Elements of Geodesy Part 2

Earth Rotation
Time systems
Conventional Systems and Franes
Tides, loading

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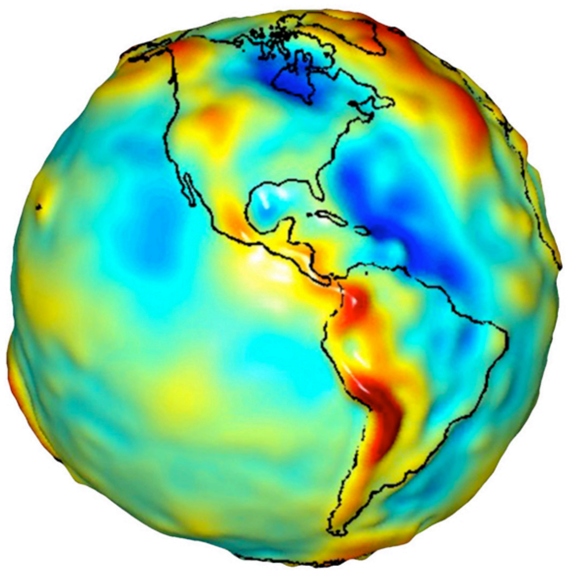
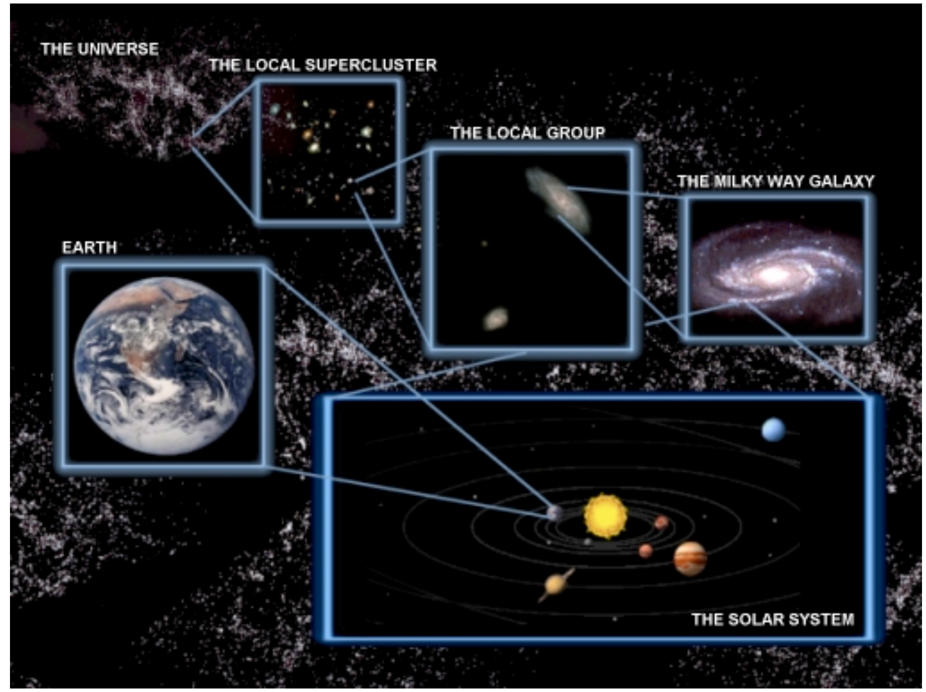


Geoid of Western Hemisphere. Image from University of Texas Center for Space Research and NASA.

The Earth in Space

- Why should we care?
  - Stars have long been essential to positioning and navigation
  - Basic physics
- Newton's law are valid in inertial frame = no force due to the motion of the frame itself
- Counter-example: the fictitious (*i.e.*, non-inertial) centrifugal force -- see to the right.
- In practice for us: orbit calculations MUCH easier in frame tied to space…



Newton's 2nd law: $\vec{F}_i = m\vec{a}_i$ (inertial frame…)

Transformation from inertial to rotating frame at uniform speed ω: $\left(\frac{d}{dt}\right)_i = \left(\frac{d}{dt}\right)_r + \vec{\omega} \times \ldots$ (cf. classical mechanics)

Positions become: $\left(\frac{d\vec{r}}{dt}\right)_i = \left(\frac{d\vec{r}}{dt}\right)_r + \vec{\omega} \times \vec{r} \Rightarrow \vec{v}_i = \vec{v}_r + \vec{\omega} \times \vec{r}$

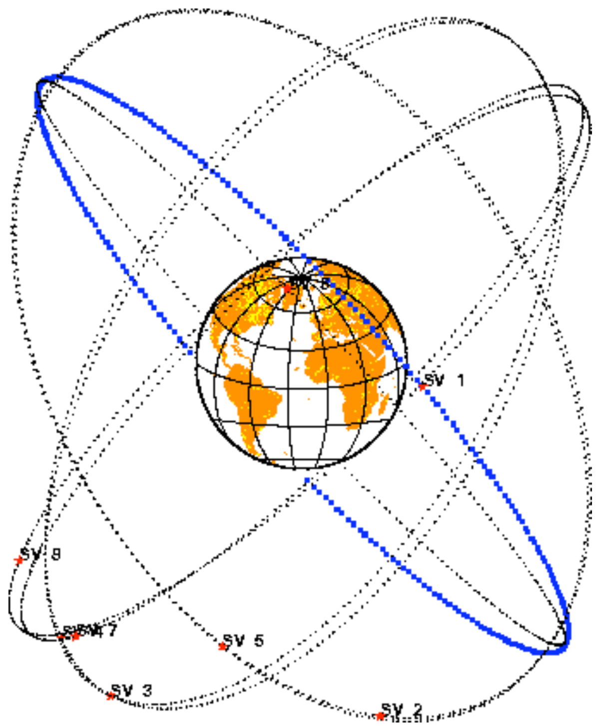
Velocities become: $\left(\frac{d\vec{v}_i}{dt}\right)_i = \left(\frac{d[\vec{v}_r + \vec{\omega} \times \vec{r}]}{dt}\right)_r + \vec{\omega} \times [\vec{v}_r + \vec{\omega} \times \vec{r}]$

$$\Rightarrow \vec{a}_i = \vec{a}_r + 2\vec{\omega} \times \vec{v}_r + \vec{\omega} \times (\vec{\omega} \times \vec{r})$$

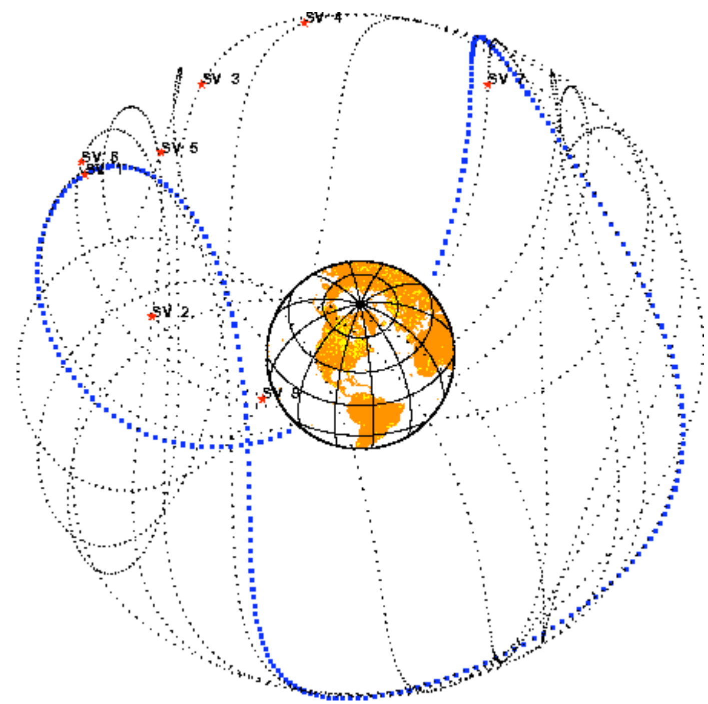
Newton's 2nd law in rotating frame: $\boxed{\vec{F}_i} - \boxed{2m\vec{\omega} \times \vec{v}_r} - \boxed{m\vec{\omega} \times (\vec{\omega} \times \vec{r})} = m\vec{a}_r$

Force applied in inertial frame — Coriolis Force — Centrifugal Force

Space-fixed versus Earth-fixed Reference Systems



GPS orbit, inertial frame

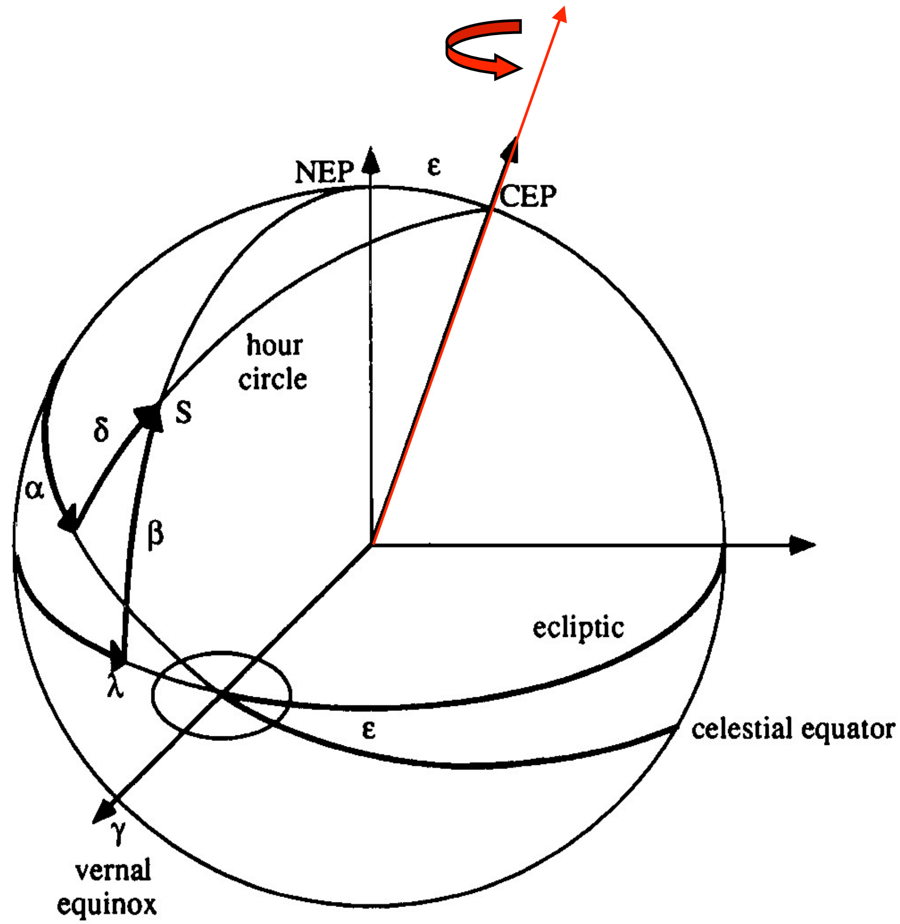


GPS orbit, Earth-fixed frame

Figures by T. Herring (MIT)

Space-fixed coordinate system

- The coordinate system:
  - Origin = Earth's center of mass
  - Pole = Celestial Ephemeris Pole, CEP
  - Earth's rotation axis coincides with CEP (actually angular momentum axis)
  - 2 fundamental planes:
    - Celestial equator, perpendicular to CEP
    - Ecliptic equator = Earth's orbital plane (its pole = North Ecliptic Pole, NEP)
  - Angle between these planes = obliquity $\varepsilon \sim 23.5^o$
  - Intersection of these planes: vernal equinox
- Coordinates of an object (e.g. star) uniquely defined by:
  - Right ascension α = angle in equatorial plane measured CW from the vernal equinox
  - Declination δ = angle above or below the equatorial plane
- Or by:
  - Ecliptic longitude λ
  - Ecliptic latitude β
- (α,δ) and (λ,β) related through rotation of ε about direction of vernal equinox.

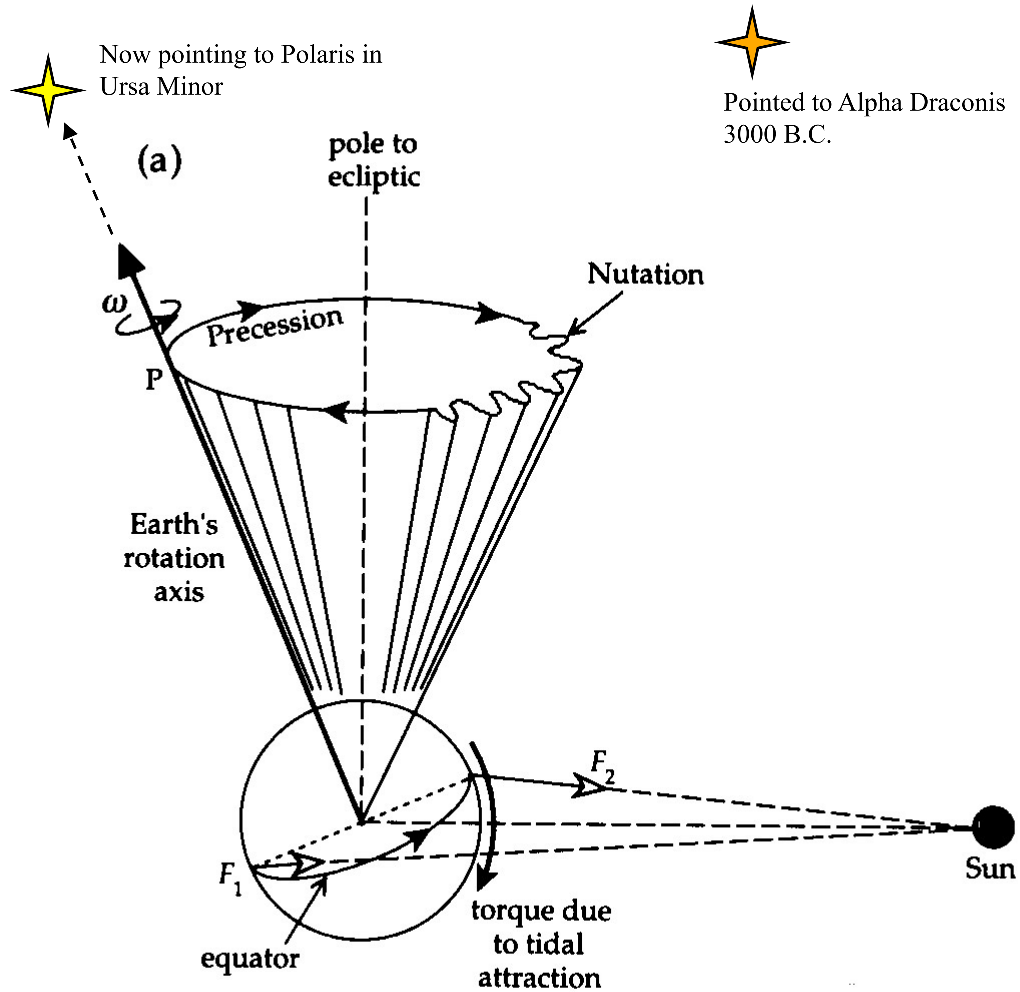


Oscillation of axes

- Earth rotation vector ω_E: $\vec{\omega}_E = \vec{\omega}\|\vec{\omega}_e\|$
- ω_E oscillates because of:
  - Gravitational torque exerted by the Moon, Sun and planets
  - Displacements of matter in different parts of the planet (including fluid envelopes) and other excitation mechanisms
- Oscillations of the Earth rotational vector:
  - Oscillations of unit vector ω:
    - With respect to inertial space (= stars), because of luni-solar tides: **precession** and **nutation**
    - With respect to Earth's crust: **polar motion**
  - Oscillations of norm = variations of speed of rotation = variations of time

Precession and Nutation

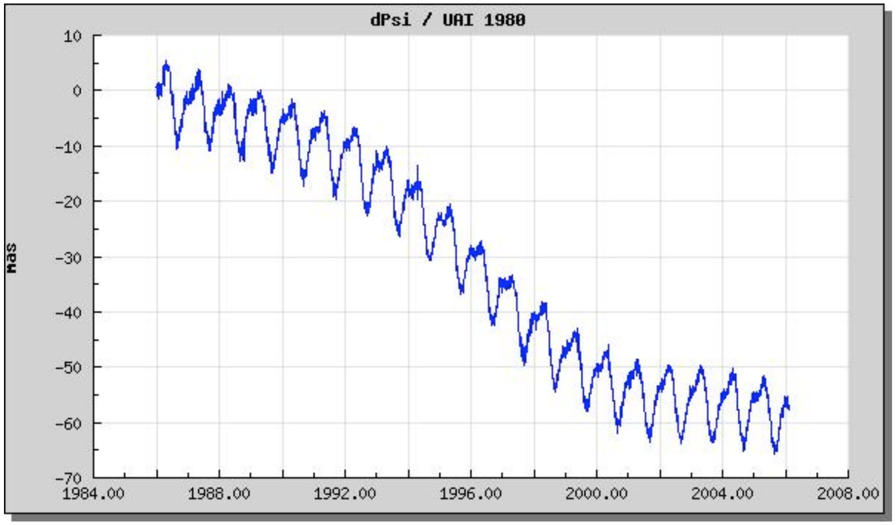
- Because of luni-solar tides, the earth rotation axis oscillates with respect to inertial space (= stars)
- This oscillation is partitioned into:
  - Secular **precession** (~25 730 yrs): Sun (or Moon) attraction on Earth equatorial buldge, which is not in the ecliptic plane => torque that tends to bring the equator in the ecliptic plane (opposed by the centrifugal force due to Earth's rotation)
  - Periodic **nutation** (main period 18.6 yrs):
    - e.g. Sun or Moon pass equatorial plane => tidal torque = 0 => creates semi-annual and semi-monthly periods
    - There are semi-annual and semi-monthly irregularities as well
    - Results in small oscillations (also called forced nutations) superimposed on the secular precession

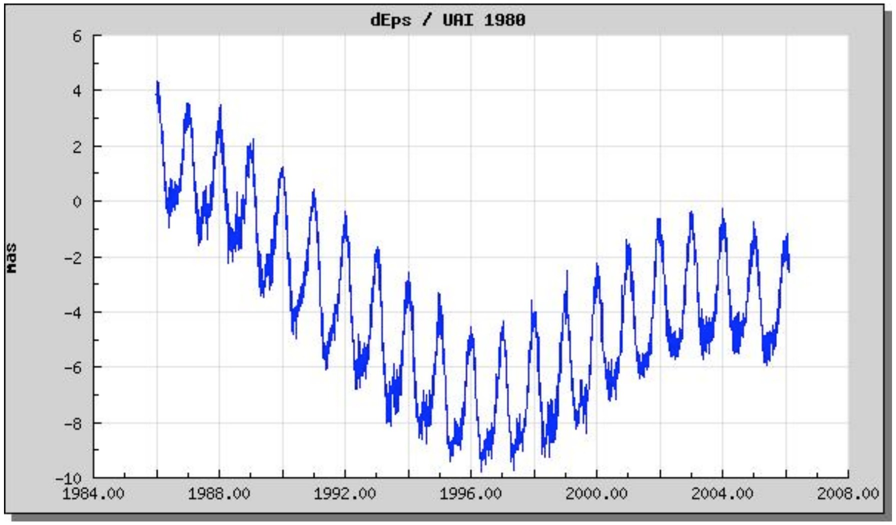


Precession and Nutation

- For an accurate treatment of precession and nutations, one must account for precise lunar and solar orbital parameters: use of astronomical tables (luntab, soltab in GAMIT)

- In addition, any process that modifies the Earth's moment of inertia will induce variations of its rotation vector.
- Recall that angular momentum $L=I\omega$ and must be conserved). For instance:
  - Solid Earth tides
  - Oceanic effects: tidal + non-tidal (currents, winds, pressure)
  - Atmospheric effects: pressure distribution
  - Free core nutations: rotation axis of core and mantle not aligned => 432 day period nutation





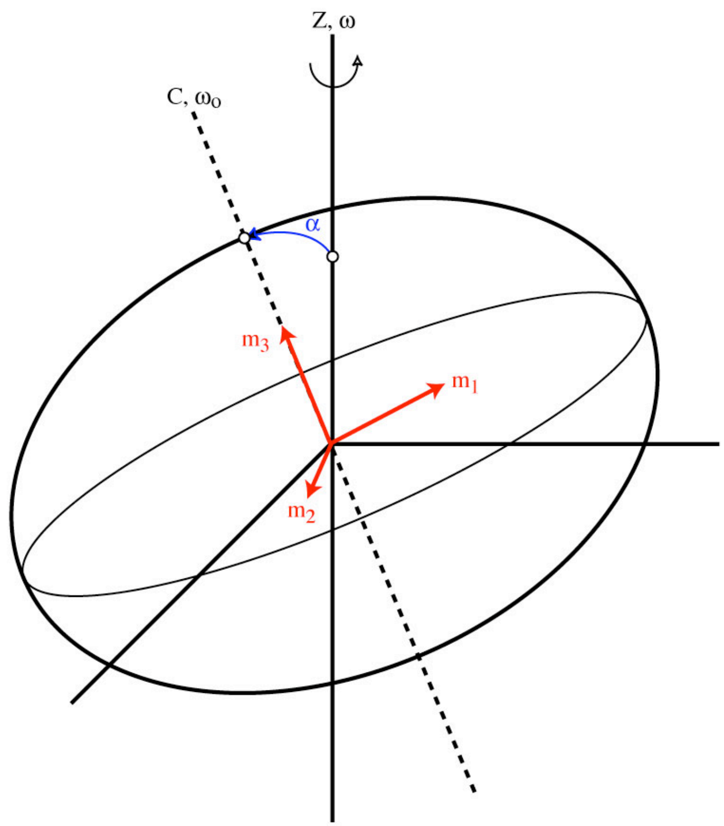
Offsets in longitude dPsi and in obliquity dEps of the celestial pole with respect to (old) precession-nutation model (IAU 1980).

1 arcsec ~30 m at the surface of the Earth => 1 mas ~ 3 cm

Chandler Wobble

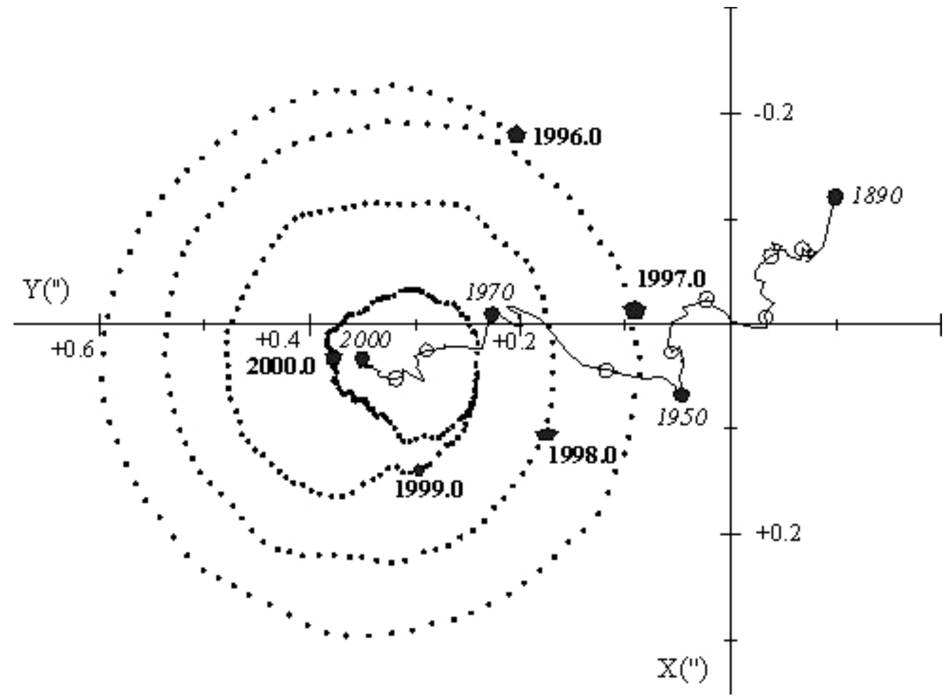
- If rotation axis of rotating solid does not coincide with polar major axis of inertia: for the angular momentum to remain constant (assuming no external forcing) the angular velocity vector has to change.
  - True for any irregularly shaped rotating solid body.
  - Happens in the absence of external forcing => “free wobble” (or “free nutation”)

- On Earth:
  - Free wobble is called “Chandler wobble” in honor of S.C. Chandler who first observed it in 1891
  - With respect to Earth surface: position of instantaneous rotation pole moves around polar major axis of inertia
  - Theory gives ω_c = 305 days, observations = 430 days…



Polar Motion

- Observed Chandler wobble: period = 433 days, amplitude ~0.7 arcsec (~15 m on Earth surface)
- Difference between observed and theoretical value?
  - A mystery for a while as astronomers were search for a 305 days period without finding it…
  - Due to non-perfect elasticity of Earth: some energy is transferred into anelastic deformation => damping of the Chandler wobble.
- Calculations using the anelasticity of Earth (Q) show that Chandler wobble should rapidly damp to zero (in less than 100 years) => there must be an excitation mechanism that keeps it going.
- Excitation mechanism not understood until recently: two-thirds of the Chandler wobble is caused by ocean-bottom pressure changes, the remaining one-third by fluctuations in atmospheric pressure (Gross, GRL, 2000).
- Polar motion actually has three major components:
  - Chandler wobble.
  - Annual oscillation forced by seasonal displacement of air and water masses, 0.15" ~ 2 m
  - Diurnal and semi-diurnal variations forced by oceanic tides ~ 0.5 m amplitude
- Non-oscillatory motion with respect to Earth's crust: polar wander, 3.7 mas/yr towards Groenland

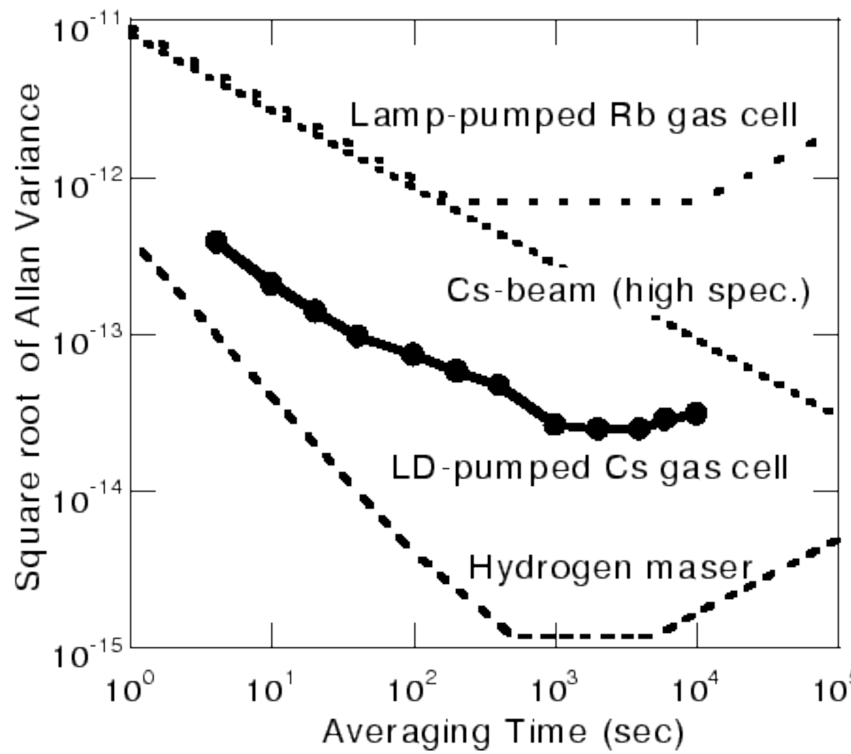


Polar motion for the period 1996-2000.5 (dotted line) and polar wander since 1890 (doc. IERS). Axes in arcsec: 1 arcsec ~30m at the surface of the Earth.

Time

- **Atomic time scale: based on frequency standards (mostly Cesium)**
  - Highly stable (e.g., 10^{-13} at 10^4 sec (~3 hours) ~3 ns)
  - Access to atomic time is direct.

- **Astronomic time scales: based on Earth rotation**
  - Sidereal time = directly related to Earth's rotation, not practical to measure for most Earth's applications
  - Universal time = more practical, related to apparent diurnal motion of Sun about Earth.
  - Not stable: Earth's rotation varies with time.
  - Instability of TAI is about 6 orders of magnitude smaller than that of UT1
  - Access to astronomical times is not direct, requires observation of stars or sun.

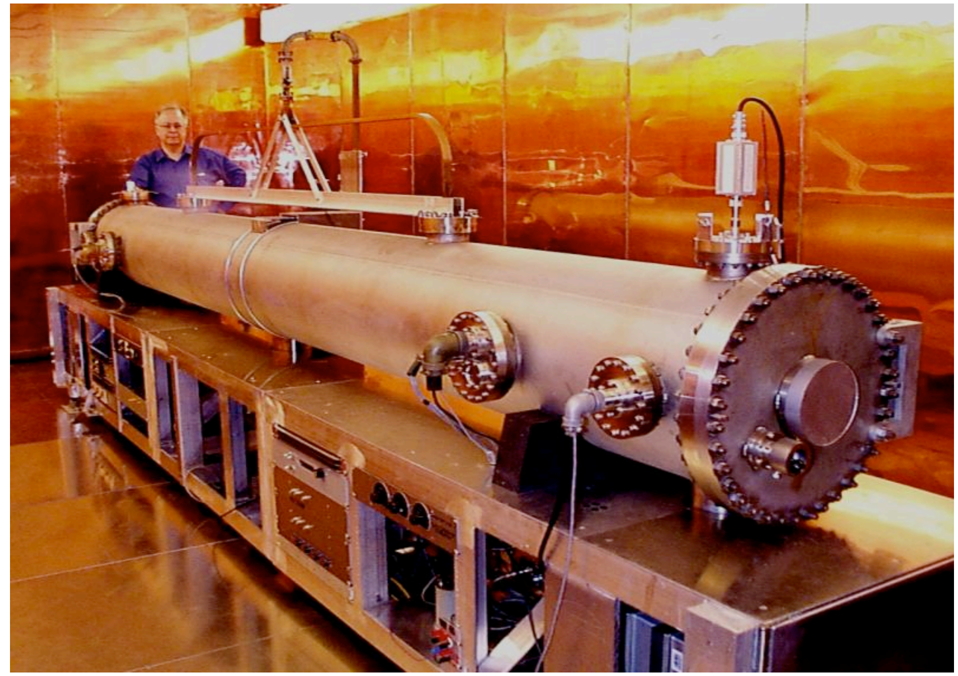


Stability of atomic frequency standards.

Allan variance = 1/2 the time average of squares of differences between successive readings over the sampling period = measurement of stability of clocks .

International Atomic Time = TAI

- Defined by its unit, the atomic second (on the geoid) = 9,192,631,770 periods of the radiation corresponding to the transition between two hyperfine levels of Ce133
- Origin so that its first epoch coincides with Universal Time UT1 (see later)
- TAI day = 86,400 seconds
- Realized by >200 atomic clocks worldwide, weighted mean calculated by BIPM (www.bipm.org).

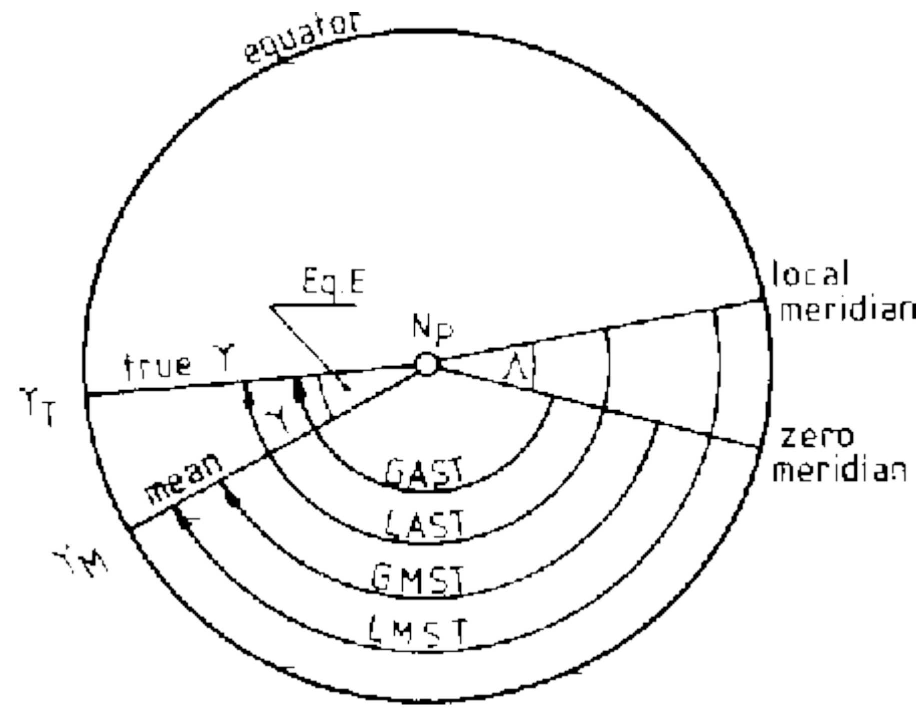


Traditional Cesium beam frequency standard

- Heated cesium to boil of atoms, different energy state
- Send them through a tube and use magnetic field to select atoms with right energy state
- Apply intense microwave field, sweeping microwave frequency about 9,192,631,770 Hz => atoms change energy state
- Collect atoms that have changed frequency state at end of tube and count them
- Adjust sweeping frequency to maximize # of atoms received at end of tube => then lock frequency
- Divide frequency by 9,192,631,770 Hz to get one pulse-per-second output

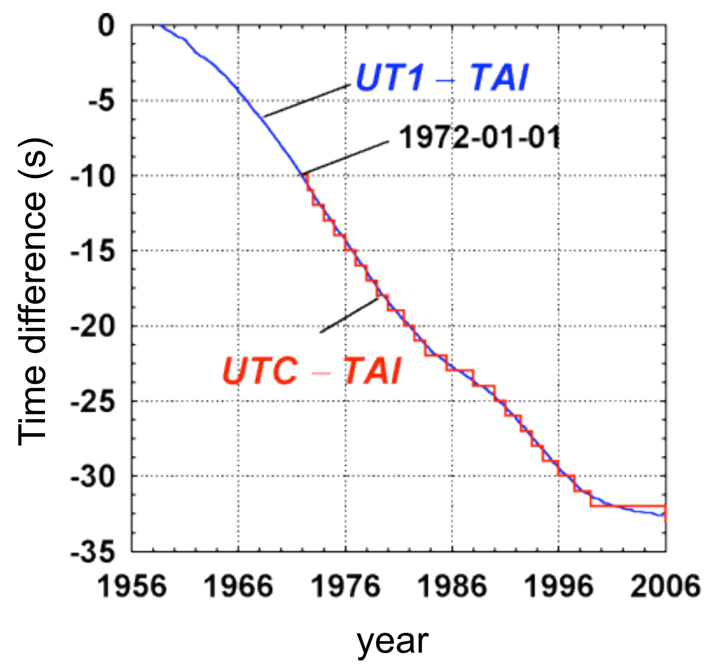
Sidereal Time - ST

- Directly related to to Earth's rotation in celestial frame
- Definition = Earth rotates 360 degrees (in celestial frame) in 1 sidereal day
- If measured at observer's location w.r.t. true vernal equinox = Local Apparent ST
- LAST measured by observations to distant stars and extragalactic radio sources
- If corrected for nutation and precession (w.r.t. mean vernal equinox) = Local Mean ST
- If measured at Greenwich = GAST or GMST



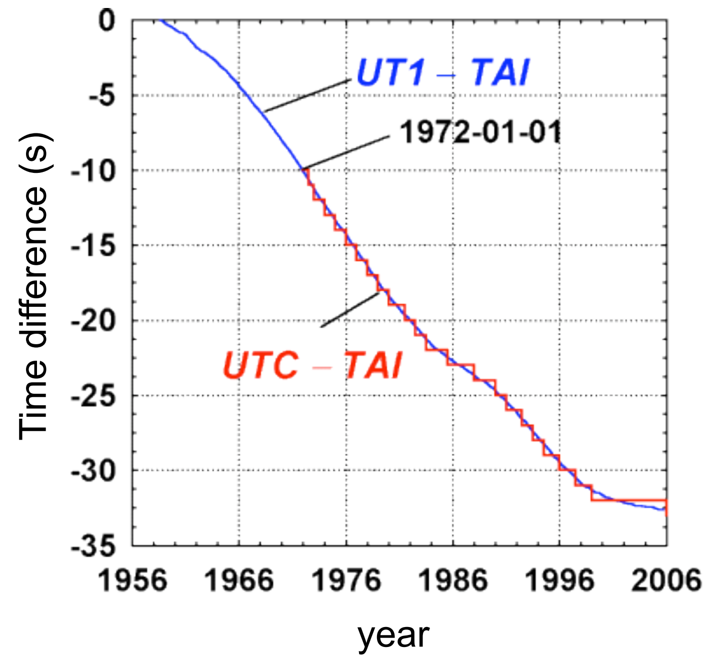
Universal Time - UT

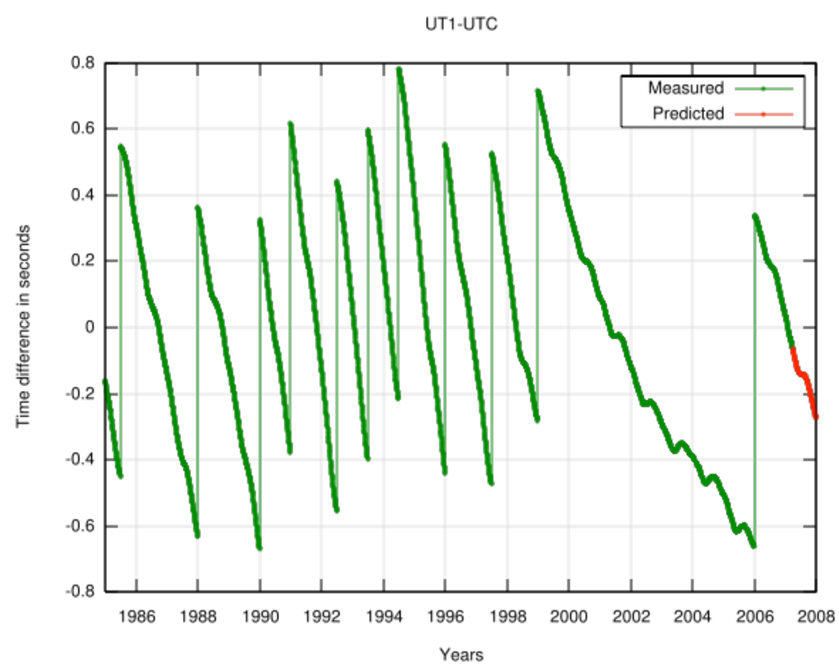
- Related to apparent motion of the sun around the Earth
- When referred to the Greenwich meridian = Universal Time (UT)
- UT is measured directly using ground stations (VLBI)
- UT not uniform because of polar motion => UT corrected for polar motion = UT1
  - UT1 has short term instabilities at the level of 10^{-8}
  - Duration of the day slowly decaying (~0.002 s/century) because of secular deceleration of Earth rotation.



TAI - UT relation?

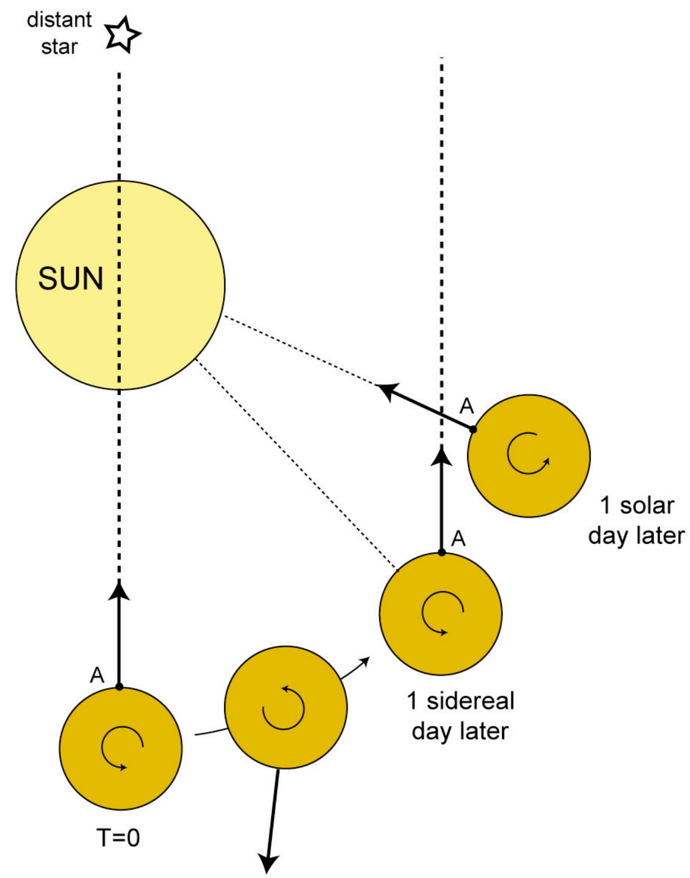
- Because of the secular deceleration of the Earth's rotation, TAI increases continuously with respect to UT1.
- If legal time was based on TAI, coincidence with solar day could not be maintained (in a couple of year TAI - UT1 can increase by a few seconds).
- Compromise: use highly stable atomic time, but adjust time to match irregular Earth rotation => UTC
  - Unit = atomic second
  - By definition, |UT1 – UTC| < 0.9 s
  - UTC changed in steps of 1 full second (leap second) if |UT1 – UTC| > 0.9 s, responsibility of the IERS (June 30 or Dec. 31)
  - UTC = broadcast time used for most civilian applications (your watch!)
- Currently: TAI-UTC = 33 s





UT - ST relation?

- It takes 365 solar days for Earth to be back at same place w.r.t. sun
- During 1 sidereal day, observer A has rotated 360 degrees
- Need to rotate by additional α to complete 1 solar day:
  - Solar day is longer than sidereal
  - Observer accumulates some "lead time" w.r.t. solar day every solar day
  - At a rate of 1/365 of a solar day = 3 min 44.90 sec per solar day
- Therefore:
  - Sidereal day = solar day - 3 min 44.90 sec = 86,164.10 s
  - Earth angular rotation:
    $\omega = 2\pi/86{,}164.10 = 7{,}292{,}115 \times 10^{-5}$ rad s^{-1} (see GRS definition)



GPS time (GPST)

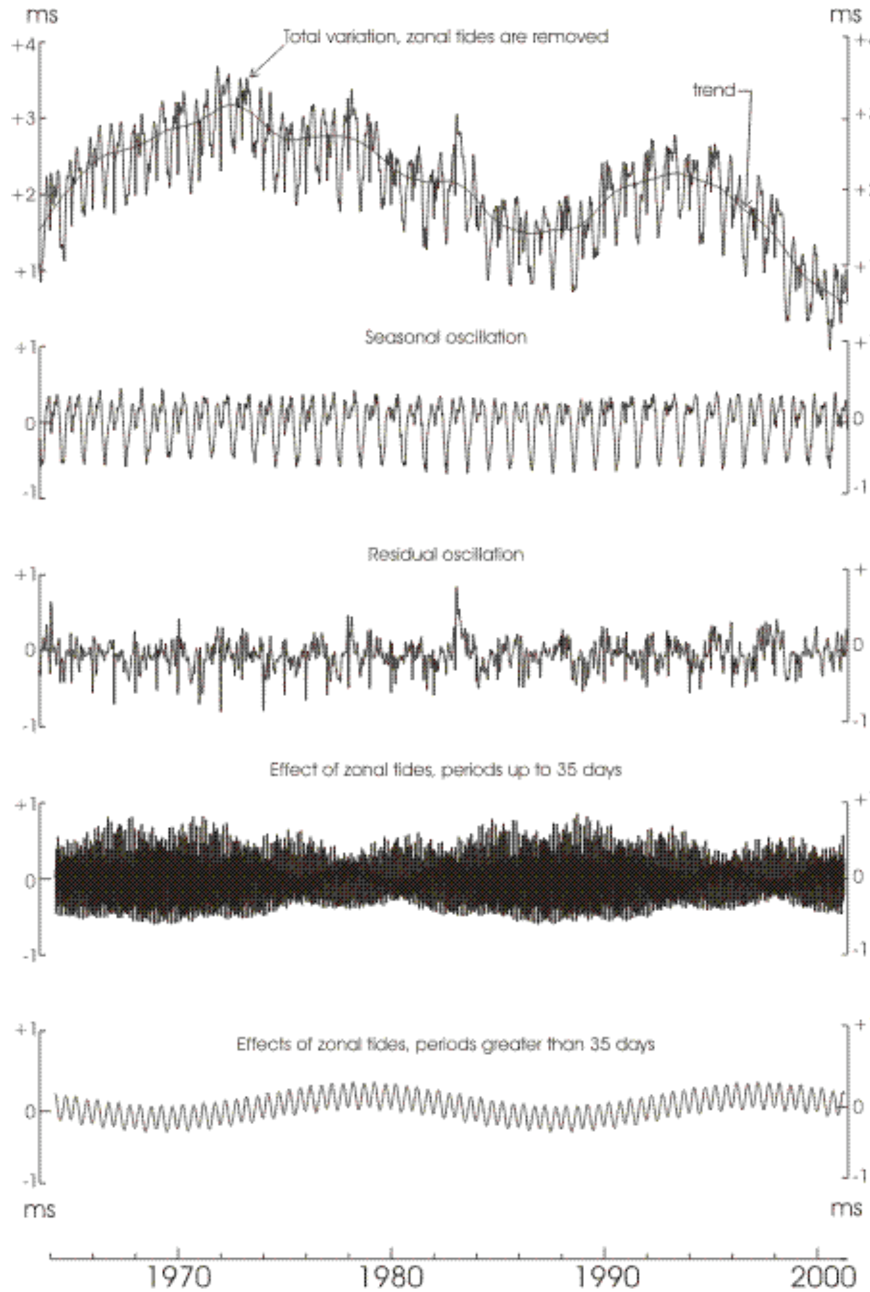
- Atomic scale, unit = SI second
- GPST = TAI – 19 s
- Coincident with UTC on January 6th, 1980, 00:00 UTC
- Not incremented by leap seconds
- Currently: TAI - UTC = 33 s => GPST = UTC + 14 s

local	2008-01-08 22:19:42	Tuesday	day 008	timezone UTC-5
UTC	2008-01-09 03:19:42	Wednesday	day 009	MJD 54474.13868
GPS	2008-01-09 03:19:56	week 1461	271196 s	cycle 1 week 0437 day 3
Loran	2008-01-09 03:20:05	GRI 9940	84 s until	next TOC 03:21:06 UTC
TAI	2008-01-09 03:20:15	Wednesday	day 009	33 leap seconds

http://www.leapsecond.com/java/gpsclock.htm

Length-of-day = LOD

- Length of Day (LOD) = difference between 86 400 sec SI and length of astronomical day:
  - Long term variations:
    - Dynamics of liquid core
    - Climate
  - Short term variations:
    - Zonal tides
    - Seasonal = climate
    - Residual: Cf. 1983 El Nino event



Time systems/Calendar

- **Julian Date** (JD): number of mean solar days elapsed since January 1st, 4713 B.C., 12:00
- **Modified Julian Date** (MJD) = JD – 2,400,00.5
  - Ex.: GPS standard epoch, JD = 2,444,244.5 (January 6th, 1980, 00:00 UTC)
  - Ex.: Standard epoch J2000.0, JD = 2,451,545.0 (January 1st, 2000, 12:00 UTC)
- **Day Of Year** (DOY): day since January 1st of the current year
- GPS calendar:
  - GPS week: Week since GPS standard epoch
  - GPS day of week: Sunday = 0 to Saturday = 6
  - GPS second: Second since GPS standard epoch

Reference Systems

- Introduced to help model geodetic observations as a function of unknown parameters of interest
  - Positions:
    - Space-fixed = celestial, tied to extra-galactic objects
    - Terrestrial = tied to solid Earth
  - Time systems: based on quantum physics or Earth rotation

- Systems vs. Frames:
  - Reference System = set of prescriptions, conventions, and models required to define at any time a triad of axes.
  - Reference Frame = practical means to “access” or “realize” a system (e.g., existing stations of known coordinates)

Reference Systems

- Systems and frames:
  - Defined by international body: the international Earth Rotation and Reference Systems Service = IERS (http://www.iers.org)
  - Mission of the IERS: *“To provide to the worldwide scientific and technical community reference values for Earth orientation parameters and reference realizations of internationally accepted celestial and terrestrial reference systems”*
  - Updated on a regular basis as models or measurements improve.

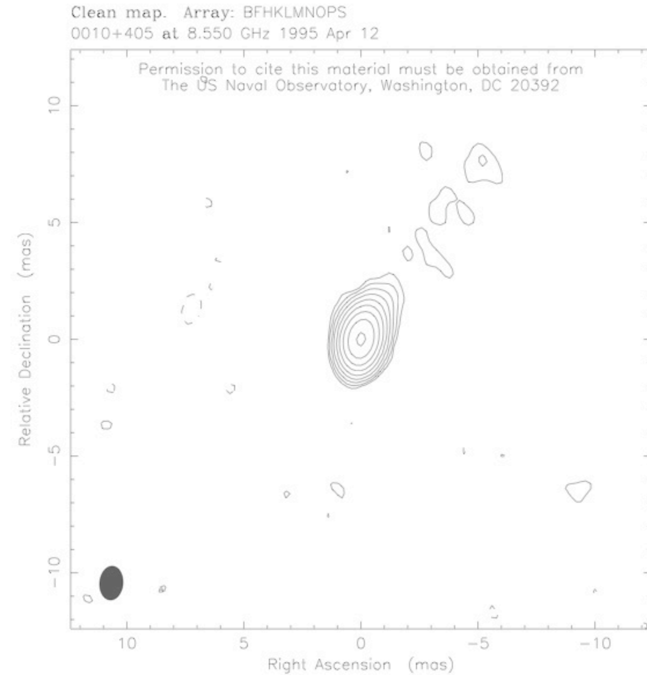
- Basic units and fundamental constants:
  - Meter = length unit (length of path traveled by light in vacuum in 1/299,792,458 of a second - CGPM 1983)
  - Kilogram = mass unit (mass of international prototype - CGPM 1901)
  - Second = time unit (9192631770 periods of the radiation corresponding to the transition between two hyperfine levels of Ce133 - CGPM 1967)

Conventional Systems

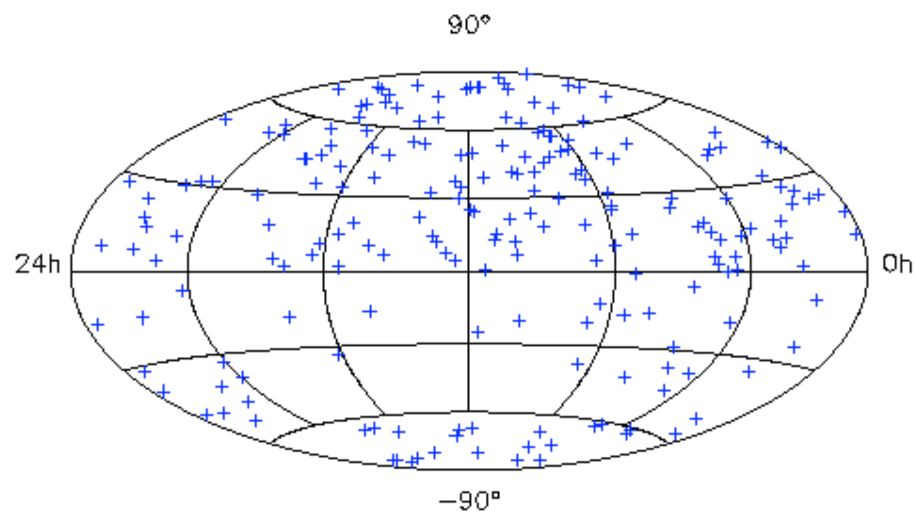
- Conventional **Inertial System**:
  - Orthogonal system, center = Earth center of mass, defined at standard epoch J2000 (January 1st, 2000, 12:00 UT)
  - Z = position of the Earth's angular momentum axis at standard epoch J2000
  - X = points to the vernal equinox
  - It is <u>materialized</u> by precise equatorial coordinates of extragalactic radio sources observed in Very Long Baseline Interferometry (VLBI) = Inertial Reference **Frame**.
  - First realization of the International Celestial Reference Frame (ICRF) in 1995.
- Conventional **Terrestrial System**:
  - Orthogonal system center = Earth center of mass
  - Z = position of the Earth's angular momentum axis at standard epoch J2000
  - X = Greenwich meridian
  - It is <u>materialized</u> by a set of ground control stations of precisely know positions and velocities = Terrestrial Reference **Frame**

International Celestial Reference Frame

- Directions of the ICRS pole and right ascensions origin maintained fixed relative to the quasars within +-20 microarcseconds.
- The ICRS is accessible by means of coordinates of reference extragalactic radio sources.
- It is realized by VLBI estimates of equatorial coordinates of a set of extragalactic compact radio sources, the International Celestial Reference frame.
- ICRS can be connected to the International Terrestrial Reference System through Earth Orientation Parameters (EOP -- more later).



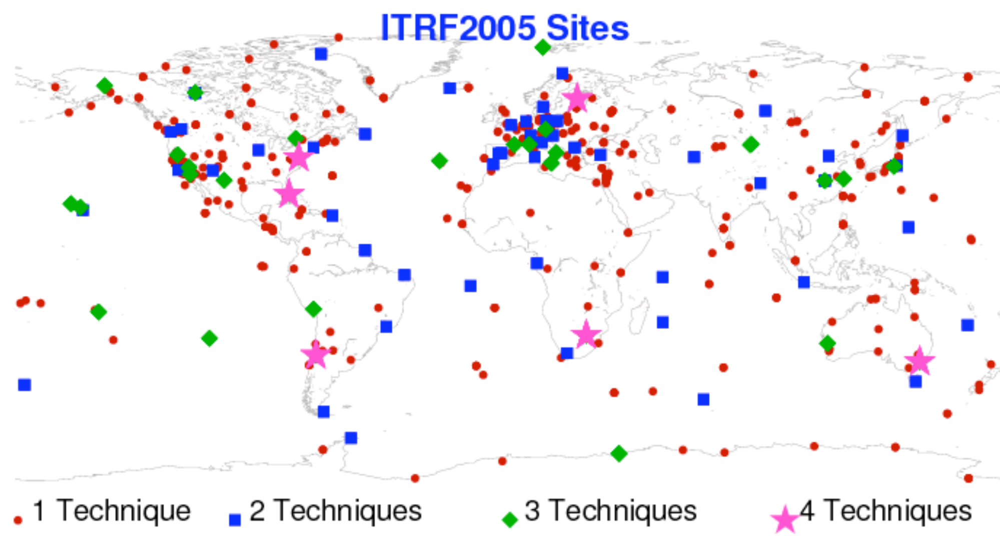
An extraglactic source "seen" by a radio telescope at 8 GHz



212 high-astrometric-quality objects define the ICRF axes

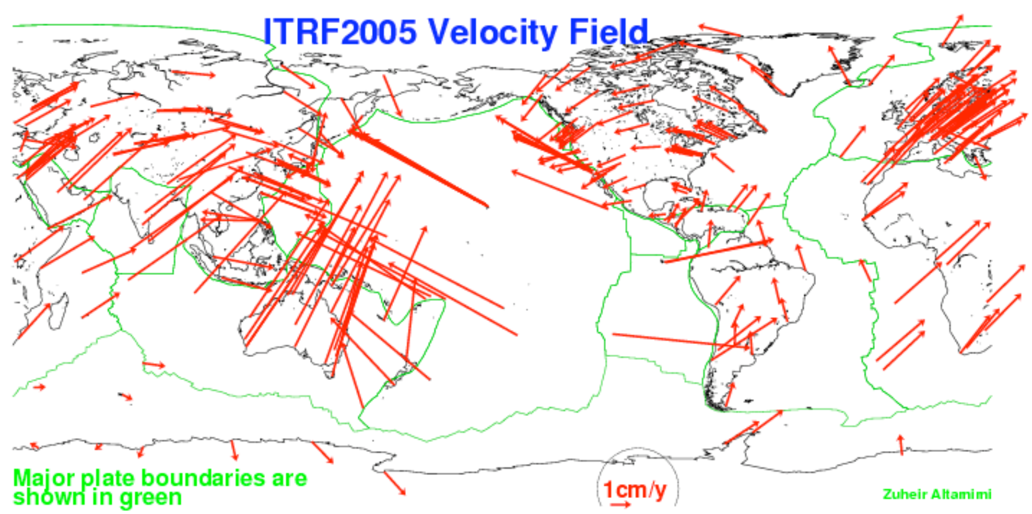
International Terrestrial Reference Frame

- Realized by a set of ground control stations, in the framework the IERS
- International Terrestrial Reference Frame (http://itrf.ensg.ign.fr/):
  - First version in 1989 (ITRF-89), current version ITRF-2005
  - Set of station positions, velocities, and epochs in an Earth centered-Earth fixed (=ECEF) Terrestrial System
  - And associated variance-covariance matrix
  - Since ITRF derives from measurements, it changes (improves) with its successive realizations
- More on ITRF and reference frames later.



Map of ground geodetic stations used in the definition of the ITRF-2005.
Note that some stations benefit from several observation techniques in colocation

Below: surface velocities associated with ITRF2005



Earth Orientation Parameters (EOP)

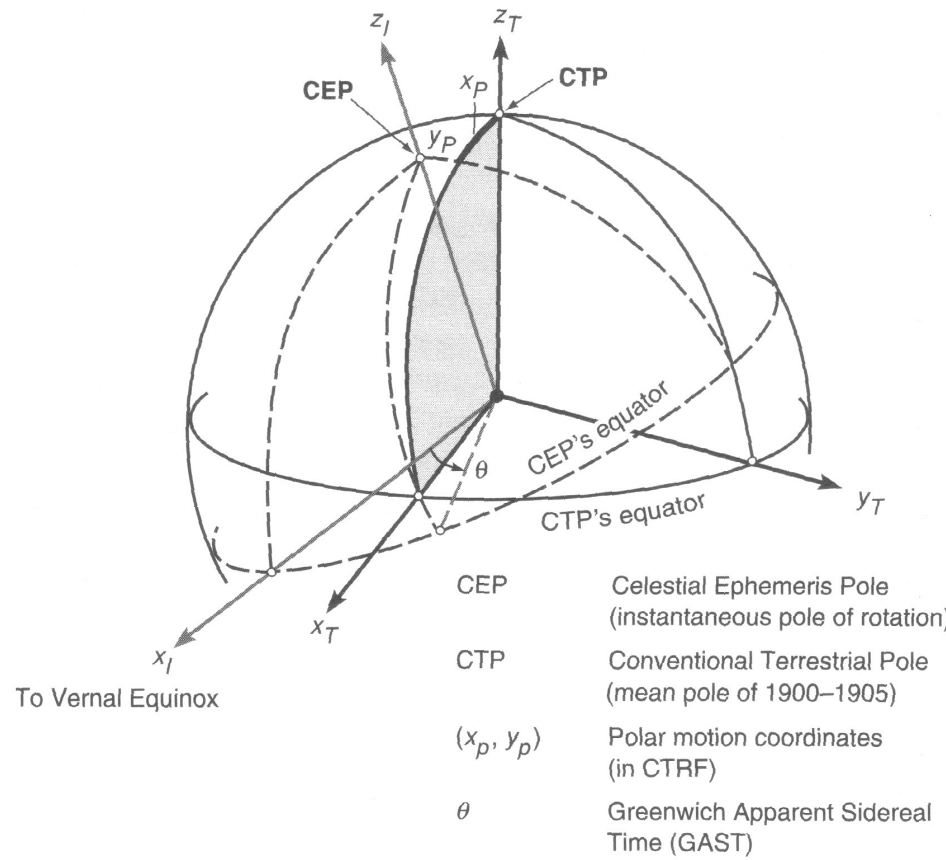
- The Earth's orientation is defined as the **rotation between**:
  - A **rotating geocentric set of axes linked to the Earth** (the terrestrial system materialized by the coordinates of observing stations) = Terrestrial System
  - A **non-rotating geocentric set of axes linked to inertial space** (the celestial system materialized by coordinates of stars, quasars, objects of the solar system) = Inertial System
- Inertial coordinates are transformed to terrestrial by combining rotations:

$$r_t = R_2(-x_p)R_1(-y_p)R_3(GAST)N(t)P(t)r_i$$

Terrestrial — Polar motion — UT1 — Nutation — Precession — Inertial

Earth Orientation Parameters (EOP)

- Nutation and Precession:
  - Rotation matrices derived from geophysical model + corrections provided by IERS.
  - P(t) = rotate from reference epoch (J2000) to observation epoch --> obtain mean equator and equinox.
  - N(t) = rotate from mean to instantaneous true equator and vernal equinox.
  - At this stage Earth rotation axis (Z-axis) coincides with CEP.
- R_3 = rotate about Z axis (=CEP) by GAST => X-axis coincides with vernal equinox.
- Polar motion:
  - R_1 = rotate about X axis by $-y_p$ (small angle)
  - R_2 = rotate about Y axis by $-x_p$ (small angle)



$$R_3(GAST) = \begin{bmatrix} \cos(GAST) & \sin(GAST) & 0 \\ -\sin(GAST) & \cos(GAST) & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R_1(-y_p) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & -y_p \\ 0 & y_p & 1 \end{bmatrix}$$

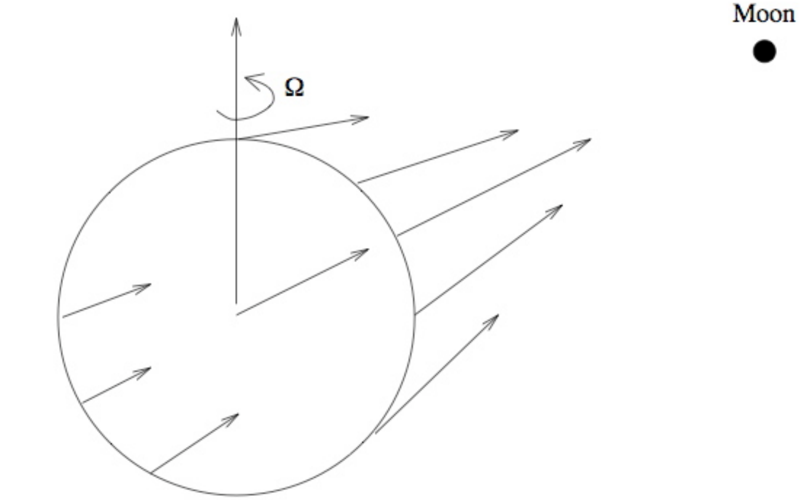
$$R_2(-x_p) = \begin{bmatrix} 1 & 0 & x_p \\ 0 & 1 & 0 \\ -x_p & 0 & 1 \end{bmatrix}$$

Earth Orientation Parameters (EOP)

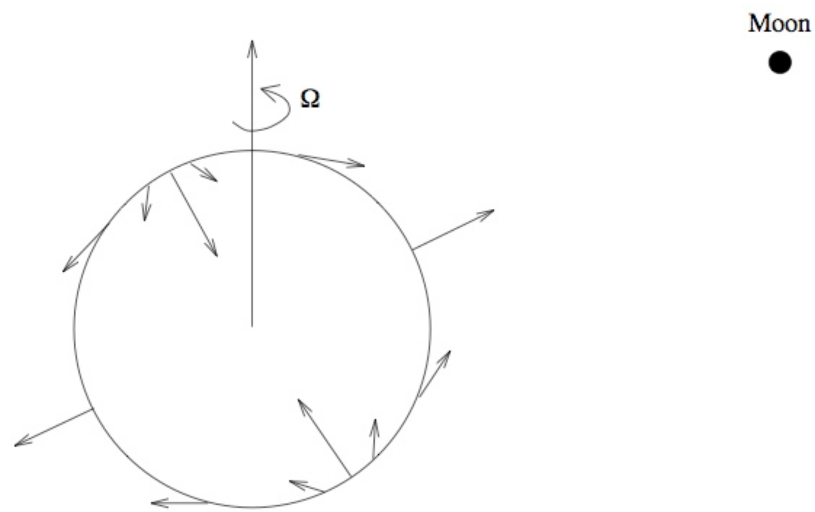
- Rotation parameters are given in astronomical tables provided by the IERS:
  - For the most precise positioning, they are used as a priori values (sometimes even adjusted) in the data inversion.
  - For non-precise applications, only R_3(GAST) matters.
- In practice, the IERS provides **five Earth Orientation Parameters** (EOP) :
  - Celestial pole offsets (dPsi, dEps): corrections to a given precession and nutation model
  - Universal time (UT1) = UT corrected for polar motion, provided as UT1-TAI
  - 2 coordinates of the pole (x_p,$-y_p$) of the CEP (corrected for nutation and precession) with respect to terrestrial Z-axis axis = polar motion

Tides

- Earth and Moon are coupled by gravitational attraction: each one rotates around the center of mass of the pair.
- Moon (or Sun) gravitational force = sum of:
  - Part constant over the Earth --> orbital motions (think of Earth as a point mass) = orbital force
  - Remainder, varies over the Earth --> tides (Earth is not a point mass…) = tidal force
- Tidal force:
  - Causes no net force on Earth => does not contribute to orbital motion
  - Fixed w.r.t. Moon
- In addition: the Earth rotates => tidal force varies with time at given location.



Total gravitational force: larger at closer distance to the Moon. Orbital force = average of all arrows.



Tidal force: total force minus orbital force.

Figs. J. Wahr

Tidal frequencies

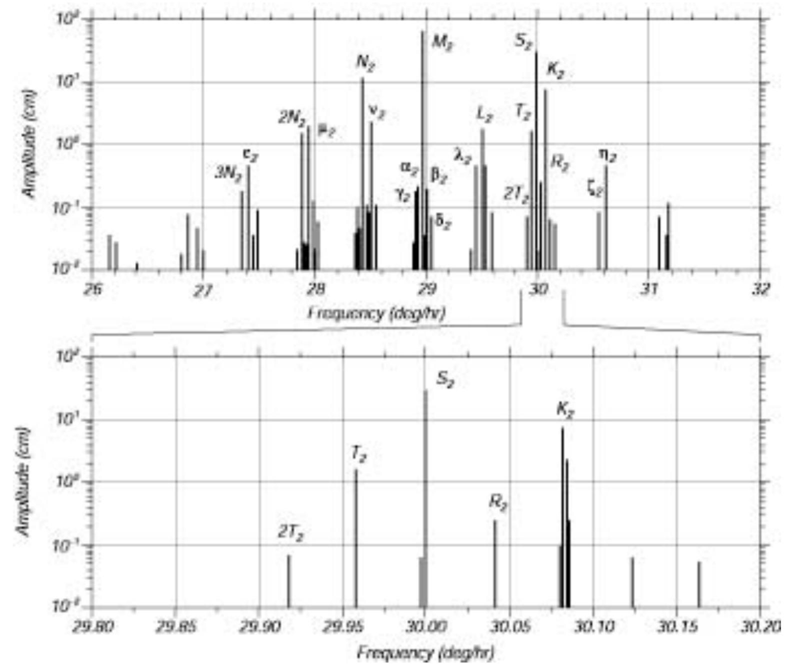
- One can show that the Earth's tidal potential can be written as:

$$V_T = \frac{3}{4} GM \frac{r^2}{R^3} \begin{bmatrix} \left(\frac{1}{3} - \sin^2 \varphi_P\right)\left(1 - 3\sin^2 \delta\right) \\ + \sin 2\varphi_P \sin 2\delta \cos(h) \\ + \cos^2 \varphi_P \cos^2 \delta \cos(2h) \end{bmatrix} \begin{matrix} \rightarrow \text{Long-period} \\ \rightarrow \text{Diurnal} \\ \rightarrow \text{Semi-diurnal} \end{matrix}$$

with φ_P,λ_P = latitude, longitude of observer, r = Earth's radius, R = earth-moon distance, δ,α = declination, right-ascension of celestial body, *h* = hour angle given by:

$$h = \lambda_P + GAST - \alpha$$

- *R, δ, h*: periodic variations with time => 3 terms have periodic variations:
  - Moon: 14 days, 24 hours, and 12 hours.
  - Sun: ~180 days, 24 hours, and 12 hours.
  - 3 distinct groups of tidal frequencies: twice-daily, daily, and long period



Constituent	Name	Period	Acceleration (nm s-2)	Amplitude, ocean (m)
Semi-diurnal				
Principal lunar	M2	12.4206 h	375.6	0.242334
Principal solar	S2	12.0000 h	174.8	0.112841
Lunar elliptic	N2	12.6584 h	71.9	0.046398
Lunisolar	K2	11.9673 h	47.5	0.030704
Diurnal				
Lunisolar	K1	23.9344 h	436.9	0.141565
Principal lunar	O1	25.8194 h	310.6	0.100514
Principal solar	P1	24.0659 h	144.6	0.046843
Elliptic lunar	Q1	26.8684 h	59.5	0.019256
Long Period				
Fortnightly	Mf	13.66 d	31.9	0.041742
Monthly	Mm	27.55 d	16.8	0.022026
Semi-annual	Ssa	182.62 d	14.8	0.019446

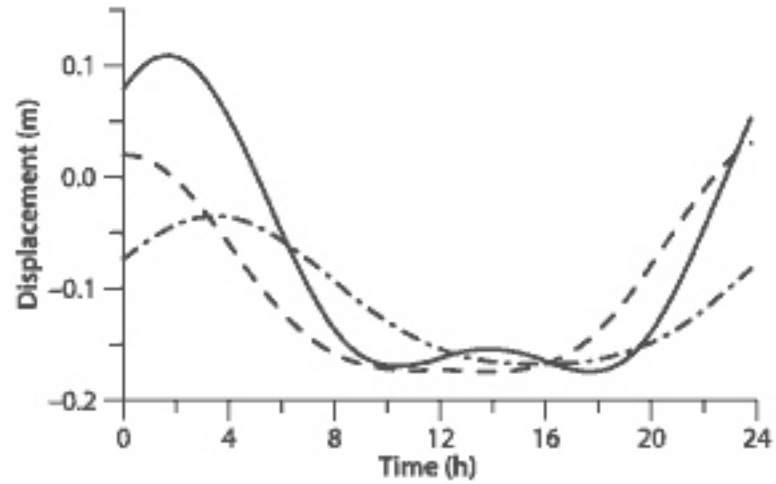
Earth Tides

- Love showed that displacement on spherical Earth is proportional to tidal potential and Love numbers (for harmonic degree n):

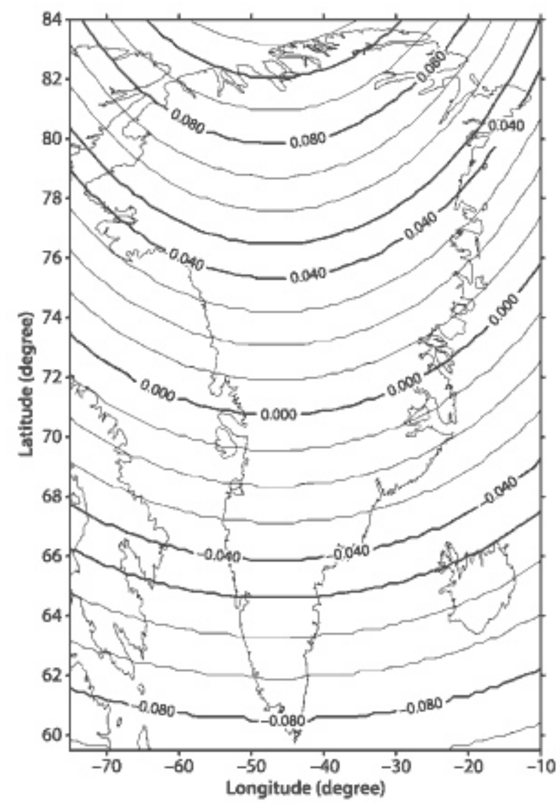
$$d_r = \frac{h_n}{g} V_T \vec{e}_r$$

$$d_t = \frac{l_n}{g} \nabla V_T \vec{e}_t = \frac{l_n}{g} \frac{\partial V_T}{d\theta} \vec{\theta} + \frac{l_n}{g \sin\theta} \frac{\partial V_T}{d\lambda} \vec{\lambda}$$

  - Love numbers for displacement = h_n and l_n (+ k_n for potential)
  - Depend on elastic properties of the Earth (from seismic velocities)
  - Solid Earth: largest contribution from harmonic degree 2: h_2=0.609;l_2 =0.085; k_2=0.3
- Displacements due to Earth tides:
  - Ex. in Greenland (figures)
  - Large compared to the precision of GPS => must be corrected (using model)



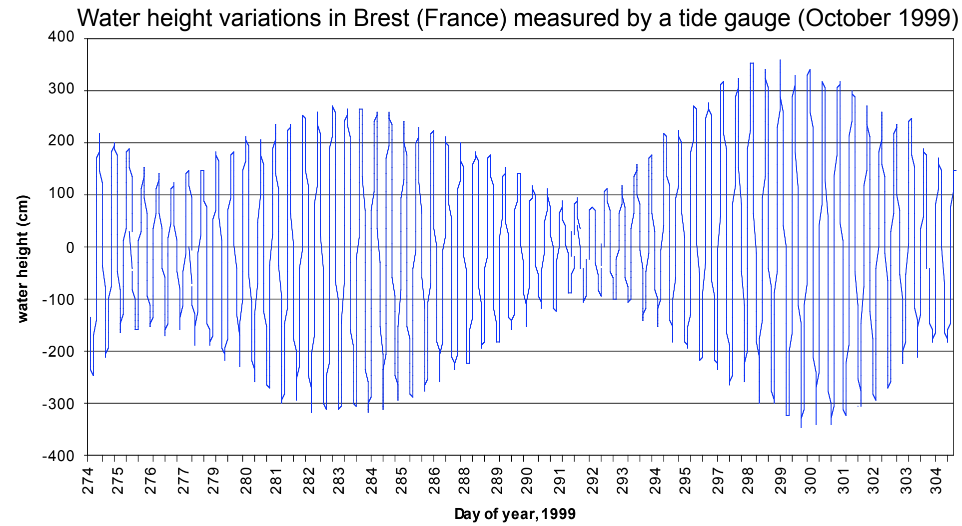
3 sites in Greenland, vertical position

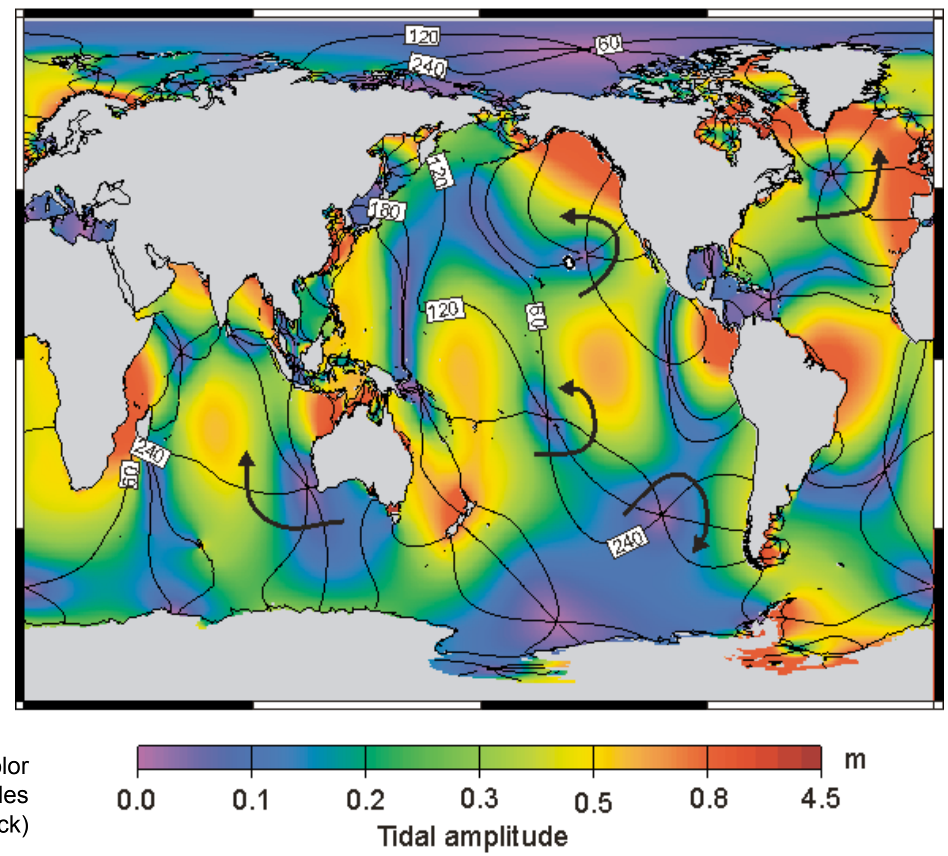


Figs. G. Xu

Ocean tides

- Tidal force results in displacements of Earth's constituents:
  - Oceans
  - Solid Earth
  - Atmosphere
- Ocean tides:
  - Measured with tide gauges
  - Complex pattern, local amplifications.
- Once tides are removed, what do tide gauges measure?





The ocean tides for harmonic M2 (period of 12 hours and 25 minutes) . The color represent the amplitude and the contour lines indicate the phase lag of the tides with a spacing of 60 degrees. (Doc. H.G. Scherneck)

Loading effects

- Earth ~elastic solid => deforms under load, as a function of:
  - Load (=source) characteristics (spatial and temporal evolution of mass)
  - Elastic properties: quantified by loading Love numbers: h_n' l_n' k_n'
- Radial deformation of elastic Earth:

$$u_r(\lambda,\varphi) = \frac{3}{\rho_e} \sum_{n=0}^{\infty} \frac{h'}{2n+1} q_n(\lambda,\varphi)$$

ρ_e = mean Earth density
h_n' = load Love number (function of assumed rheology)
N = degree of spherical harmonic series
$q_n(\lambda,\varphi)$ = spherical harmonic expansio of surface load

- Ocean tides are one of the major sources of load:
  - Result is centimeters of radial motion
  - Higher power at diurnal and semi-diurnal periods (K1, M2)
  - Loading effect larger in coastal regions, decreases land-ward

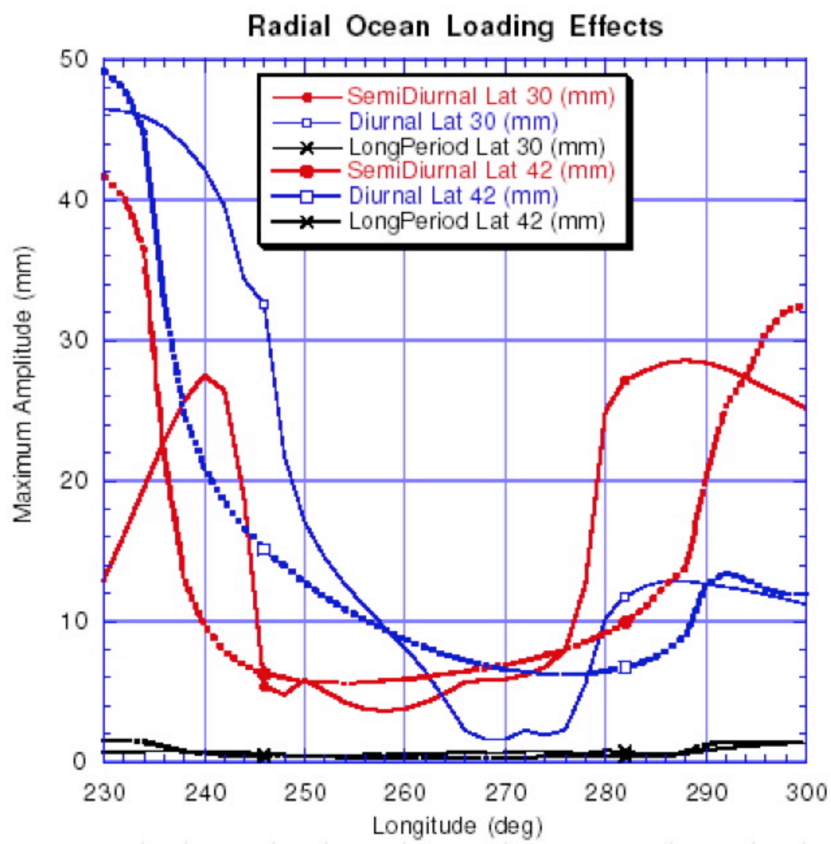


Fig. T. Herring

Loading effects

- Additional loading sources include
  - Atmospheric pressure:
    - Centimeters: ~0.5 mm/mbar
    - Amplitude related to weather patterns => mostly short period
  - Ground water:
    - Rivers + soil + snow
    - Centimeters: ~0.5 mm/cm of water
    - Higher power at seasonal period
- Ultimate GPS precision requires correcting for loading effects:
  - Ocean loading:
    - Routine
    - Ocean tidal models accurate (except some local areas)
  - Atm and hydro:
    - Still experimental
    - Must rely on pressure and continental water measurements (and models…)

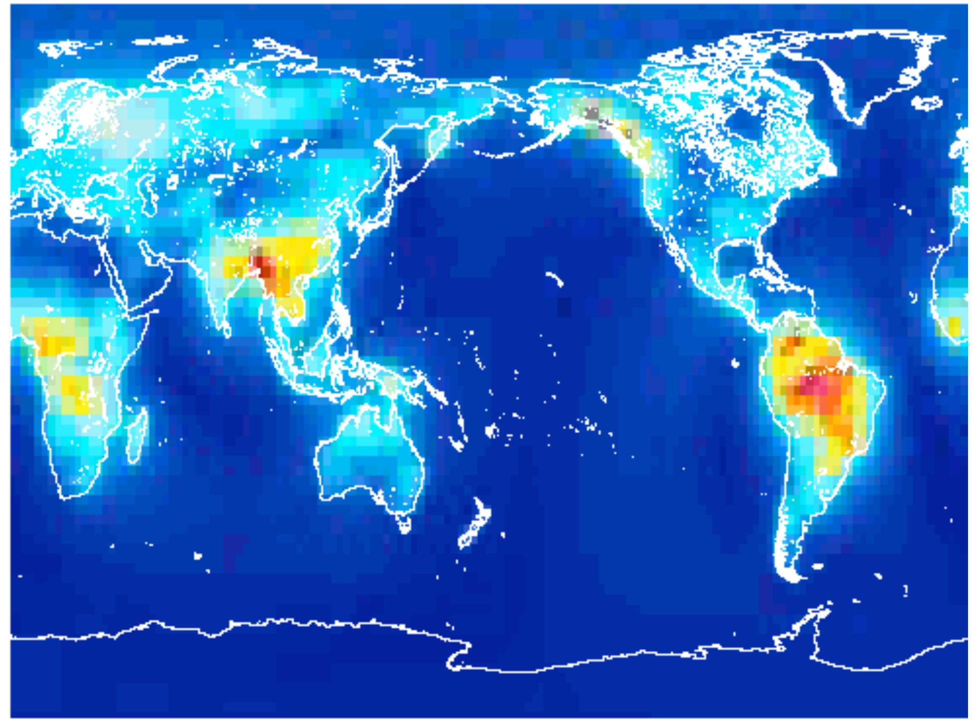
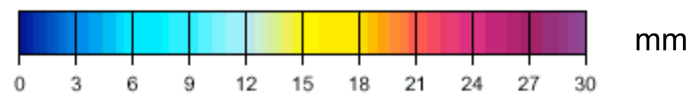


Fig. T. vanDam



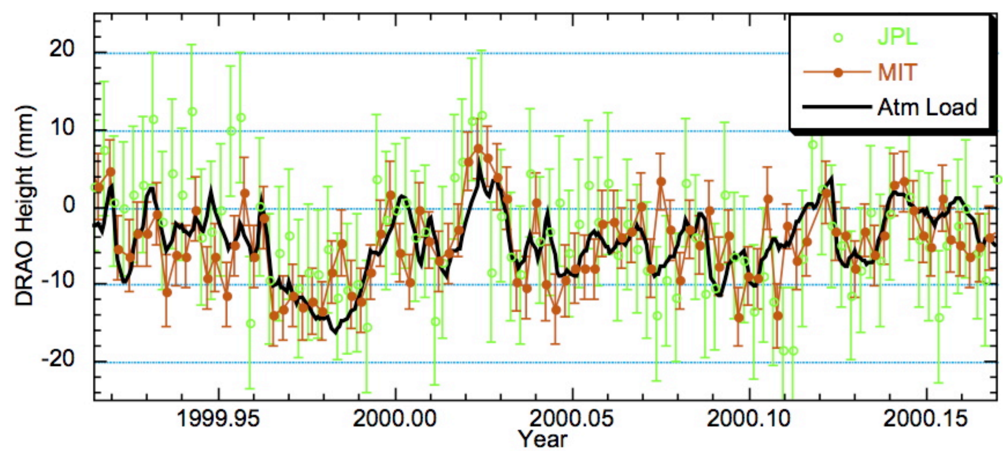
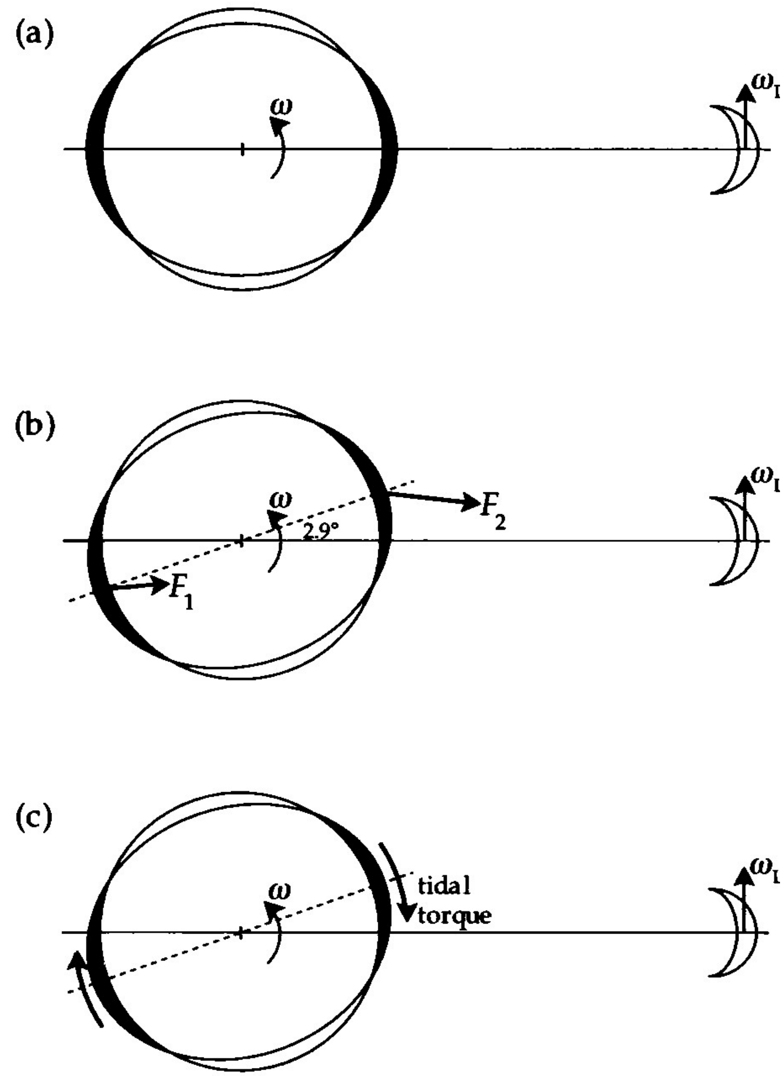


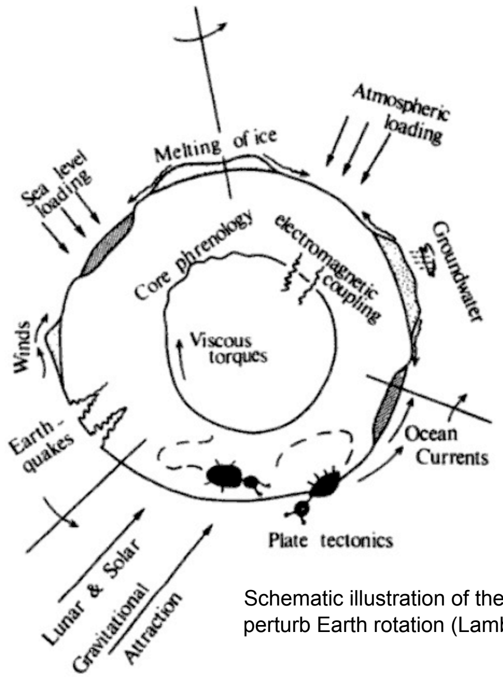
Fig. T. Herring

Tidal friction and LOD

- If the Earth was purely elastic => tidal bulge aligned with the Moon (a)
- But Earth tidal response is not instantaneous because of Earth anelasticity
  - => slight delay between high tide and Moon alignment (~12 min)
  - => creates torque that tends to bring the the tidal bulge axis back into the Earth-Moon direction, in a direction opposite to the Earth's rotation
  - Deceleration of the Earth's rotation => increase of length-of-day: ~2 s/100,000 yr
  - Analysis of growth rings of fossil corals, 350 Ma old => 1 day = 22 hr, 1 year = 400 days
- The Earth tidal bulge creates a similar torque on the Moon, in opposite direction (conservation of Earth-Moon angular momentum) => deceleration of the Moon revolution
- Because of Kepler's third Law ($period^2/a^3$=const), the Moon-Earth distance increases (~3.8 cm/yr)

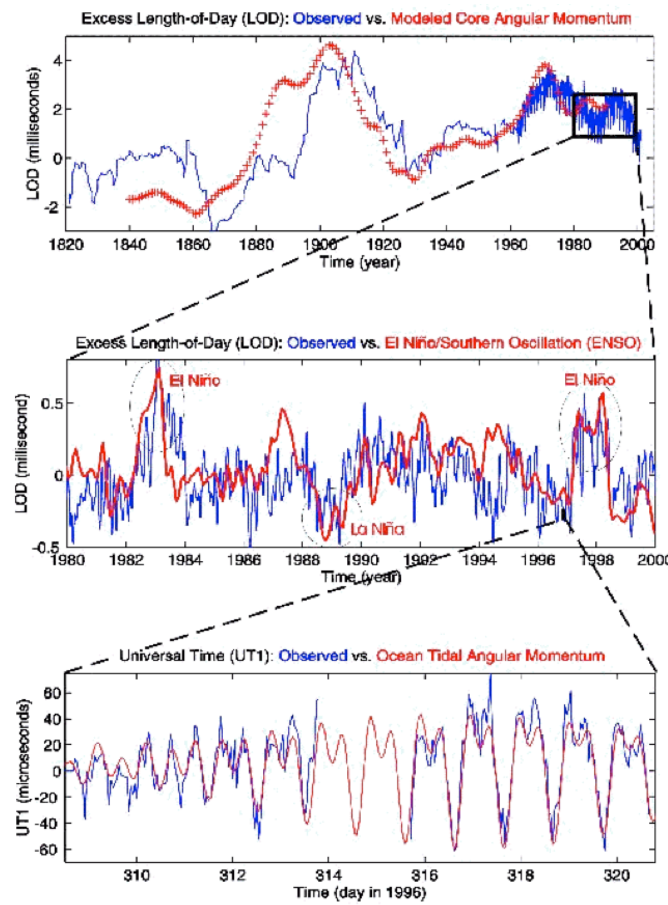


Geophysical Fluids and Earth Rotation



Schematic illustration of the forces that perturb Earth rotation (Lambeck, 1980)

- Geophysical fluids act on Earth rotation ω in 2 ways:
  - By the torques (τ) they exert on the planet
  - By the modifying the Earth moment of inertia (*I*)
- Since angular momentum of the whole Earth system has to be conserved (recall that $L=Iw$ and $\tau=dL/dt$): torques and changes in moment of inertia result in changes in ω.
- Any geophysical process involving mass transport will trigger Earth rotation variations with spatial and temporal characteristics function of the triggering process:
  - Atmosphere: pressure systems = air mass moving around the planet
  - Oceans: water displacements due to tides, wind, thermohaline fluxes
  - Whole earth: body tide, mantle flow (e.g. post-glacial rebound), tectonic plate motion, earthquakes
  - Liquid core: the “geodynamo”
  - Continents: snow and groundwater



Chao, 2004: LOD/UT1 variations with respect to various geophysical excitation sources ranging from core flow, to El Ninos, to ocean tides

Geophysical Fluids and J_2dot

- Recall that the dynamic oblateness of the Earth J_2 relates to the Earth moment of inertia via:

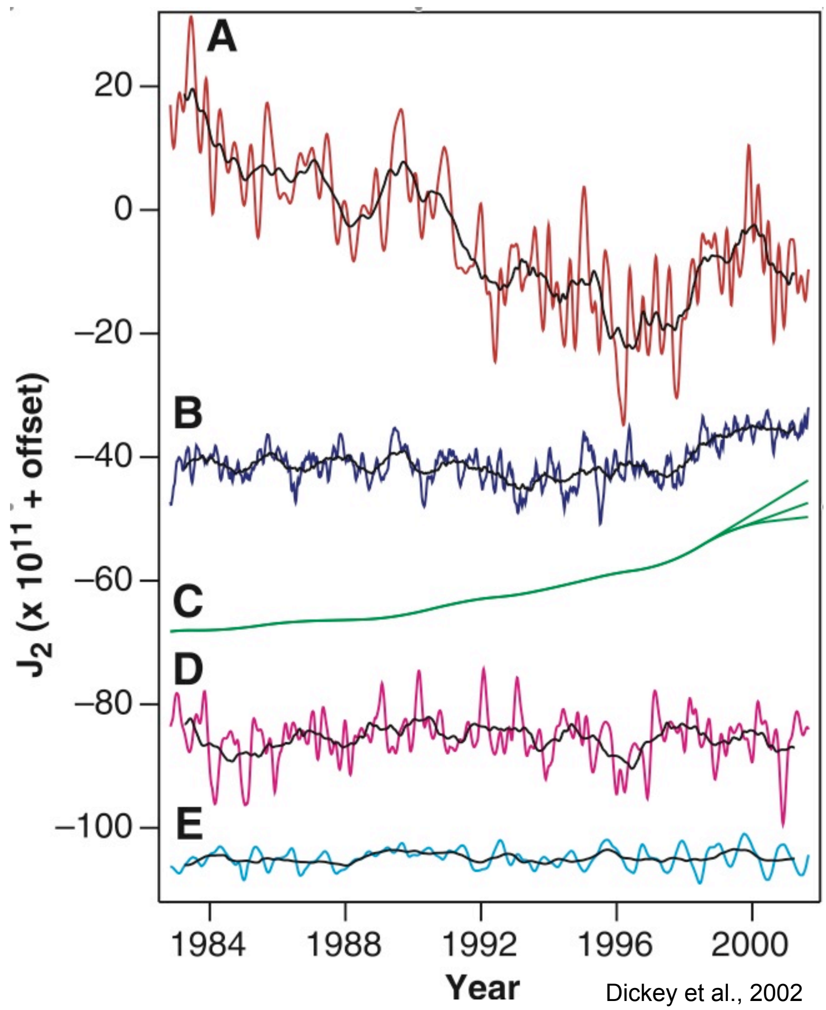
$$J_2 = \frac{C - A}{Ma^2}$$

- Similar to tidal torque exerted by moon and sun on Earth that cause precession, Earth exerts a torque on artificial satellites => precession of the satellite orbit = "regression of the nodes"
- In the simplified case of a circular orbit, one can show that the angular change in the position of the node is given by:

$$\frac{\Delta\Omega}{2\pi} = -\frac{3}{2}\frac{a^2}{r^2} J_2 \cos i$$

with i = inclination of satellite's orbit plane w.r.t. equatorial plane, r = orbital radius

- Since one can track the position of satellites from Earth-based stations, $\Delta\Omega$ can be measured => J_2 can be determined using geodetic observations.
- Actually, higher-order coefficients as well => determination of the "satellite geoid".
- In practice, this is more involved since orbits are elliptical.



Dickey et al., 2002

A = geodetic observations of J2
B = theoretical effect of oceans on J2
C = theoretical effect of subpolar ice melt
D = theoretical effect of atmosphere
E = theoretical effects of groundwater

⇒ Until 1996: J_2 decreases, a result of postglacial rebound (1,000 years scale)

⇒ 1997-1998: J_2 increases because of surge in ice melt and mass shift in oceans (also strong El Nino event, 1998 warmest global mean temperature on record).