cycle
- Proportional to $1/\nu^2$
- Differential effect

$$\tau_{ion} = \tau_{ion\ 2} - \tau_{ion\ 1}$$



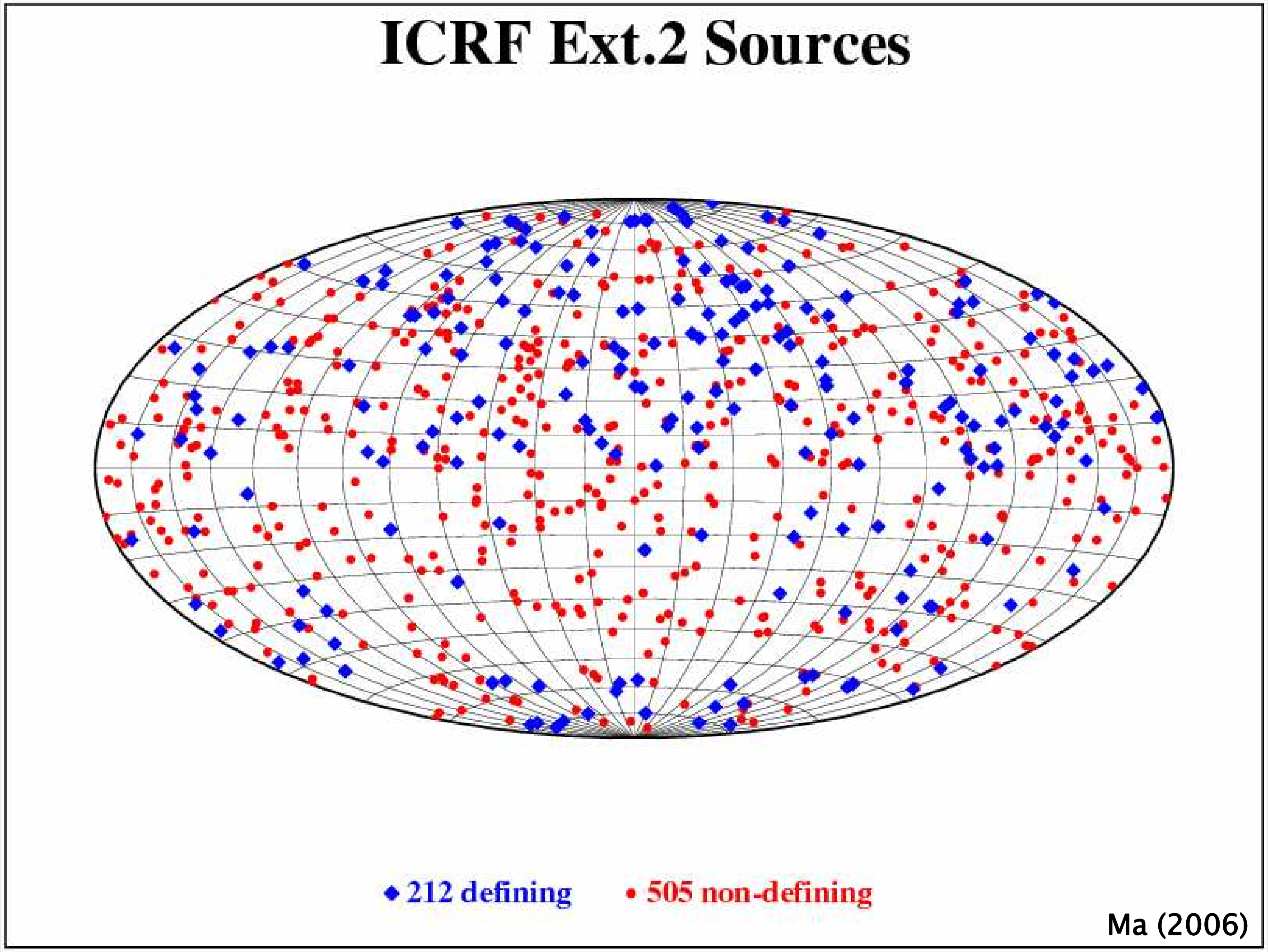
In practice:

τ_{ion} removed by linear combination of the delays measured at 2.3 GHz (S band) and 8.4 GHz (X band)

The International Celestial Reference Frame

- ICRF (International Celestial Reference Frame) built in 1995 by a Working Group of the IAU (Ma et al. 1998)
- Based on all VLBI astrometric/geodetic data acquired between 1979 and 1995
- 1.6 Million pairs of group delay and phase delay rate observations
- ICRF comprises 608 extragalactic sources
    - 212 defining sources
    - 294 candidate sources
    - 102 other sources
- Orientation of frame consistent with optical FK5 system
- ICRF-Ext.1 (1999) and ICRF-Ext.2 add another 59 + 50 sources => 717 sources today

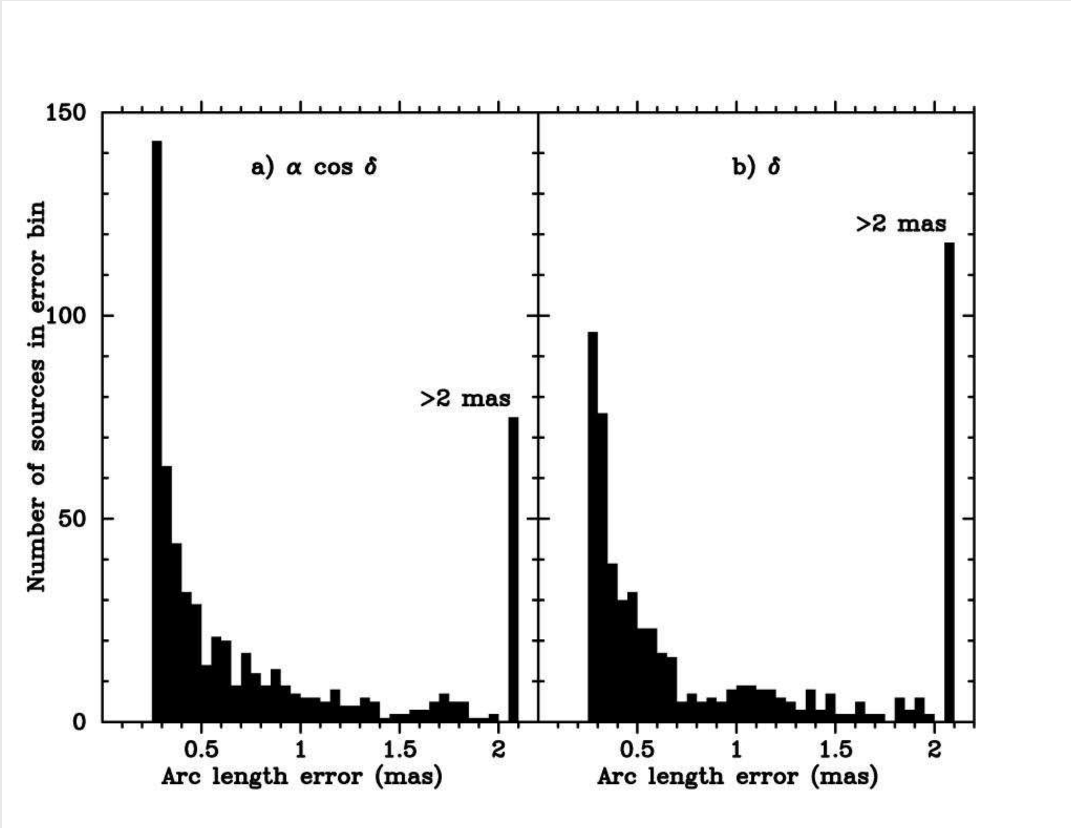
ICRF sky distribution



Ma (2006)

ICRF position accuracy

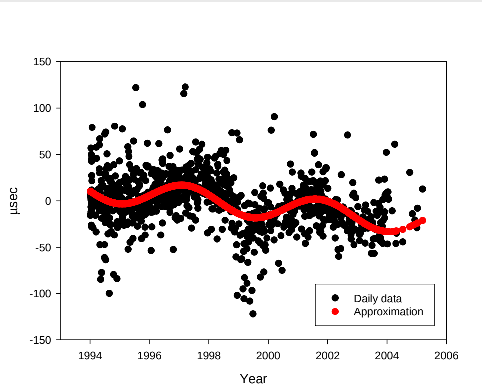
- Individual source position accuracy: $\geq$ 0.25 mas



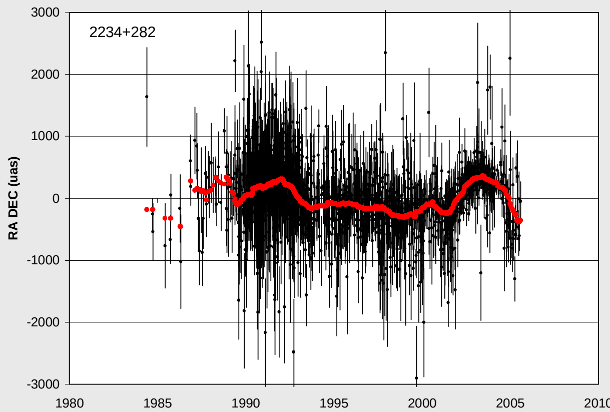
- Orientation of reference frame known to 0.02 mas

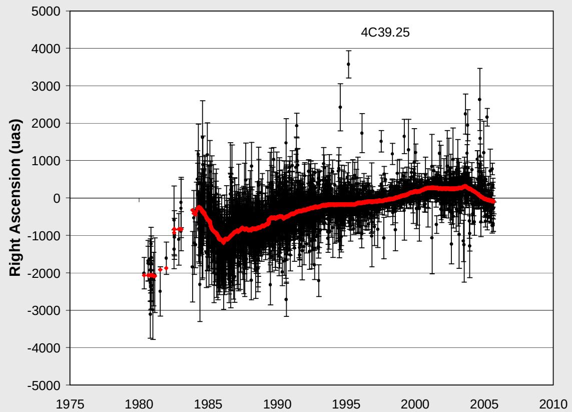
Future: ICRF-2

- Currently being built by a Working Group of the IAU and IVS
- Should be presented at IAU 2009 General Assembly
- Will add all VLBI data acquired since 1995
- Improved modeling (troposphere)
- Improved source categorisation
  - => accounts for source position variability and source structure to identify defining sources
- Source position variability



Titov (2006)

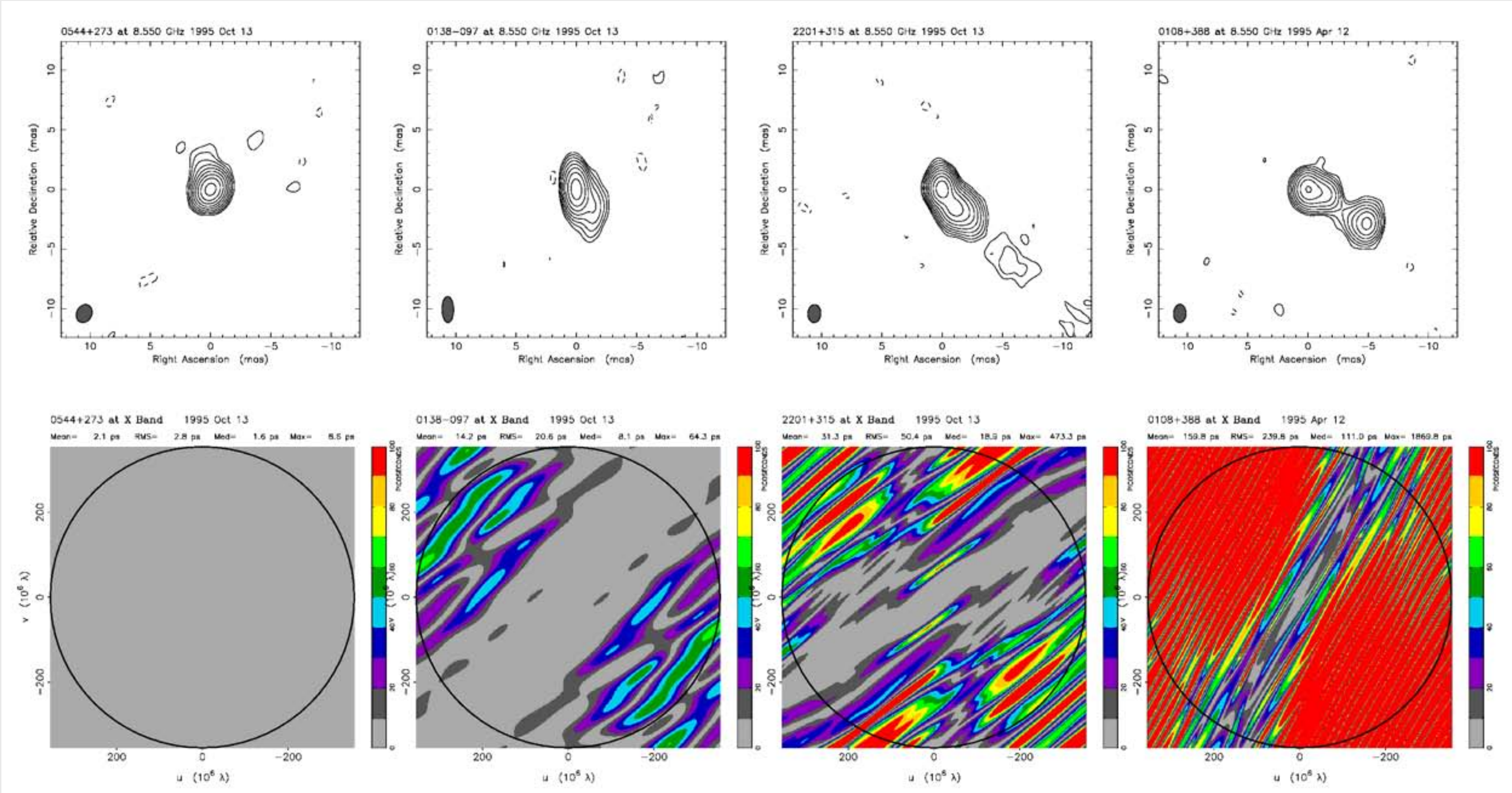




MacMillan (2006)

Future: ICRF-2

- Impact of source structure on the VLBI group delay



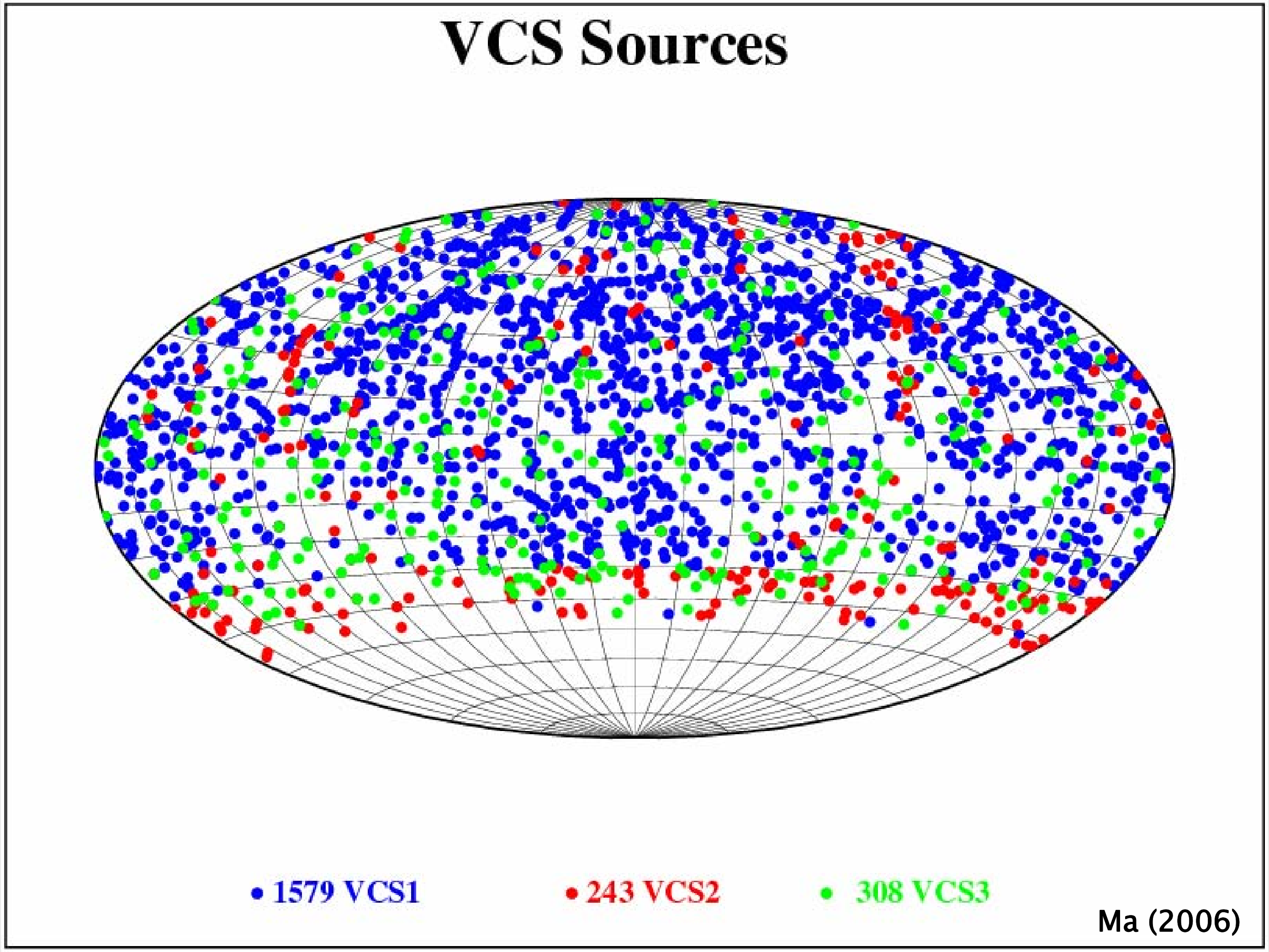
Four « structure index » categories defined to identify the most compact sources

Charlot (2002)

The VLBA Calibrator Survey (VCS)

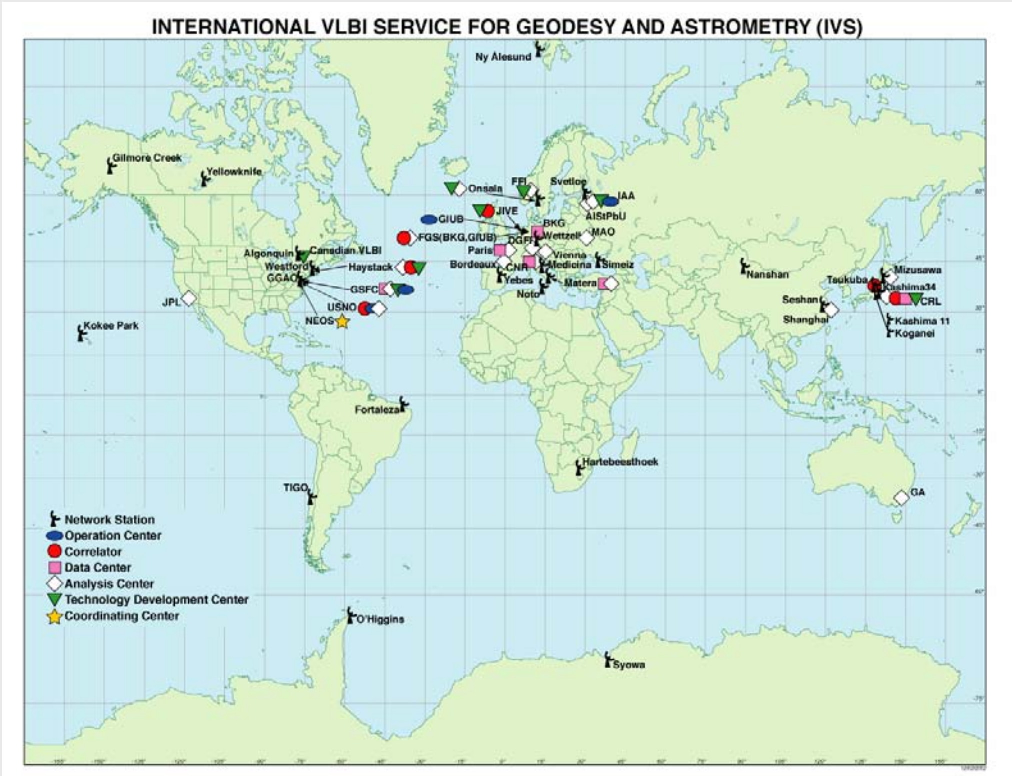
- Based on a series of VLBA experiments conducted since 1994
- Most of the sources observed only in one experiment
- Declination > −45°
- Milliarcsecond position accuracy
- Successive steps:
  - VCS1: 1579 sources (Beasley et al. 2002)
  - VCS2: 243 sources (Fomalont et al. 2003)
  - VCS3: 308 sources (Petrov et al. 2005)
  - VCS4: 258 sources (Petrov et al. 2006)
  - VCS5: 569 sources (Kovalev et al. 2006)
- Includes VLBI images as well
- Provides a dense grid of calibrators for phase-referencing

VCS sky distribution



+ 258 VCS4 + 569 VCS5 (not shown)

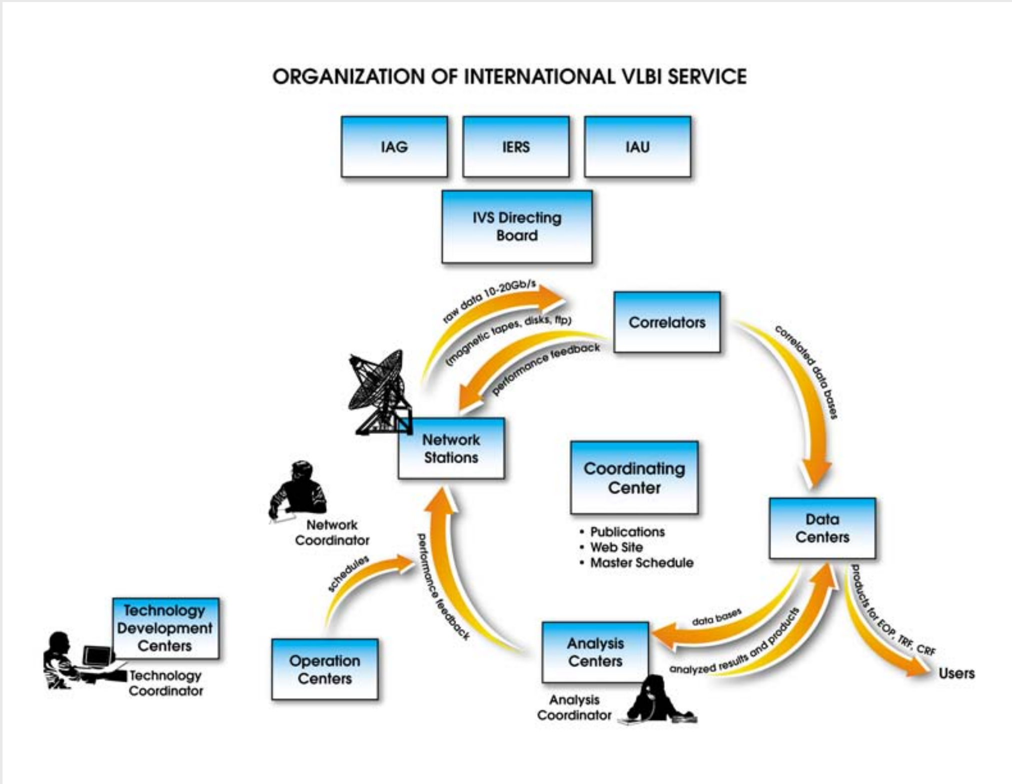
International VLBI Service for Geodesy and Astrometry



> 30 institutes around the world

IVS monitors…

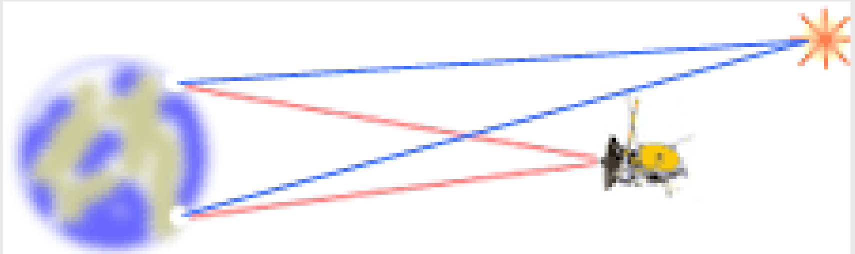
- the celestial frame
- the Earth’s orientation
- the terrestrial frame



IVS observing

- Several 24-hour sessions conducted each week
- Additional 1- to 2-hour sessions every day for Earth rotation
- Data immediately available from IVS data centres

Phase-referenced astrometry



- Observe alternately a target and an angularly-close (~1°) calibrator
  - target: e.g. weak extragalactic source, stellar object, spacecraft,...
  - calibrator: e.g. ICRF or VCS source
  - cycle calibrator/target of a few minutes
- Then, differentiate the measured phases for the calibrator and target
  - do not require phase connection
  - modeling errors scale with calibrator/target angular separation
- Permits accurate relative (narrow-angle) astrometry
  - see talk/demo by A. Brunthaler tomorrow...

The end

Thanks!