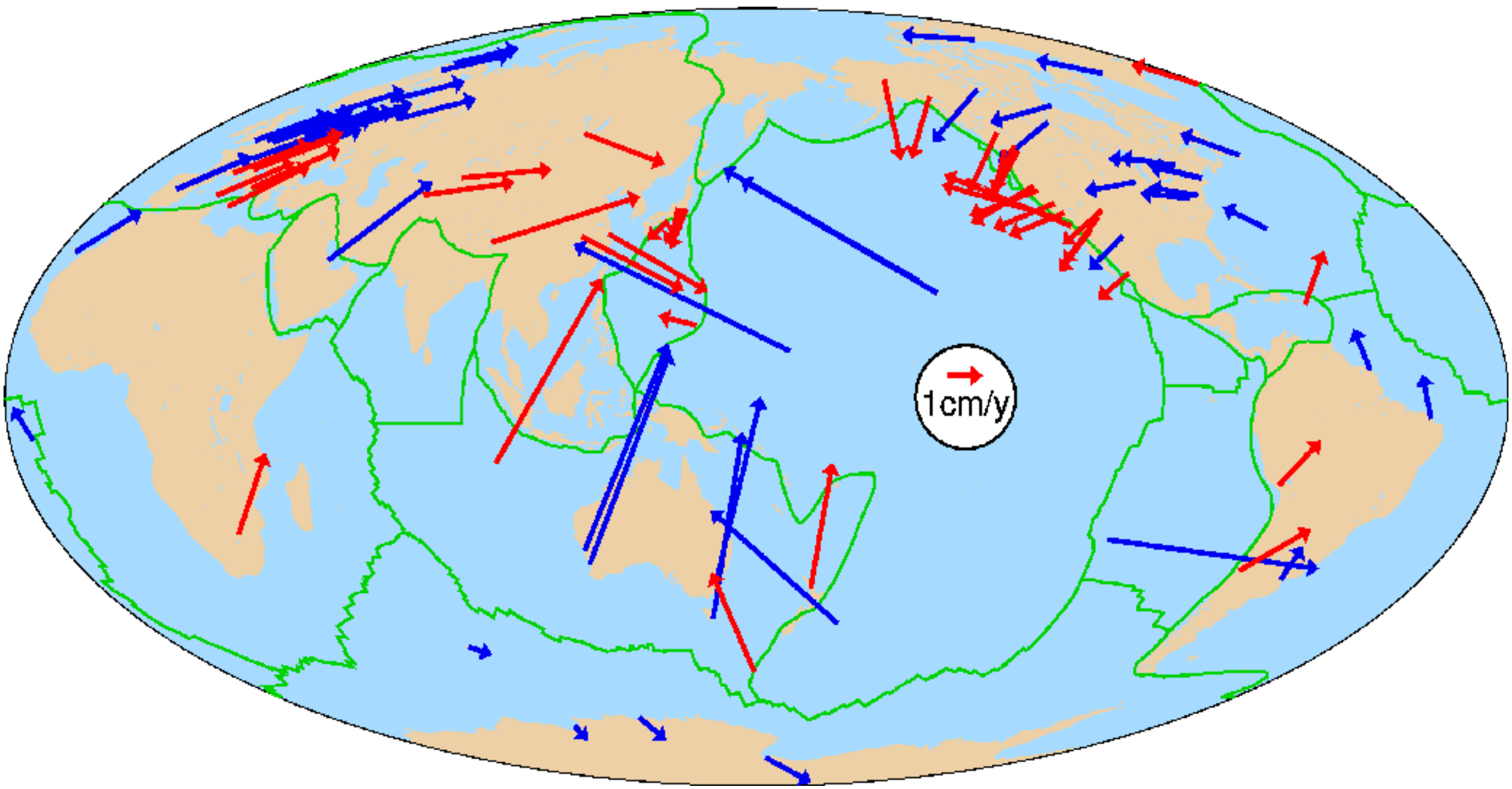
GEOS 655 Tectonic Geodesy

Jeff Freymueller
jfreymueller@alaska.edu
Elvey 413B, x7286

Application of Geodesy to Tectonics

Uncertainties < 1 mm/y

Blue: stable part of tectonic plates **Red: deforming zones**



Geodesy

- **Etymologically comes from Greek: « geôdaisia »: « dividing the Earth »**
- **Study of the form, dimensions, rotation and gravity field of the Earth**
- **Main geodesy activity: determination of point/ object positions over the Earth surface or near-by space**
- **Geodesy is particularly relevant today because everything on the surface of the planet is moving, and we can measure these movements precisely.**

The “Three Pillars of Geodesy”

- **Positioning**
  - GPS/GNSS, VLBI, SLR, DORIS
- **Earth Rotation and Orientation**
  - Position of the Earth in space
- **Gravity Field**
- All three dynamic
- All linked and interdependent

Very Very Old Geodesy

Eratosthenes (276-194BC) measured the radius of the earth to be 5950 km, in error by 6.7% (6378.137 km).

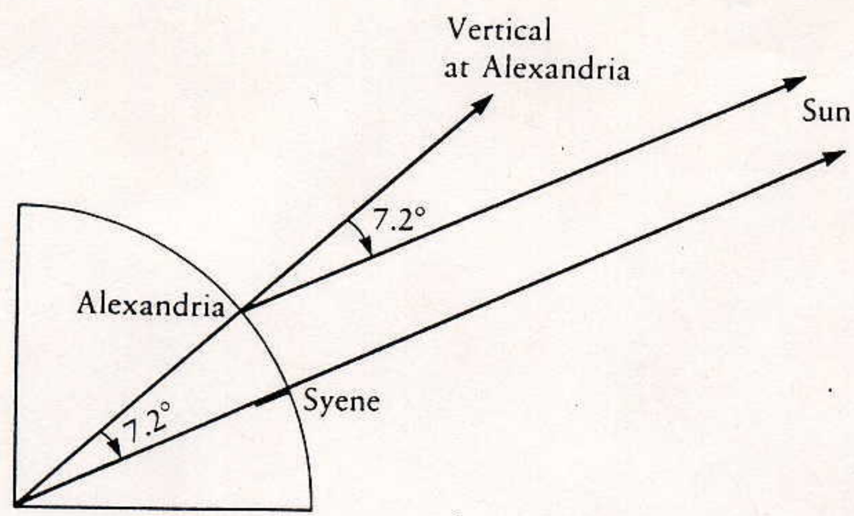


FIGURE 1.3
The observation of Eratosthenes.

Pythagoras (580-500BC) had proposed that the Earth and heavenly bodies were spherical in shape, based on the sphere being the most harmonious solid shape.

Astronomy, Geodesy, Surveying and Navigation

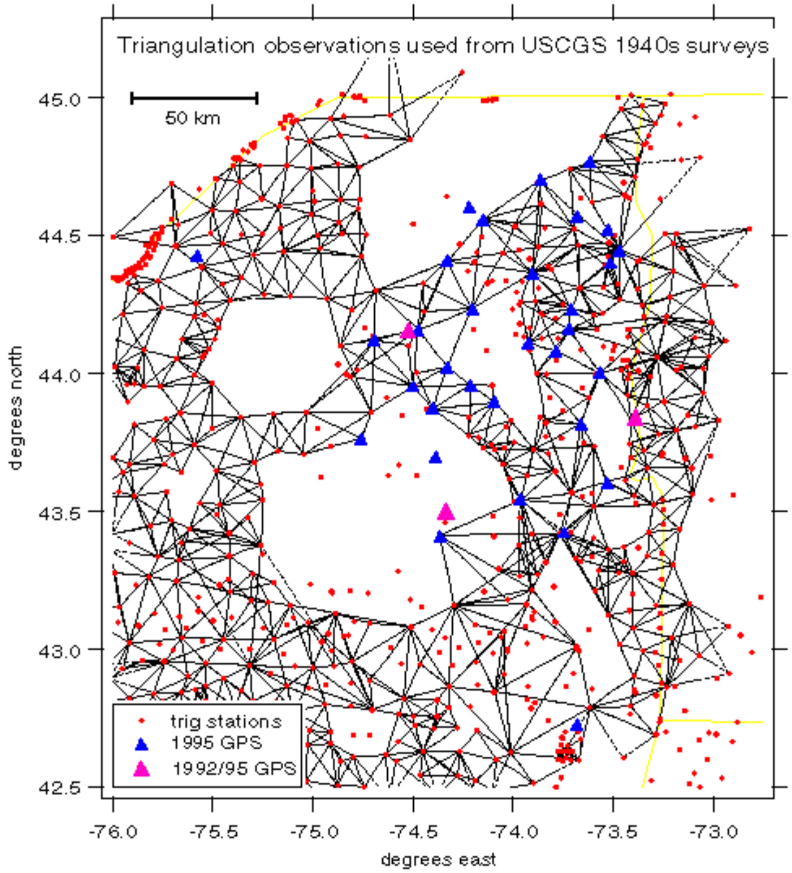
Peter Apian's *Geographia* 1533

• The tools were, to a great extent, the same. The measurement of angles was *the* central issue.

Astronomy, Geodesy, Surveying and Navigation

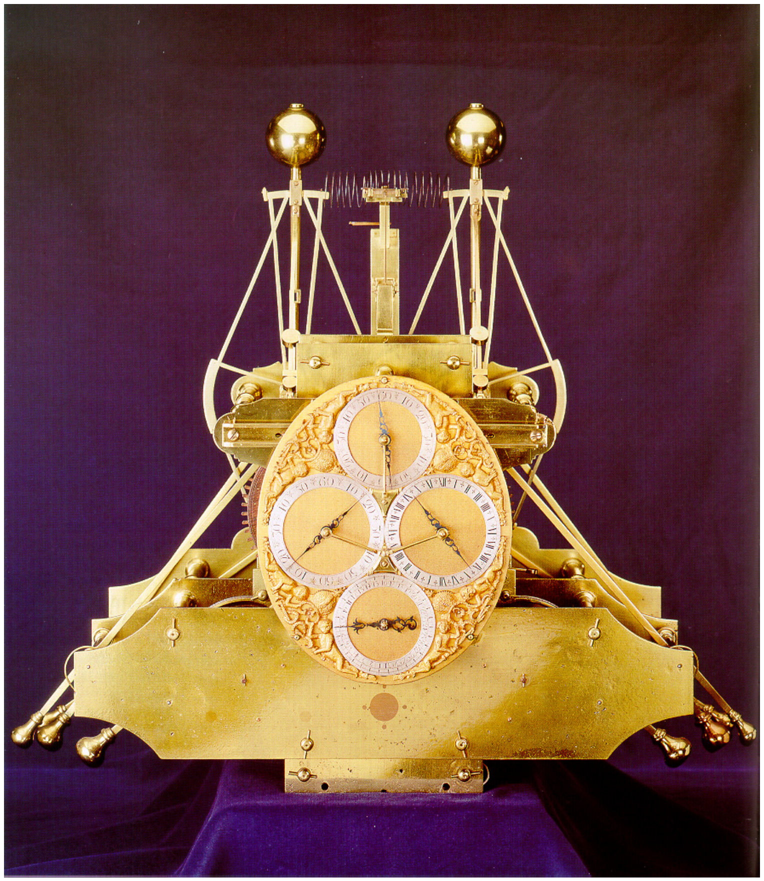
- The ***principles*** of navigation, surveying and geodesy remained *in essence* the same from Apian's times until 1950, but the tools improved:
  - *Theodolites* replaced the *cross-staffs*
  - Marine chronometers made the measurement of lunar distances obsolete (for navigation)
- In *fundamental astronomy* the celestial and global terrestrial reference systems and the transformation between them was established in greater and greater detail.

Geodetic Networks



- The measurement technology controls the way that geodesy is done
- Horizontal: Triangulation by measurement of angles.
- Vertical: Leveling along transects (usually roads).

Clocks in Astronomy and Navigtion



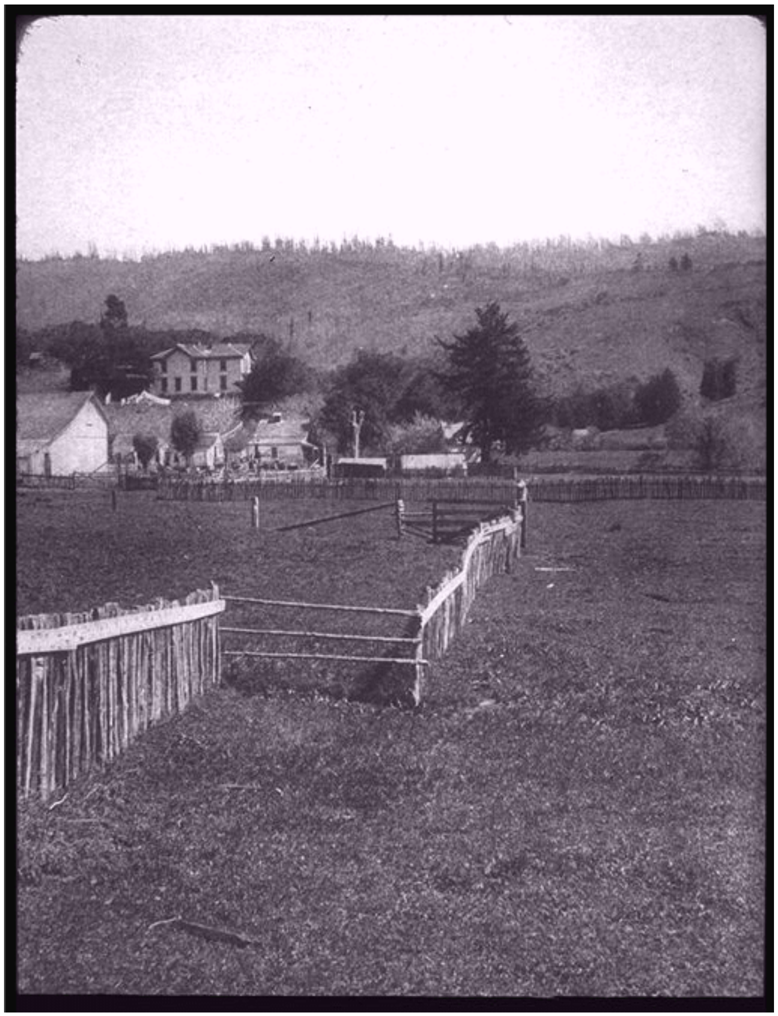
Harrison I, First marine chronometer

- J. Harrison (1693-1776) developed the first marine chronometers, which could cope with astronomical time determination for navigation.
- For precise static positioning the rotating Earth and the planetary and lunar orbital motion were the state-of-the-art clocks.
- Until about 1950 the earth was the most precise clock available.
- Since the 1950s atomic clocks successively took over the task of defining time.

Timeline

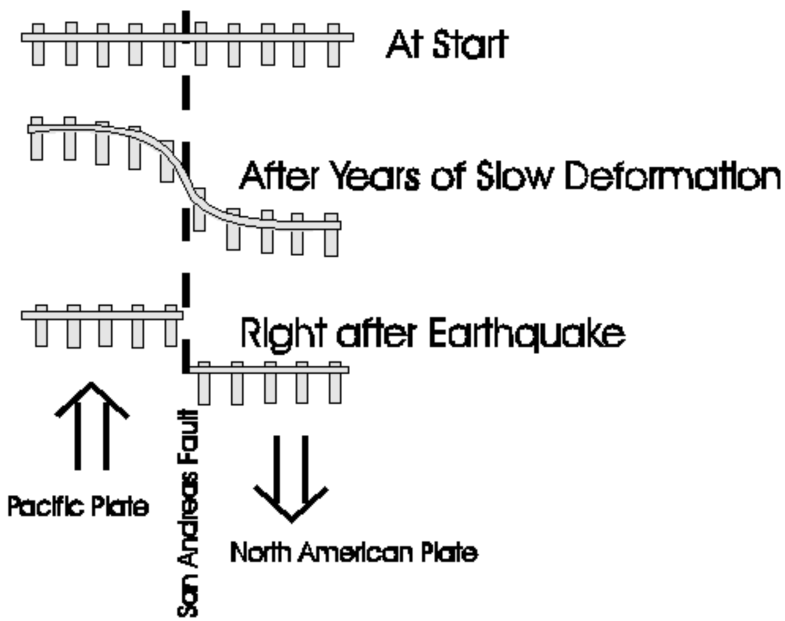
- 1910: Displacements from 1906 San Francisco earthquake measured from repeated triangulation.
- 1964-1967: Plate tectonic revolution
- 1970s: USGS begins systematic EDM measurements
- Early 1980s: VLBI and SLR become mature, measure plate motions and start to measure plate boundary deformation in western US
- 1985: First GPS campaign aimed at measuring crustal motion

H. F. Reid: Elastic Rebound



- From an examination of the displacement of the ground surface which accompanied the 1906 earthquake, Henry Fielding Reid, Professor of Geology at Johns Hopkins University, concluded that the earthquake must have involved an "elastic rebound" of previously stored elastic stress.

Observations of fault offsets



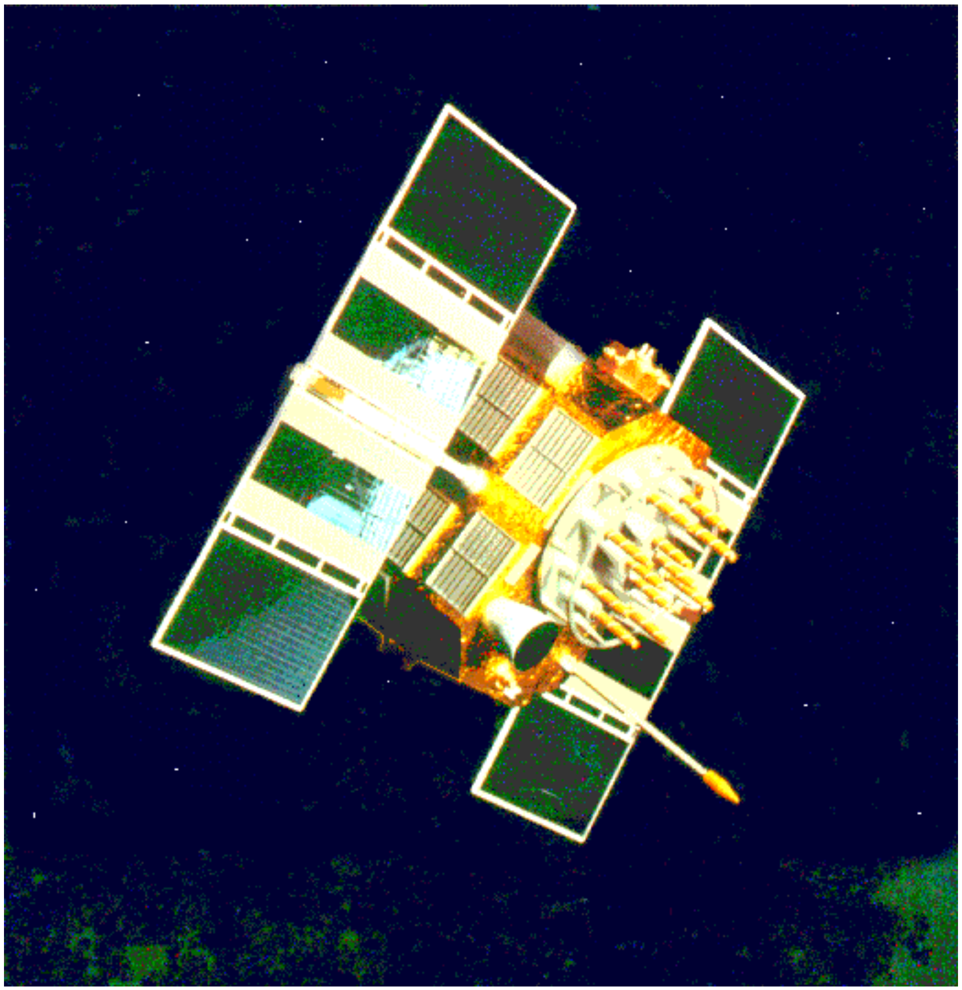
- Early observations indicated that something was happening on faults between earthquakes
- None of this made much sense until after plate tectonics was established

Timeline for GPS

- 1985: GPS campaigns begin in California to measure tectonics
  - Precision is at level of 2-3 cm
- Late 1980s: First reliable estimates of motion from GPS
- 1991: GIG 1991 first global network
  - Precision is ~ 1 cm
- 1992: Start of IGS Pilot Service (daily precise orbit computation)
- 1994: IGS begins as operational service; GPS constellation complete
- 1995: Kobe and Northridge earthquakes spur development of large continuous GPS networks in Japan and California
- Late 1990s: GPS results for tectonics, earthquake displacements, postseismic deformation common
  - Precision approached ~5 mm (now 2-3 mm via reanalysis)
- Now: Continued development: Continuous networks, high-rate GPS dynamic displacements, etc.

EDM: Electro-optical Distance Measurements

Revolution of the Space Age



- Fundamental change was from measurement of **angles** to measurement of **distances.**
- Precise distance measurements require precise timing.

Space Geodesy Techniques

- Very Long Baseline Interferometry (VLBI)
- Lunar Laser Ranging (LLR)
- Satellite Laser Ranging (SLR)
- DORIS
- GNSS (Global Navigation Satellite Systems)
  - Global Positioning System (GPS)
  - GLONASS (Russia)
  - GALILEO (EU)
  - Beidou (“Compass”) (China)
  - QZSS (Japan)

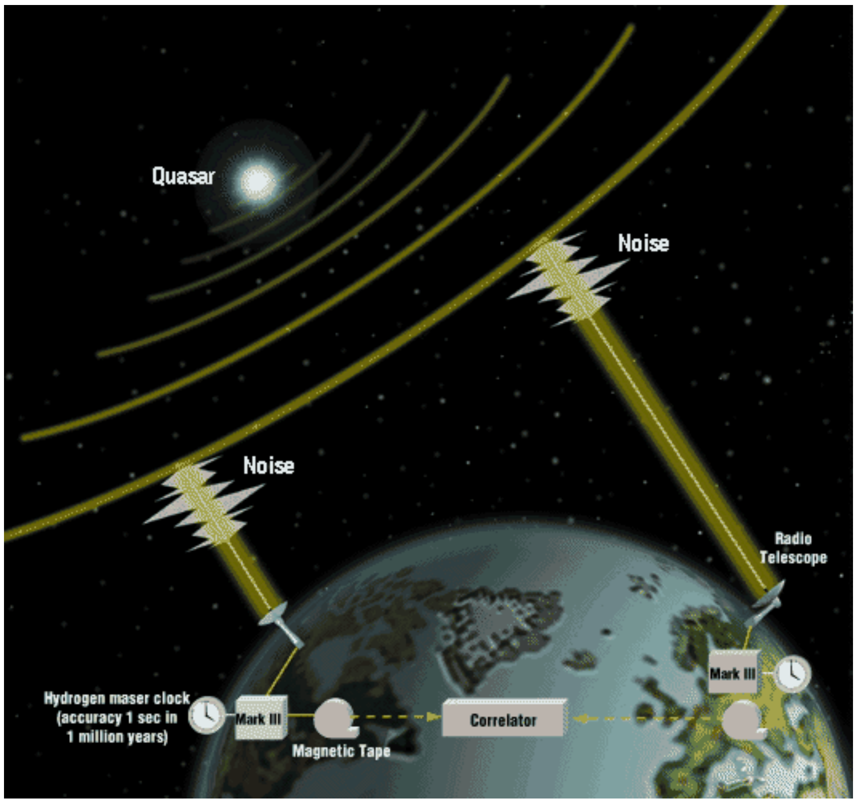
International Association of Geodesy
Space Geodesy Services

- International Earth Rotation and Reference Systems Service (IERS) (1988)
- Intern. GNSS Service (IGS) (1994)
- Intern. Laser Ranging Service (ILRS) (1998)
- Intern. VLBI Service (IVS) (1999)
- Intern. DORIS Service (IDS) (2003)
- And more …
- Unifying project: Global Geodetic Observing System (GGOS)

http://www.iag-aig.org/

VLBI and SLR

VLBI – Very Long Baseline Interferometry



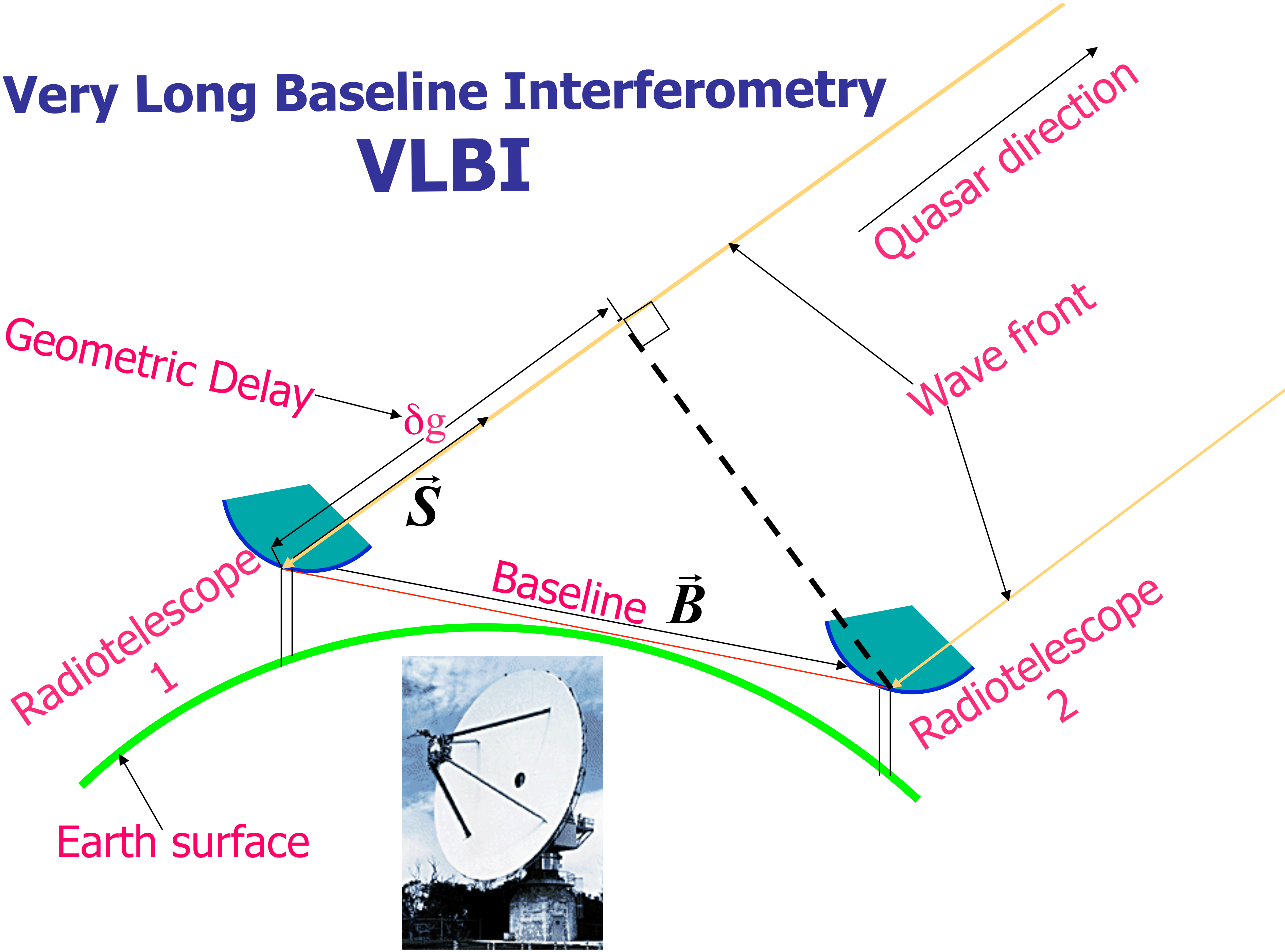
SLR – Satellite Laser Ranging

VLBI and SLR

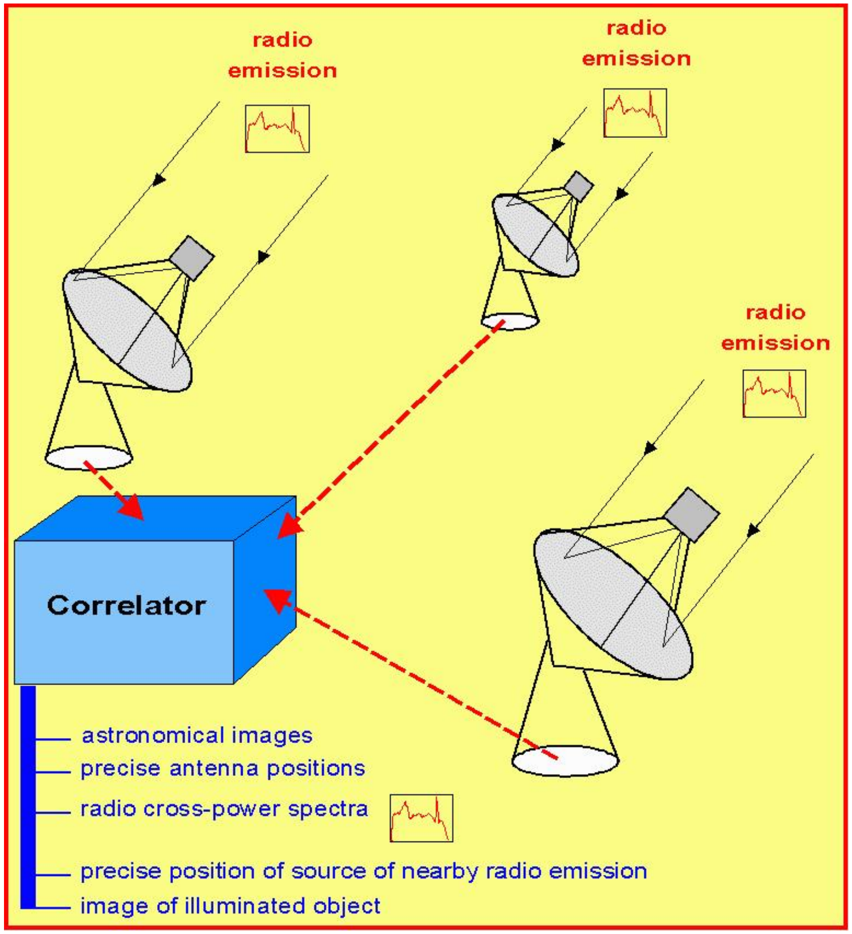
- Originally for measurement of crustal motion
- Today's critical uses:
  - SLR: determination of geocenter
  - SLR: changes in earth's gravity field (J2, etc).
  - SLR: tracking of some satellites
  - VLBI: earth rotation rate
  - VLBI: earth orientation in space
  - both: contribute to stable definition of reference frame
- IAG services provide weekly solutions for ITRF
  - IVS for VLBI
  - ILRS for SLR


VLBI

Very Long Baseline Interferometry
VLBI



Quasar Radio Emissions Recorded

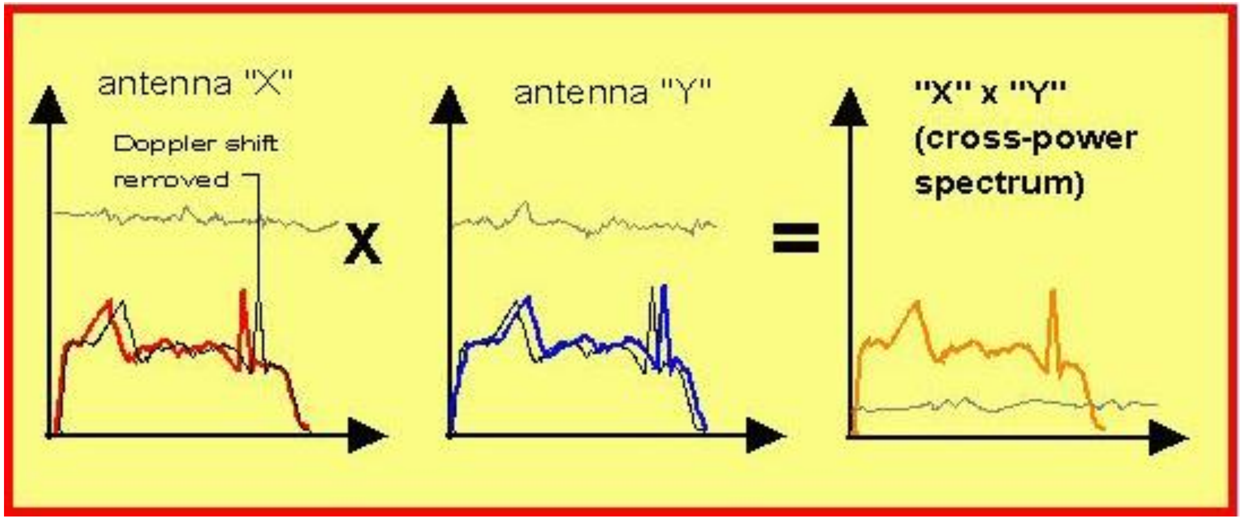


- Quasar = "Quasi-stellar object"
- Each quasar emits a unique and time-varying radio signal
- Radio emissions from quasars recorded
  - Several telescopes record same quasar at same time
  - Then re-orient and record a different quasar
  - Repeat
- Recordings sent to special computer called a correlator

The VLBI Correlator

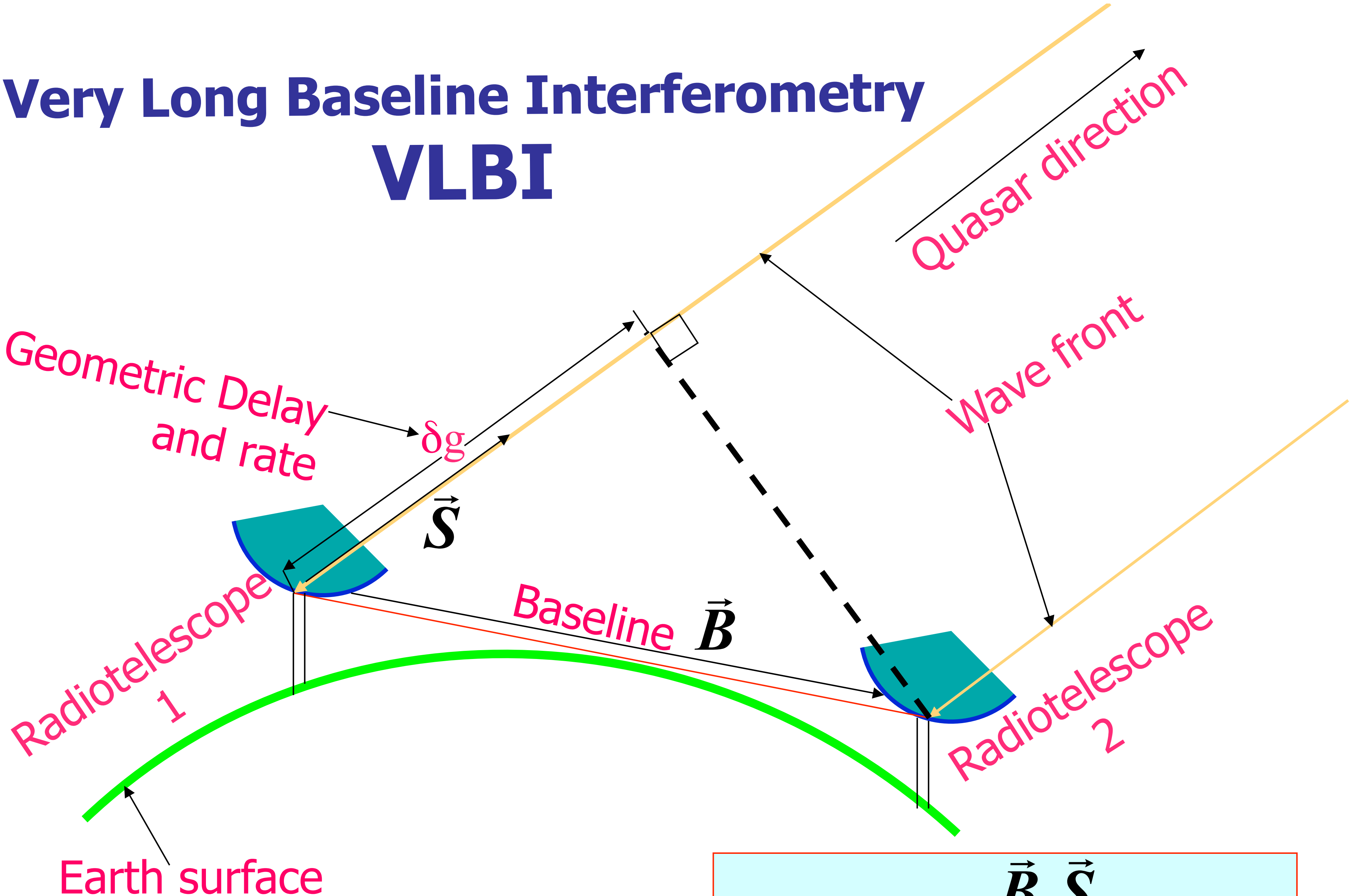
Looked like a movie-version computer command center.
Today the correlator is done in software, and data can be digital streams

Cross-correlation



- Signals cross-correlated (spectral), 3 observables:
  - Phase delay (ambiguous but very precise)
  - Group delay (unambiguous)
  - Phase delay rate of change (unambiguous)

Very Long Baseline Interferometry
VLBI

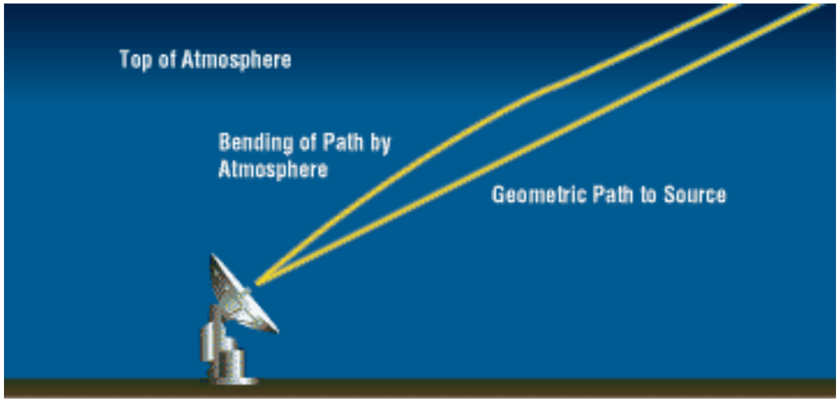


$$\delta g \equiv \tau(t) = \frac{\vec{B}.\vec{S}}{c} + \Delta\tau(t)$$

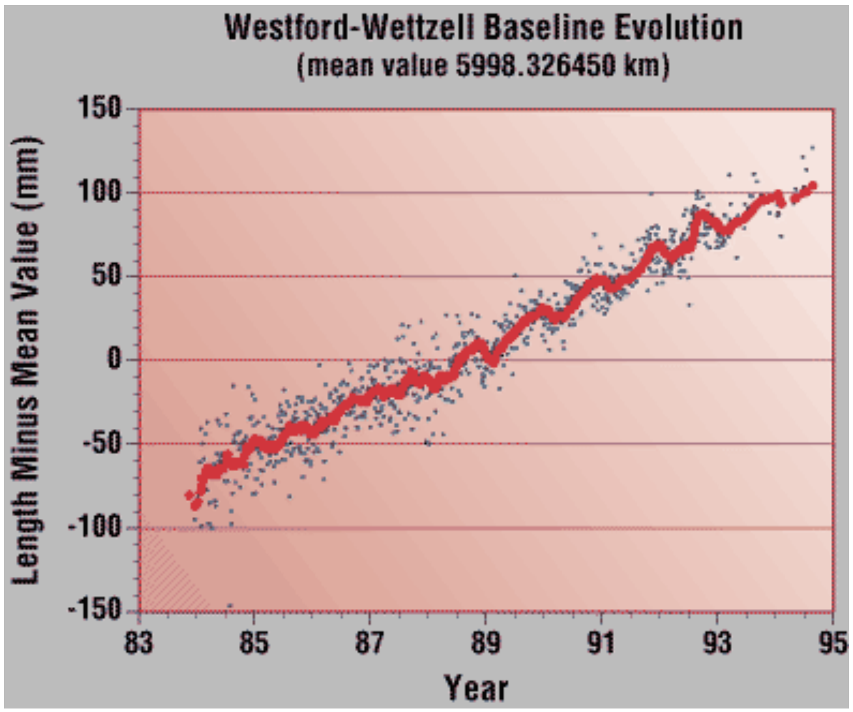
Observation Equation

$$\delta g \equiv \tau(t) = \frac{\vec{B}.\vec{S}}{c} + \Delta\tau(t)$$

- Measurements to different quasars mean different direction vectors **S**.
  - Measure different components of B
- Tau represents other path delays

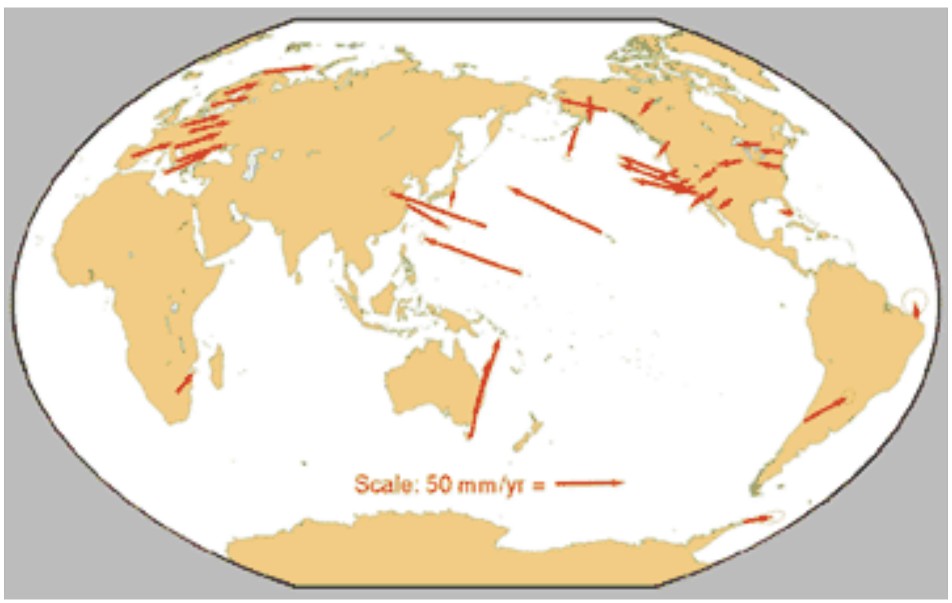


A Sample VLBI Baseline



- Plot shows evolution of baseline length
  - Westford (Massachusetts)
  - Wettzell (southern Germany)
- Note improvement in scatter over time
- Baseline length is invariant to rotations of network = most precise measure

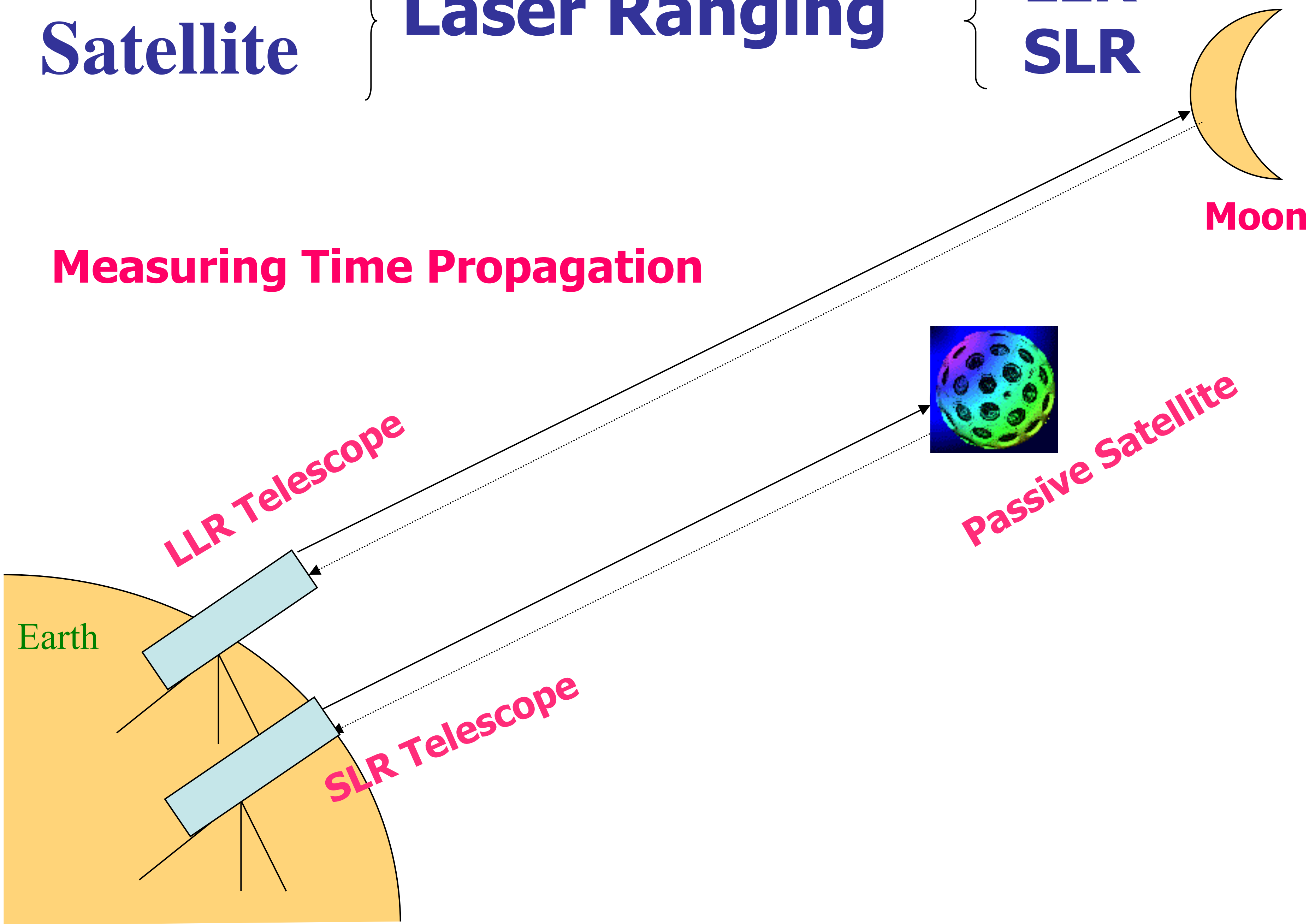
VLBI Site Velocities Circa 1995



- No sites in former Soviet Union, most of Africa
- Poor southern hemisphere coverage
- But sufficient to prove that plate motions over 1980-1990 agreed with NUVEL-1 model

Today there are a few more sites, but not many more – very expensive

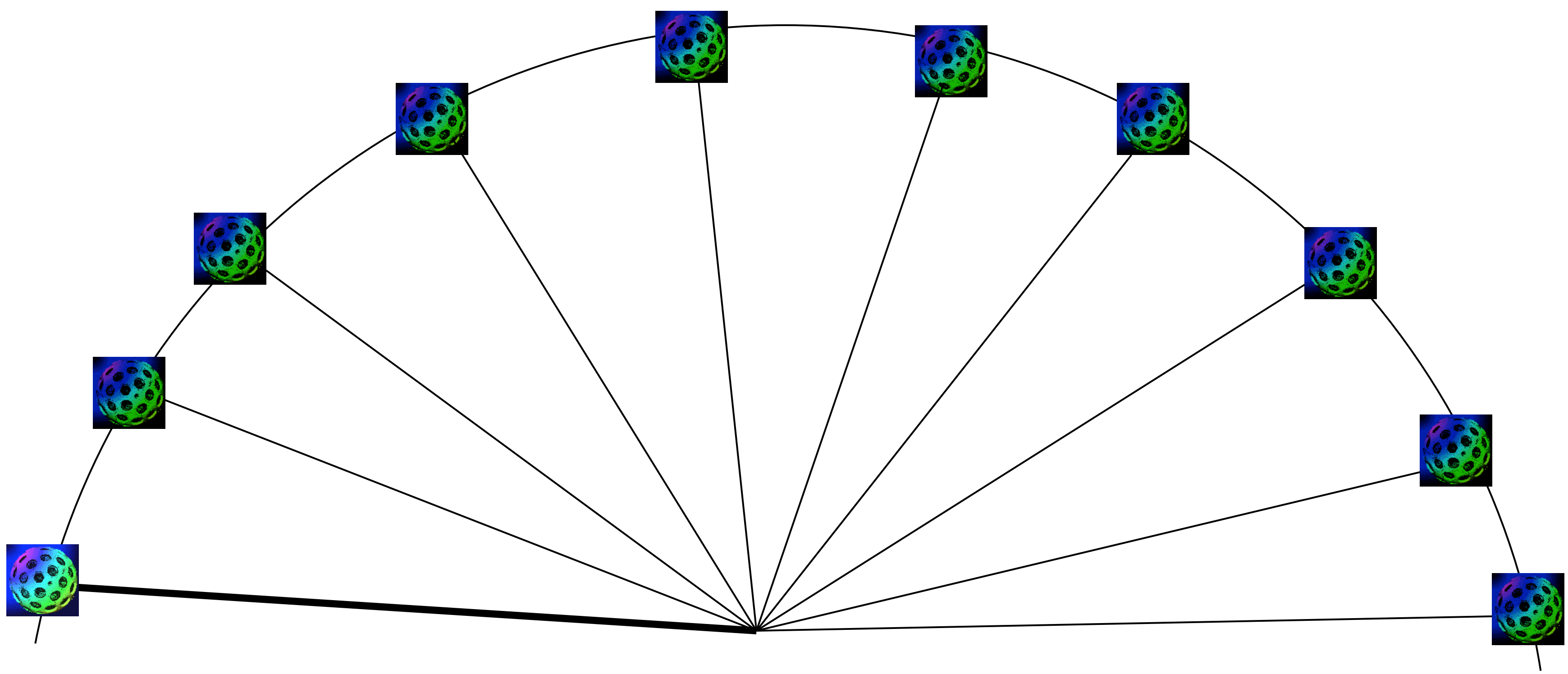
Lunar / Satellite — Laser Ranging — LLR / SLR



SLR Principles

- Emit laser pulse; start clock
- Photon detector stops clock on returned pulse
  - Shorter-duration pulse = higher precision
- No need for simultaneous observations, high-accuracy timing, just an accurate "stopwatch"
- Many pulses sent for each orbit

SLR Principles

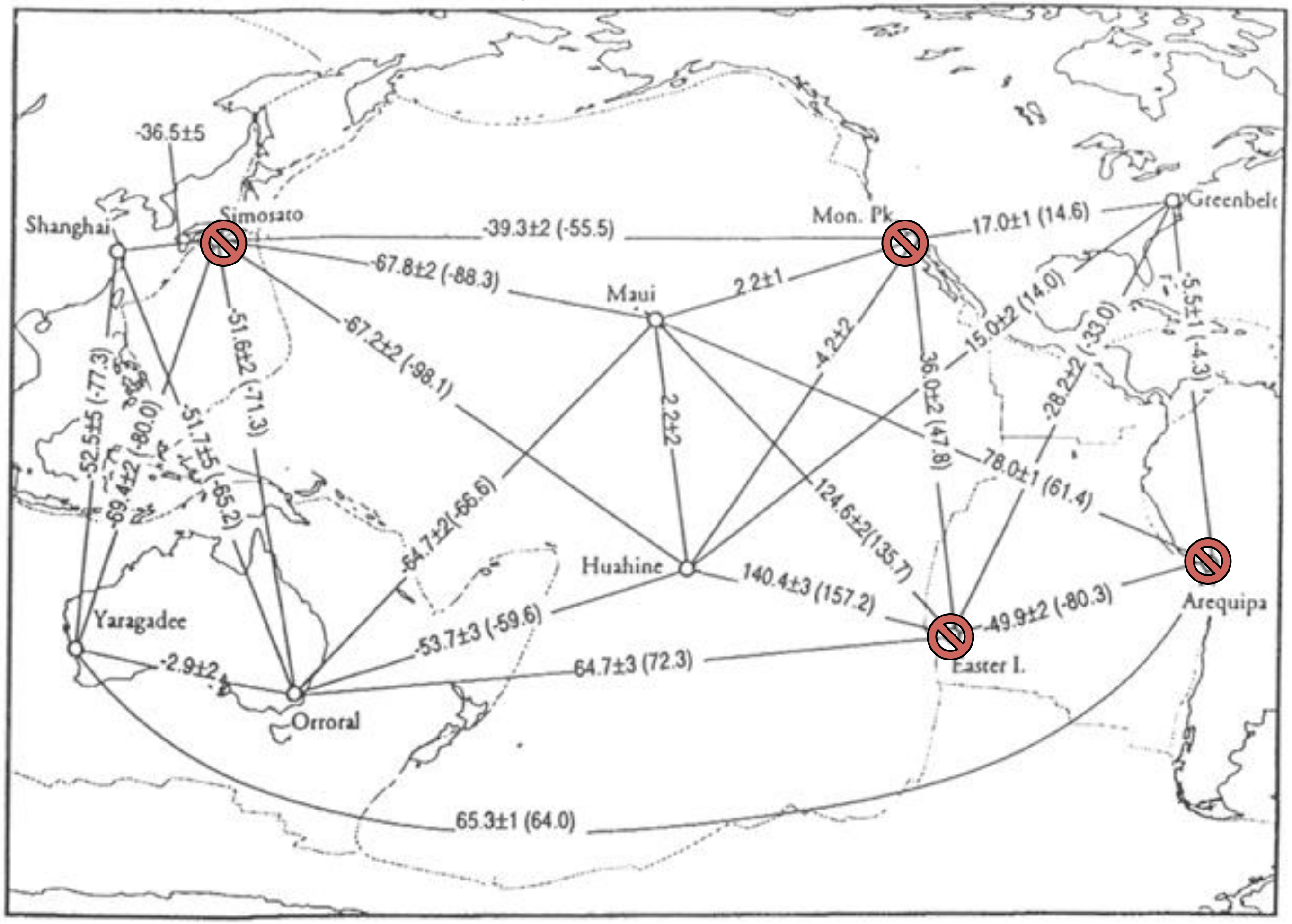


SLR Principles

- In practice, one week's data is used to determine a weekly average position. Until the 2000s they used monthly solutions.
  - SLR is less precise than GPS
- SLR satellites have very stable orbits, can estimate a single orbit for >10 years of observations
  - Solve for orbit initial conditions and Earth's gravity field
- SLR very sensitive to geocenter, large-scale gravity field

SLR Compared to Plate Model

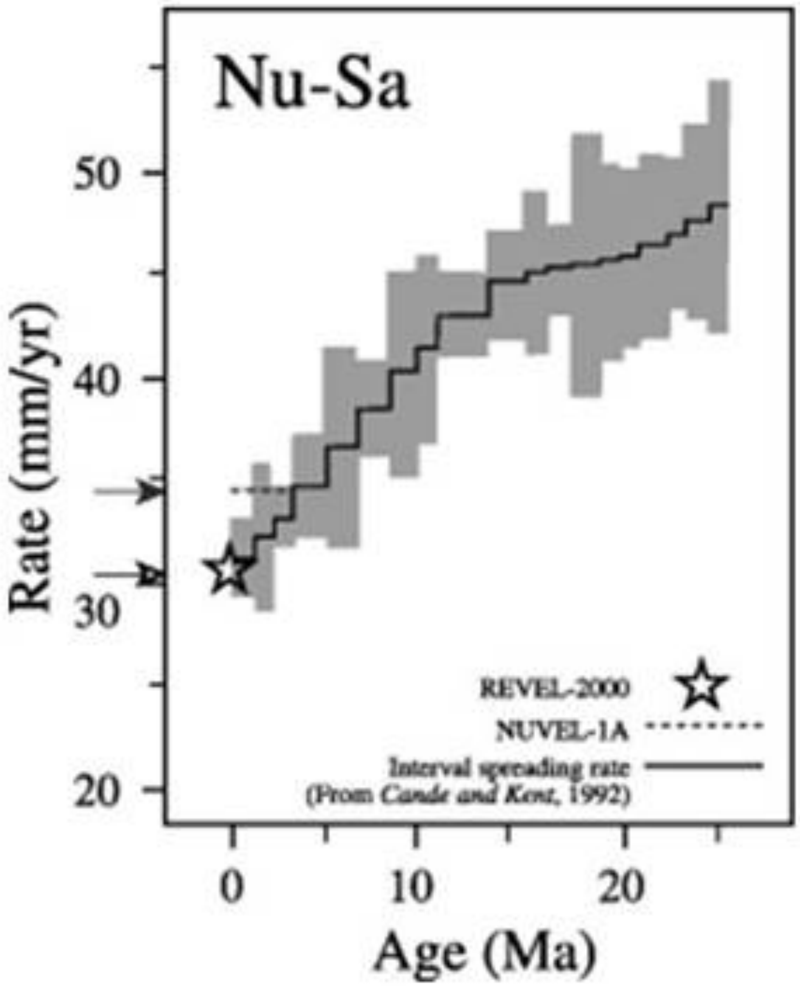
Early 1990s results



Geodesy and NUVEL-1A

- Geodetic plate motion rates in the 1980s were about 5-6% slower than the NUVEL-1 plate motion model predicted, but all in the same direction.
- The cause was an error in the magnetic timescale. When the timescale was updated in the early 1990s, the anomaly used for NUVEL-1s magnetic profiles was found to be about 6% older.
- The plate motion model was recalibrated and geodesy and geology were found to agree.

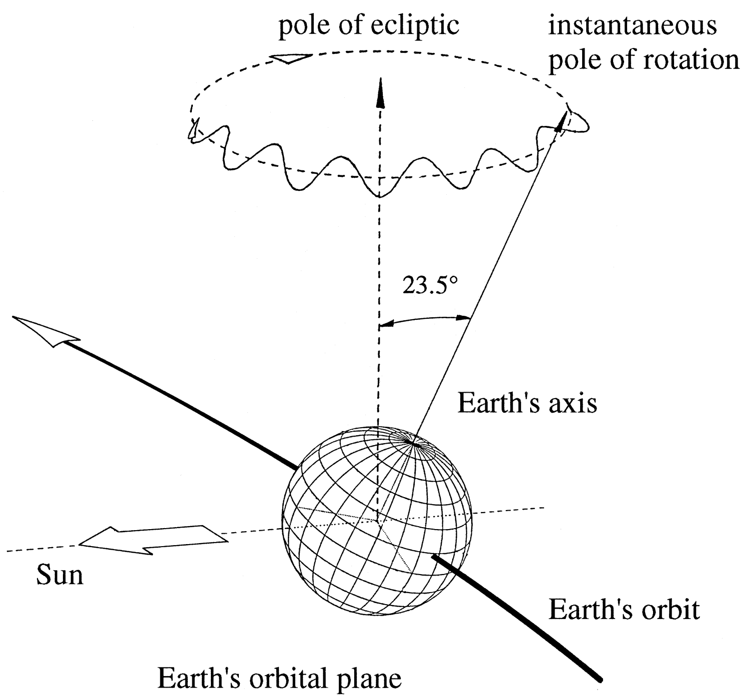
An Update on this Theme



- Nazca–South America motion has slowed down over the last 15 Ma
- Geodesy agrees with the most recent geologic time (~1 million year average)

Norabuena et al.

Earth Rotation



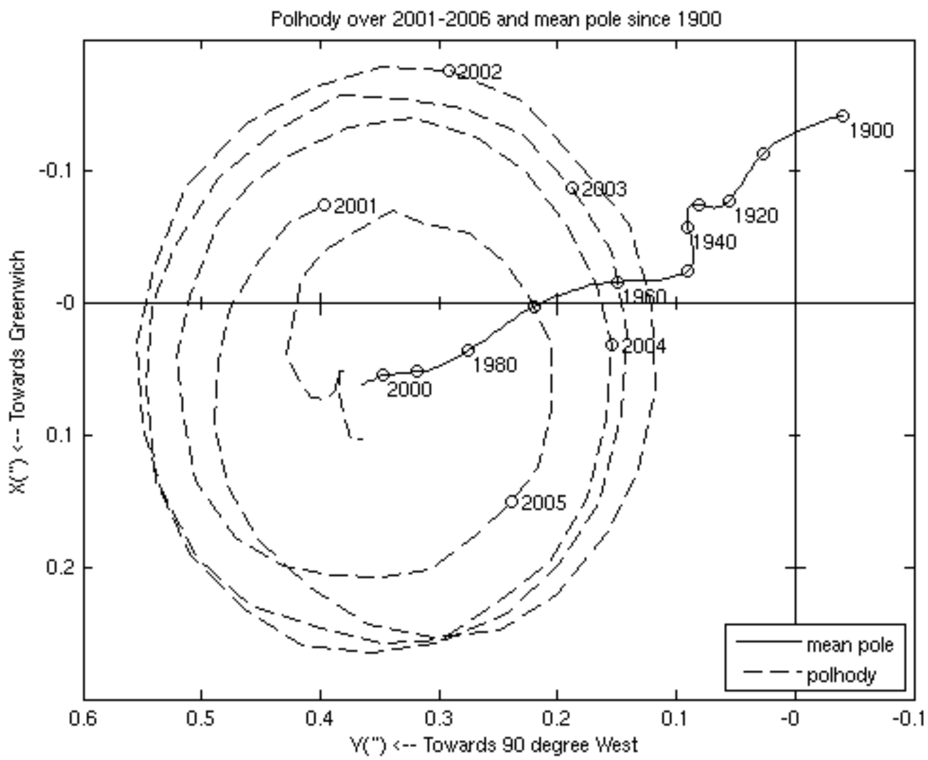
The Earth's rotation axis in inertial space

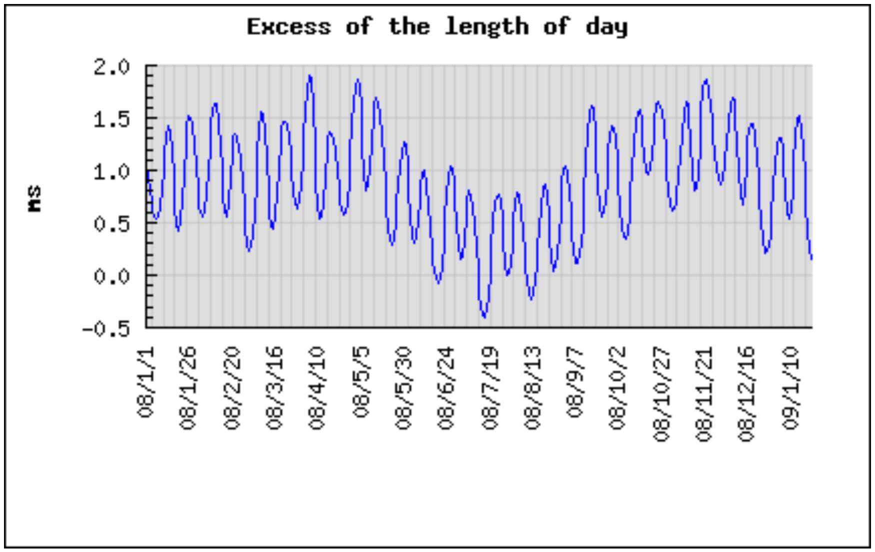
- The Earth rotates in inertial space (precession, nutation, length of day)
- Rotation axis moves on the Earth surface (polar wobble)
- The Earth was the *best clock* till about 1950!

Year	Discoverer	Effect
300 B.C	Hipparchus	Precession in longitude (50.4″/y)
1728 A.D.	J. Bradley	Nutation (18.6 years period, amplitudes of 17.2″ and 9.2″ in ecliptical longitude and obliquity, respectively)
1765 A.D.	L. Euler	Prediction of polar motion (with a period 300 days)
1798 A.D.	P.S. Laplace	Deceleration of Earth rotation (length of day)
1891 A.D.	S.C. Chandler	Polar motion, Chandler period of 430 days and Annual Period

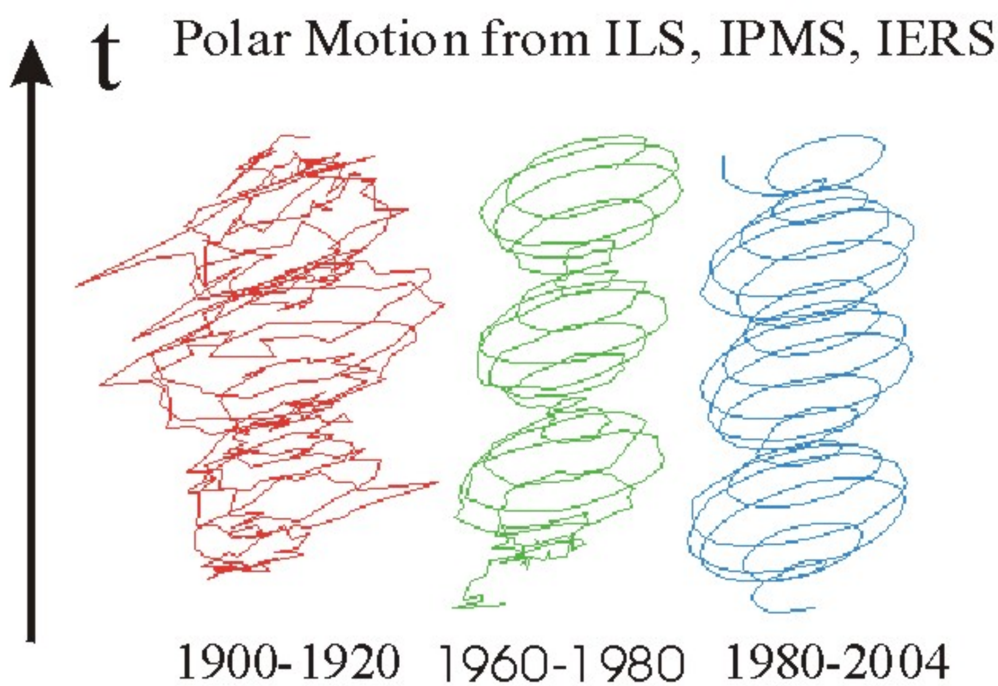
Earth’s Rotation Axis and Rotation Rate

- Long-term, short-term changes in pole location,



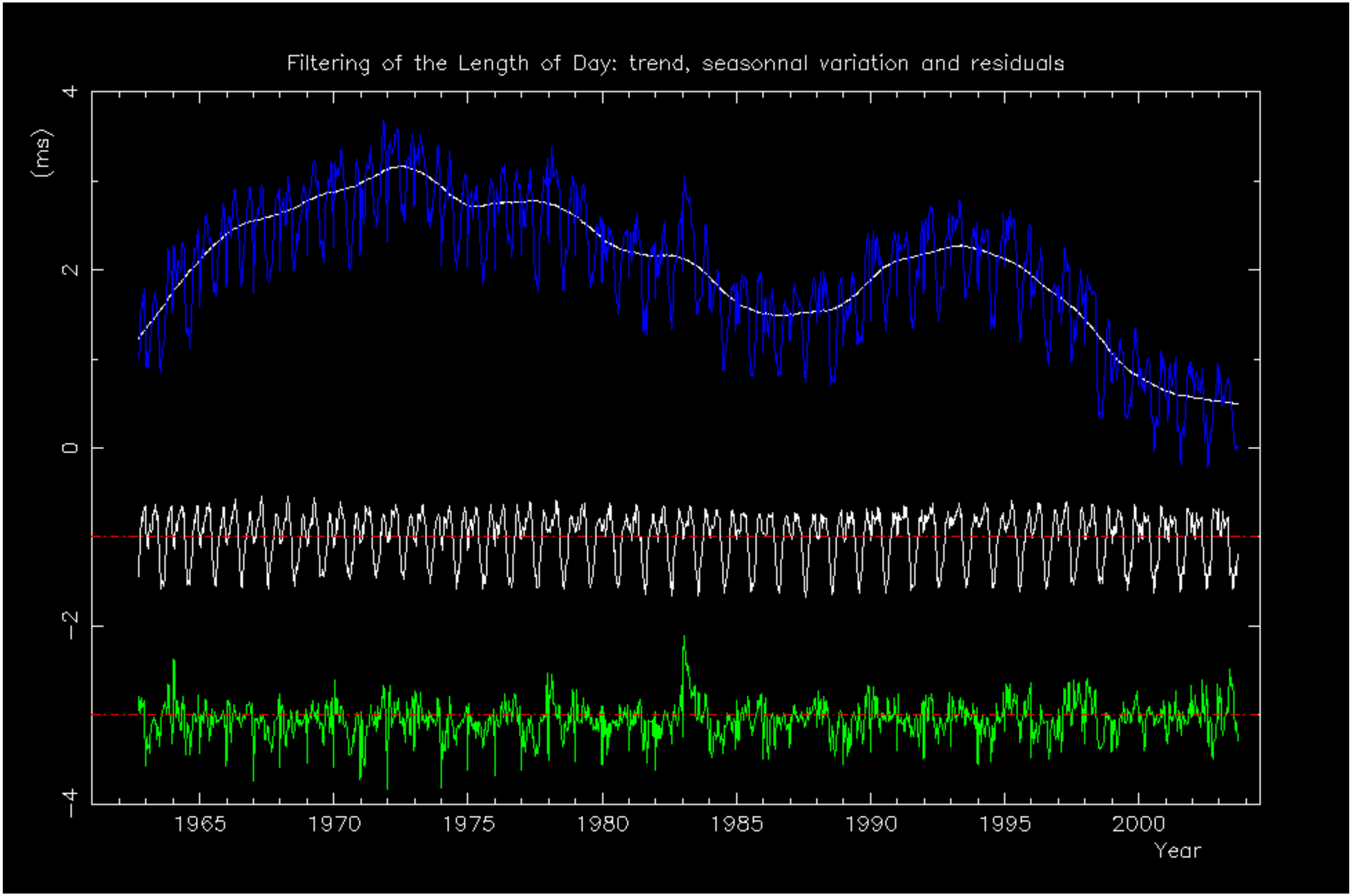


Services in IAG: ILS, IPMS, IERS

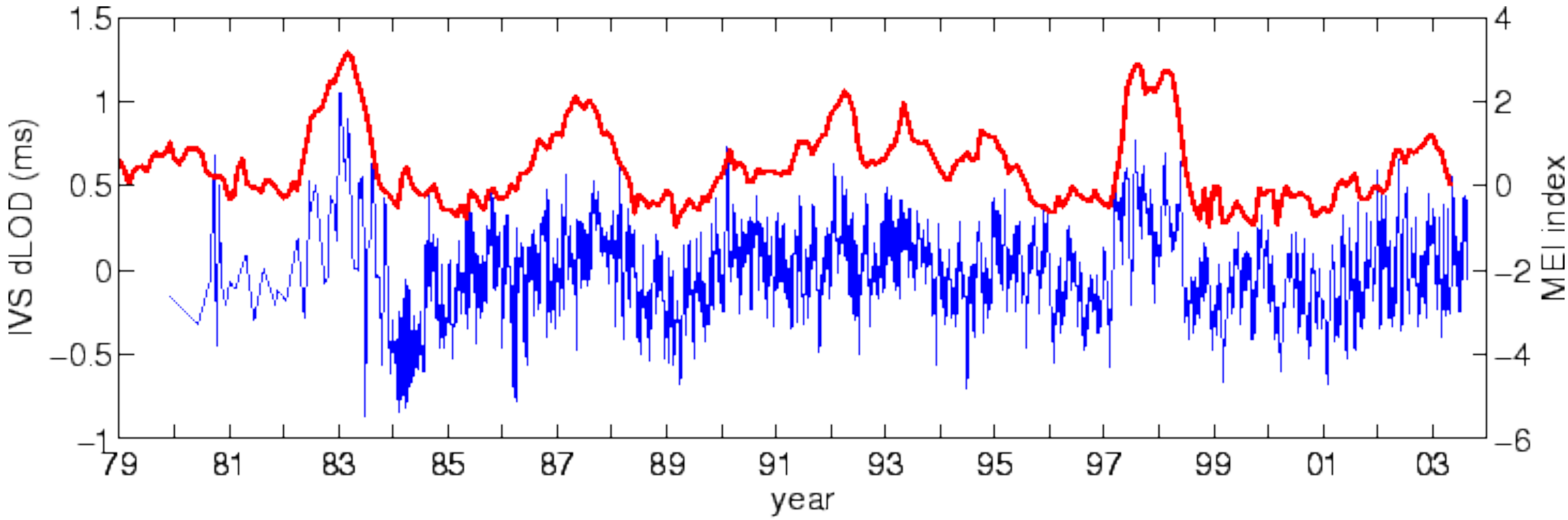


- IAG sets up a service for global monitoring tasks, if there are *products* and an *important user community*.
- The ILS monitored Polar Motion with 100 mas accuracy, the IPMS did the same with an accuracy of few 10 mas, the IERS with < 0.1 mas.

- ILS: International Latitude Service (1899-1959)
- IPMS: International Polar Motion Service (1960-1987)
- International Earth Rotation Service (since 1988)

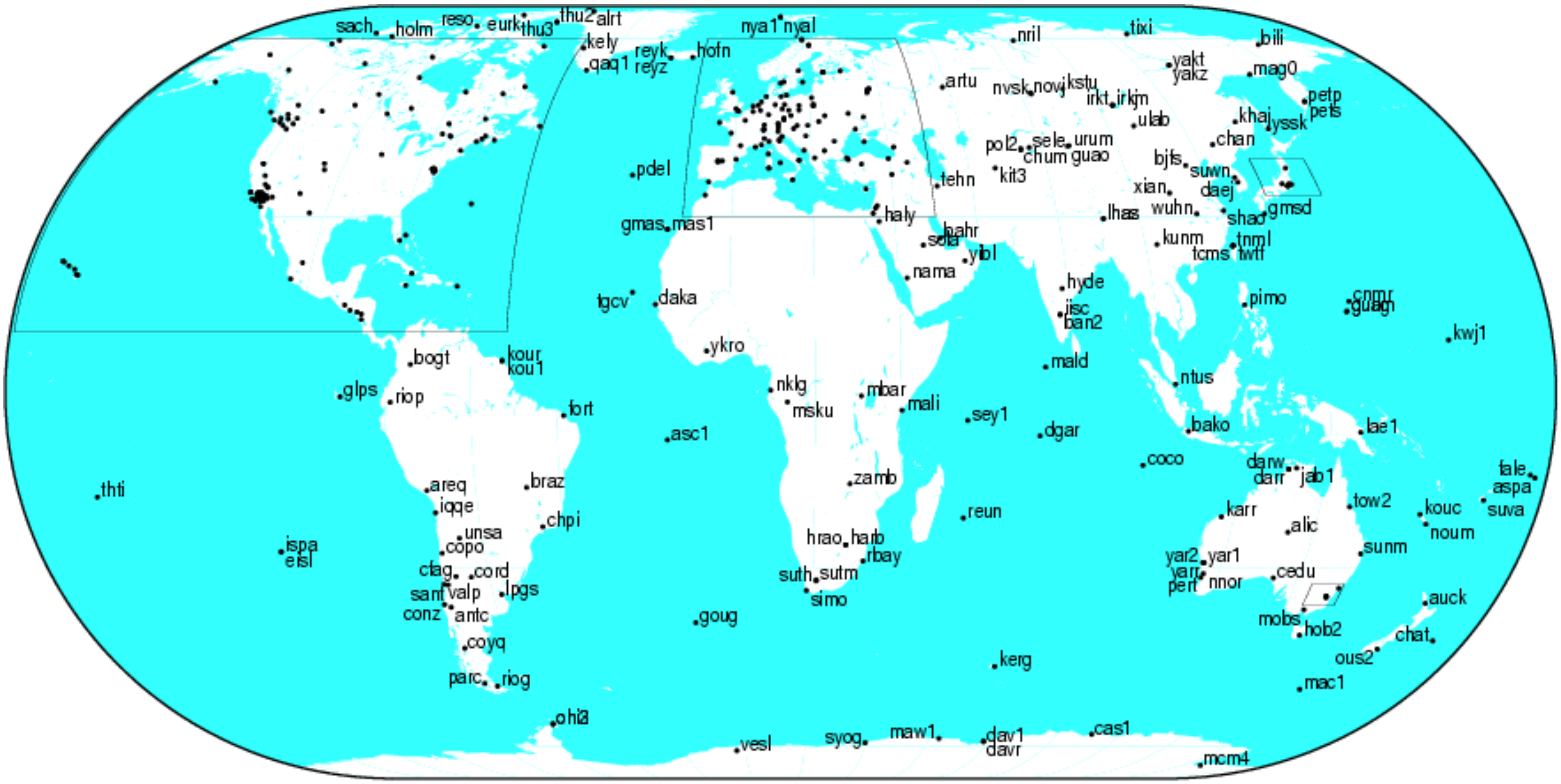

Filtering of the Length of Day: trend, seasonnal variation and residuals
(ms)
4
2
0
−2
−4
1965
1970
1975
1980
1985
1990
1995
2000
Year

Length of Day vs. ENSO



- Excess Length of Day (LOD) (red) correlates with El Niño-Southern Oscillation index (blue). Exchange of angular momentum between Solid Earth (rotation) and atmosphere/ocean.

IGS GPS/GNSS Network



GMT Jan 2 17:23:51 2005

IGS = International GNSS Service

- IGS coordinates operation of global satellite tracking network
- IGS provides
  - Daily and weekly coordinate solutions
  - Daily and weekly precise orbit products
  - Estimates of earth orientation/rotation
- IGS Central Bureau
  - http://www.igs.org run by JPL
- Several projects (ionosphere estimates, GPS at tide gauges, precise time transfer, etc.)

Getting IGS Data and Products

- 9 IGS Analysis Centers
  - 4 in USA: NGS, JPL/NASA, UC San Diego, MIT
- 4 IGS Global Data Centers: Raw data, orbits, clocks, troposphere, ionosphere
  - UC San Diego (SOPAC, sopac.ucsd.edu)
  - NASA/CDDIS (cddis.gsfc.nasa.gov)
  - Institute Geographique National, France (igs.ensg.ign.fr)
  - Korean Astronomical and Space Institute (gdc.kasi.re.kr)

Why is a Terrestrial Reference System (TRS) Needed ?

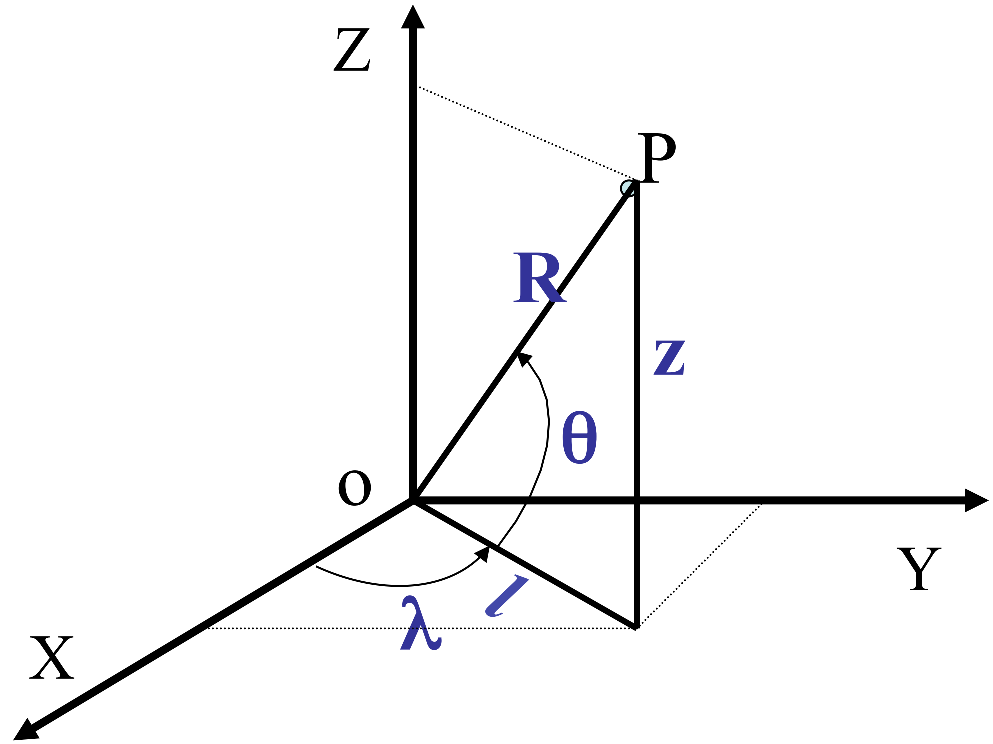
- **One of the goals of Space Geodesy is to estimate point positions over the Earth surface**
- **Stations positions are neither observable nor absolute quantities. They have to be referred to some reference**
- **TRS: Mathematical model for a physical Earth in which point positions are expressed and have small variations due to geophysical effects. (Ideal definition)**
- **It is a spatial reference system co-rotating with the Earth in its diurnal motion in space.**
- **Cannot define motions without defining positions!**

Ideal Terrestrial Reference System in the Context of Space Geodesy

- **Origin**: **Geocentric: Earth Center of Mass**
- **Scale**: **SI Unit**
- **Orientation**: **Equatorial (Z axis is the direction of the Earth pole)**

Coordinate Systems

- **3D**:
  - Cartesian: X, Y, Z
  - Ellipsoidal: λ, φ, h
  - Mapping: E, N, h
  - Spherical: R, θ, λ
  - Cylindrical: *l*, λ, Z
- **2D**:
  - Geographic: λ, φ
  - Mapping: E, N
- **1D** : Height system: H



$$OP \left| \begin{array}{l} l\cos\lambda \\ l\sin\lambda \\ z \end{array} \right.$$

Cylindrical

$$OP \left| \begin{array}{l} R\cos\theta\cos\lambda \\ R\cos\theta\sin\lambda \\ R\sin\theta \end{array} \right.$$

Spherical

ITRF

- Geocenter defined by SLR (Satellite Laser Ranging) data
  - SLR satellites are simple spheres and orbits can be modeled over a several year period
  - GPS satellites are complex and orbits can be modeled over a few days to a week.
- Scale defined through speed of light (in practice, through VLBI (Very Long Baseline Interferometry)
- GPS densifies frame

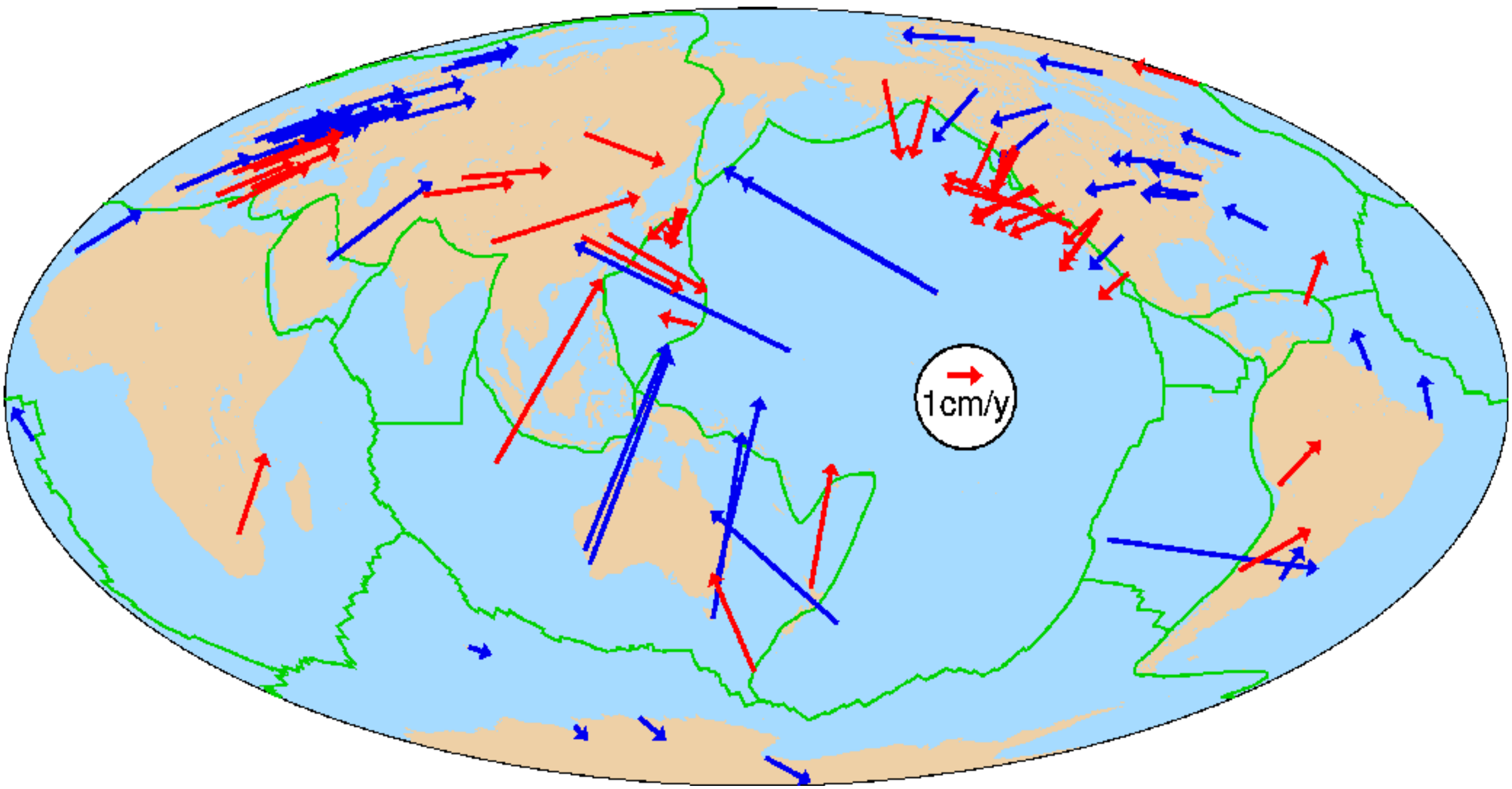
Velocity Reference

- To know what is moving, you must know what is fixed (zero motion)
- But all plates are moving
- Solution is to define plates within ITRF and choose a global rotation rate that makes plate rotations consistent with the NUVEL1A-NNR plate model
- Result is set of positions and velocities

ITRF2000 Horizontal Velocities

Uncertainties < 1 mm/y

Blue: stable part of tectonic plates   Red: deforming zones



ITRF2000 Vertical Velocities