Science Overview

2017 TOW Meeting

Karine Le Bail

NVI, Inc. – NASA/GSFC

Outline

- What we do with the data / Analysis
- How we use the data / Products & applications

  Three components of Space Geodesy

  – Terrestrial Reference Frame;

  – Celestial Reference Frame;

  – Earth Orientation Parameters.

ANALYSIS

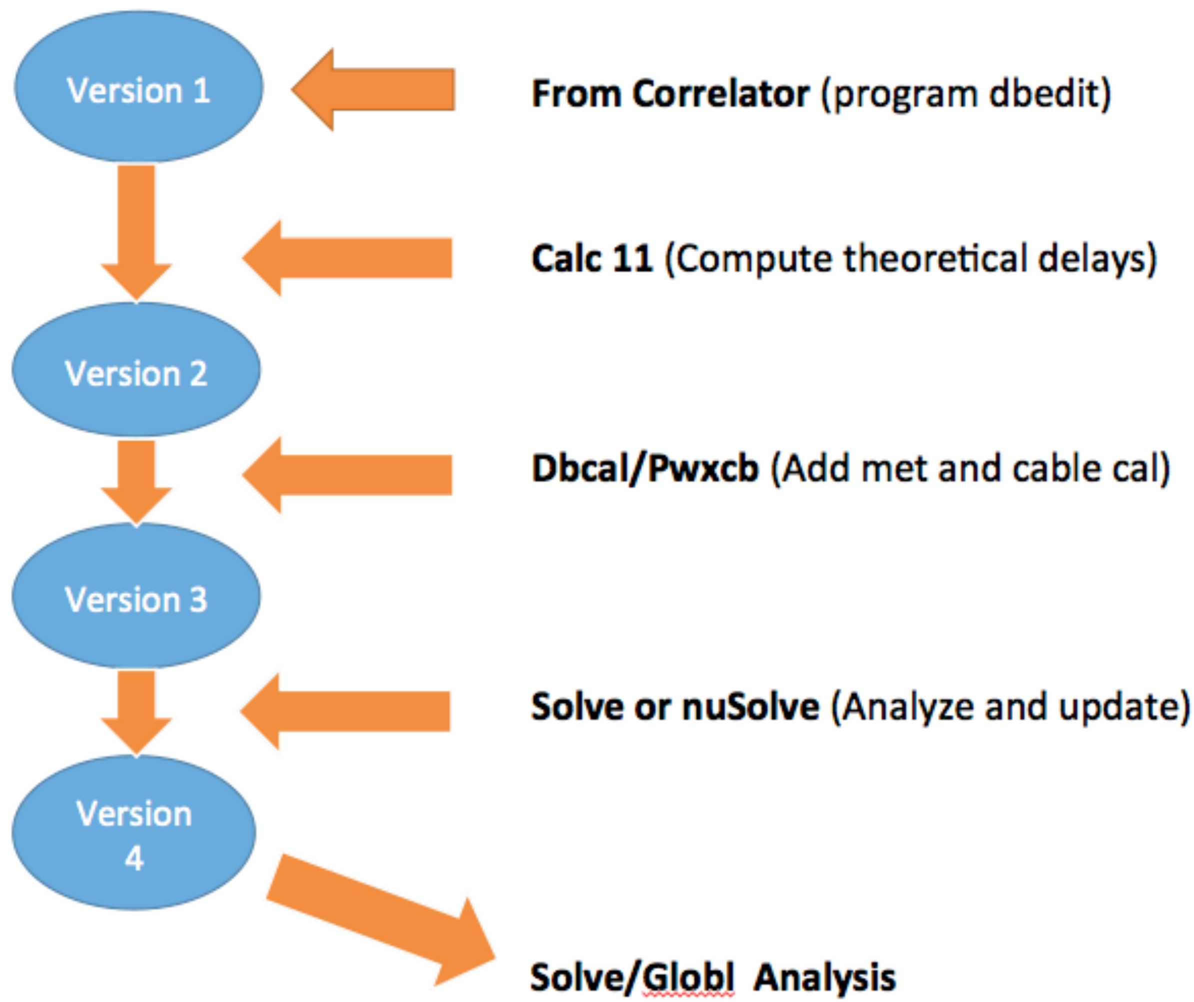
Analysis centers and software packages

- 29 IVS Analysis centers: North America (CA, DC, MA, MD), Europe (Austria, France, Germany, Italy, Norway, Sweden, Turkey, Ukraine), Russia, Asia (China, Japan, South Korea), Australia.
- Various software packages: *Calc/Solve*, nuSolve, VieVS, OCCAM, MODEST, SteelBreeze, GLORIA, Bernese, GEOSAT,…

Source: https://ivscc.gsfc.nasa.gov/

Data flow

GSFC example



Source: D. Gordon /D. MacMillan previous TOW Science talks

Importance of meteorological data recorded onsite
Impact of missing or erroneous met data

Pressure => used to calculate the zenith hydrostatic delay.

Temperature => used to calculate the linear expansion of the telescope components as VLBI telescopes are deformed by time-dependent temperature effects.

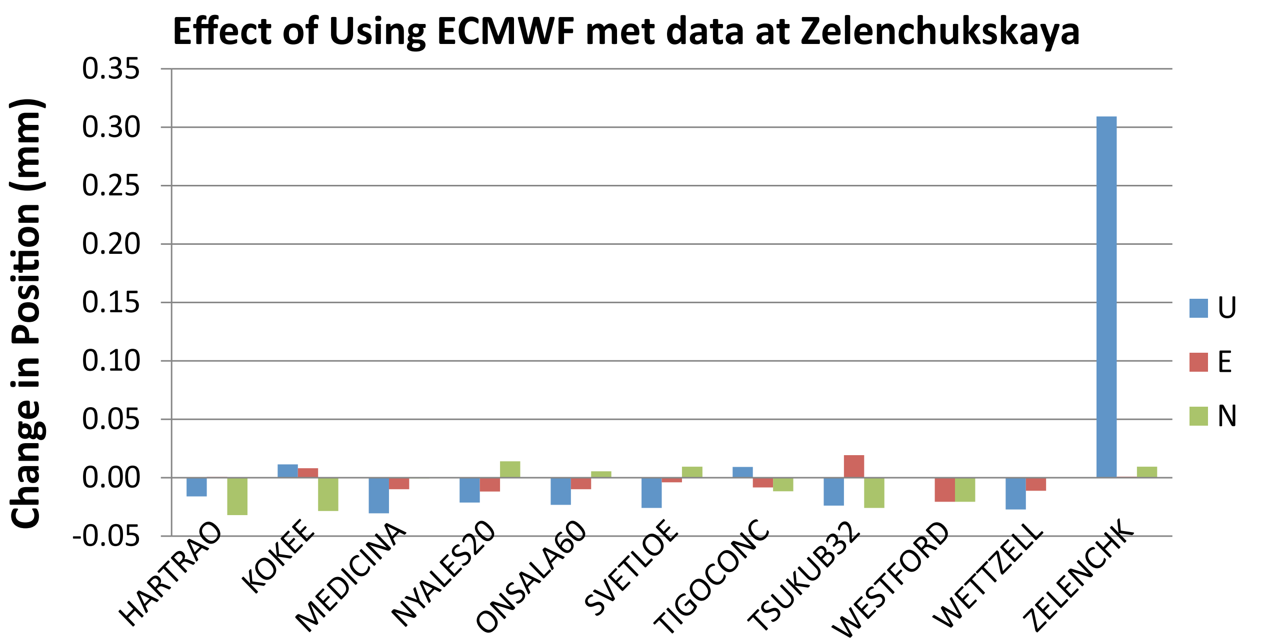
⇒ The meteorological data affects the results of the analysis.

Calc/Solve uses a default value when no met data in the databases.

Example of Zelenchuskaya. No met data recorded during CONT08.

Compared the impact of using external pressure data (ECMWF) instead of the default value of *Calc/Solve*.

- The **WRMS** is affected (0.12mm);
- The **determination of the Up component** varies within a significant level (see figure).



Importance of meteorological data recorded onsite
Thermal expansion of VLBI antennas

- **Thermal expansion** of VLBI antennas has been proven a significant effect **changing the height of the VLBI reference point by as much as 20 mm**.
- Model includes delay contributions arising from deformation of the antenna pillar and foundation, axis offset, vertex and subreflector heights.
- Expansion depends on dimensions of antenna, material expansion coefficients, and temperature variation.
- The thermal expansion model is implemented in *Solve*.

Table 5: Dimensions and expansion coefficients of frequently used geodetic VLBI telescopes.

Telescope	Foundation part (concrete)		Antenna part (steel)				
	h_f [m]	γ_f [$\frac{10^{-5}}{°C}$]	h_p [m]	h_v [m]	h_s [m]	h_d [m]	γ_a [$\frac{10^{-5}}{°C}$]
Effelsberg	0.0	1.0	50.0	8.5	28.0	–	1.2
Hartebeesthoek	0.0	1.0	12.7	2.3	9.4	6.7	1.2
Madrid	3.0	1.0	16.8	2.7	10.8	–	1.2
Matera	3.0	1.0	10.5	3.8	5.7	–	1.2
Medicina	2.3	1.0	15.5	4.3	4.3	–	1.2
Noto	2.2	1.0	15.7	4.2	5.0	–	1.2
O'Higgins	1.0	1.0	6.2	–	–	–	1.2
Onsala	11.3	1.0	2.9	3.4	5.5	–	1.2
Westford	16.9	1.0	2.0	3.0	3.6	–	1.2
Wettzell	8.0	1.0	4.0	3.7	7.9	–	1.2

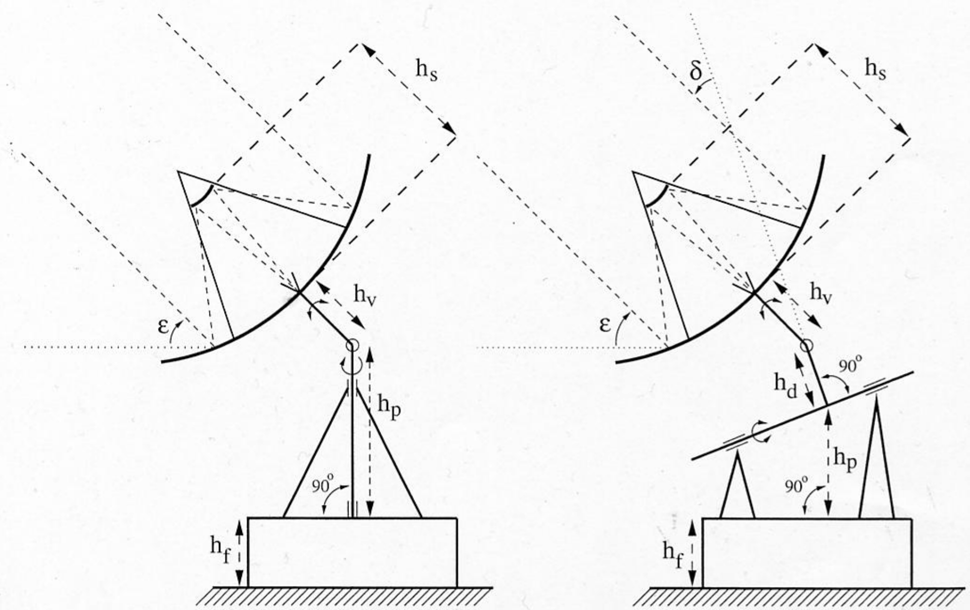


Figure 12: Left: Alt-azimuthal telescope mount. Right: Polar telescope mount.

Products of the analysis

Three components of Space Geodesy:

- Terrestrial Reference Frame (TRF);
- Celestial Reference Frame (CRF);
- Earth Orientation Parameters (EOP).

PRODUCTS

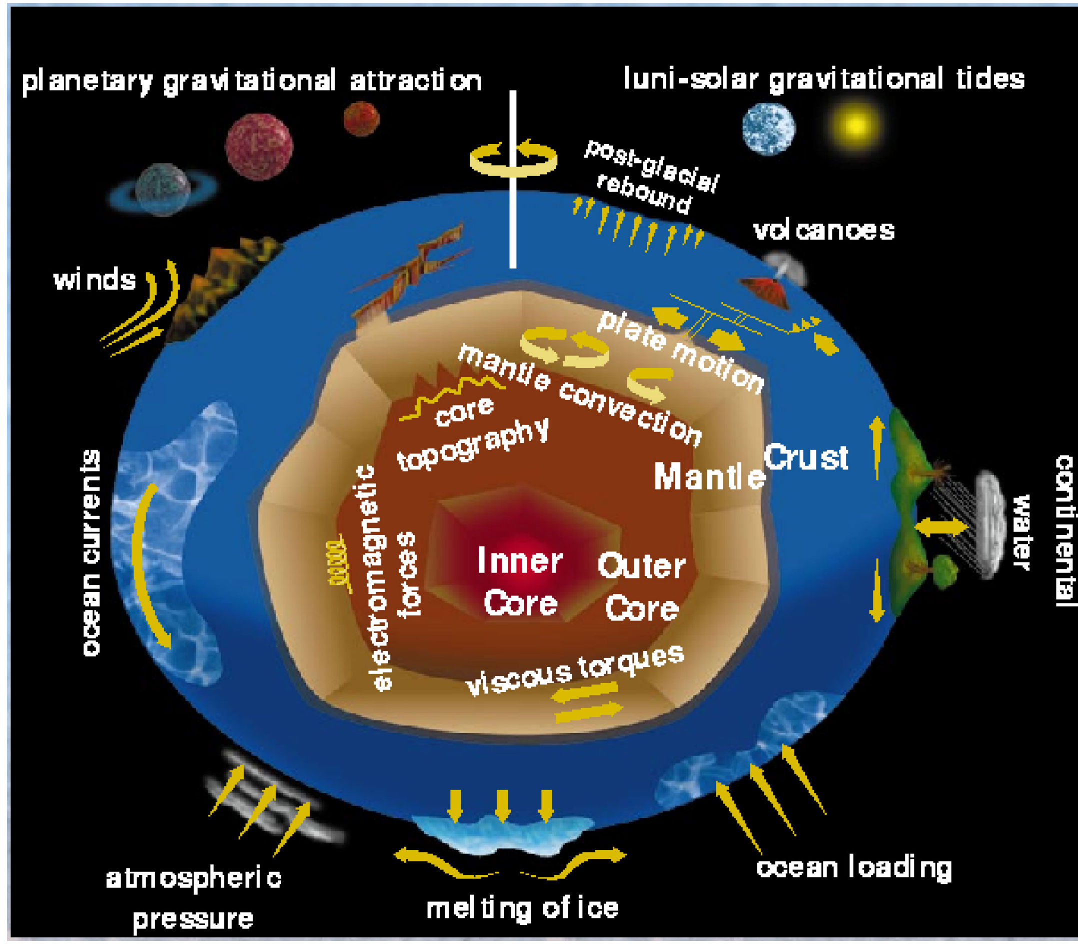
Terrestrial Reference Frame

Terrestrial Reference Frame

Factors that Affect Earth's Shape

- This illustration depicts many of the factors that affect how the Earth's shape changes. They include factors such as: winds, earthquakes, post-glacial rebound, plate motion, melting of ice, atmospheric pressure and more.

- To be able to quantify these effects, it is necessary to have a reference frame: the **Terrestrial Reference Frame**.



Credit: NASA.

Terrestrial Reference Frame
ITRF

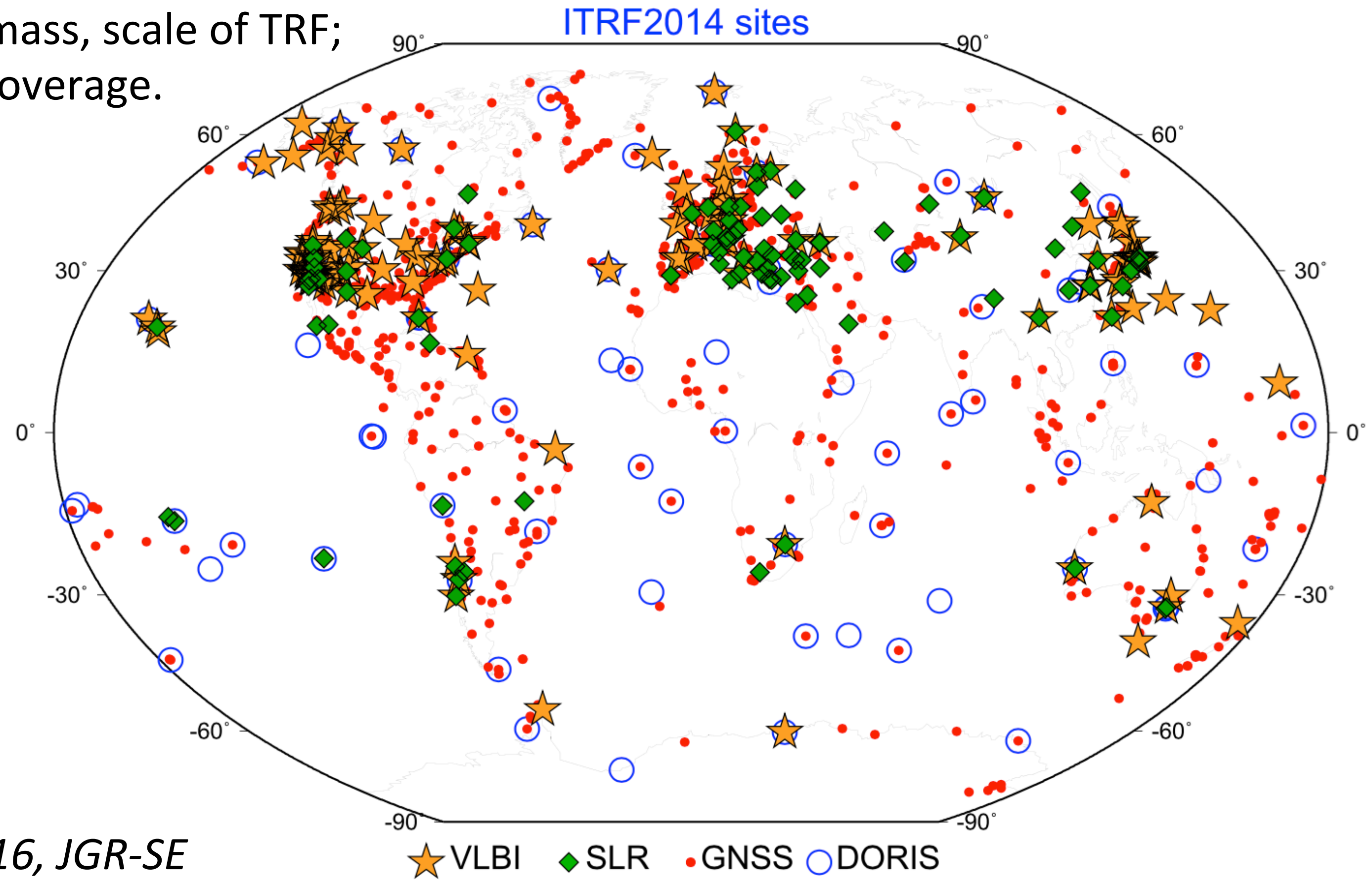
- A **Terrestrial Reference Frame** (TRF) defines the positions and velocities of a dense set of reference sites over the Entire Earth at a specified epoch.
- The International Terrestrial Reference Frame (ITRF) is a combination of TRF's from the four space geodetic techniques (VLBI, GPS, SLR, DORIS). Local ties are used to link the different stations of a same site.
- Current official ITRF is ITRF2014. Reference epoch is 2010.0. Two innovations were introduced in the ITRF2014 processing:
  - Annual and semi-annual terms were estimated for stations with sufficient time-spans of the four techniques;
  - Post-Seismic Deformation (PSD) models were determined by fitting GNSS/GPS data at major GNSS/GPS Earthquake sites (124 sites). The models were then applied to the three other techniques at earthquake co-location sites.

- VLBI : Precision of current sites: Most positions ~1 mm. Most velocities <0.1 mm/year.

Terrestrial Reference Frame

ITRF2014

- Positions and velocities for 1499 stations located at 975 sites (158 VLBI sites).
- Contributions from VLBI, GPS, SLR, and DORIS
  - **VLBI: scale of TRF, nutation, UT1-UTC**;
  - GPS: polar motion, densification;
  - SLR: center of mass, scale of TRF;
  - DORIS: global coverage.



Source: Altamimi et al. 2016, JGR-SE

Terrestrial Reference Frame

Earthquakes

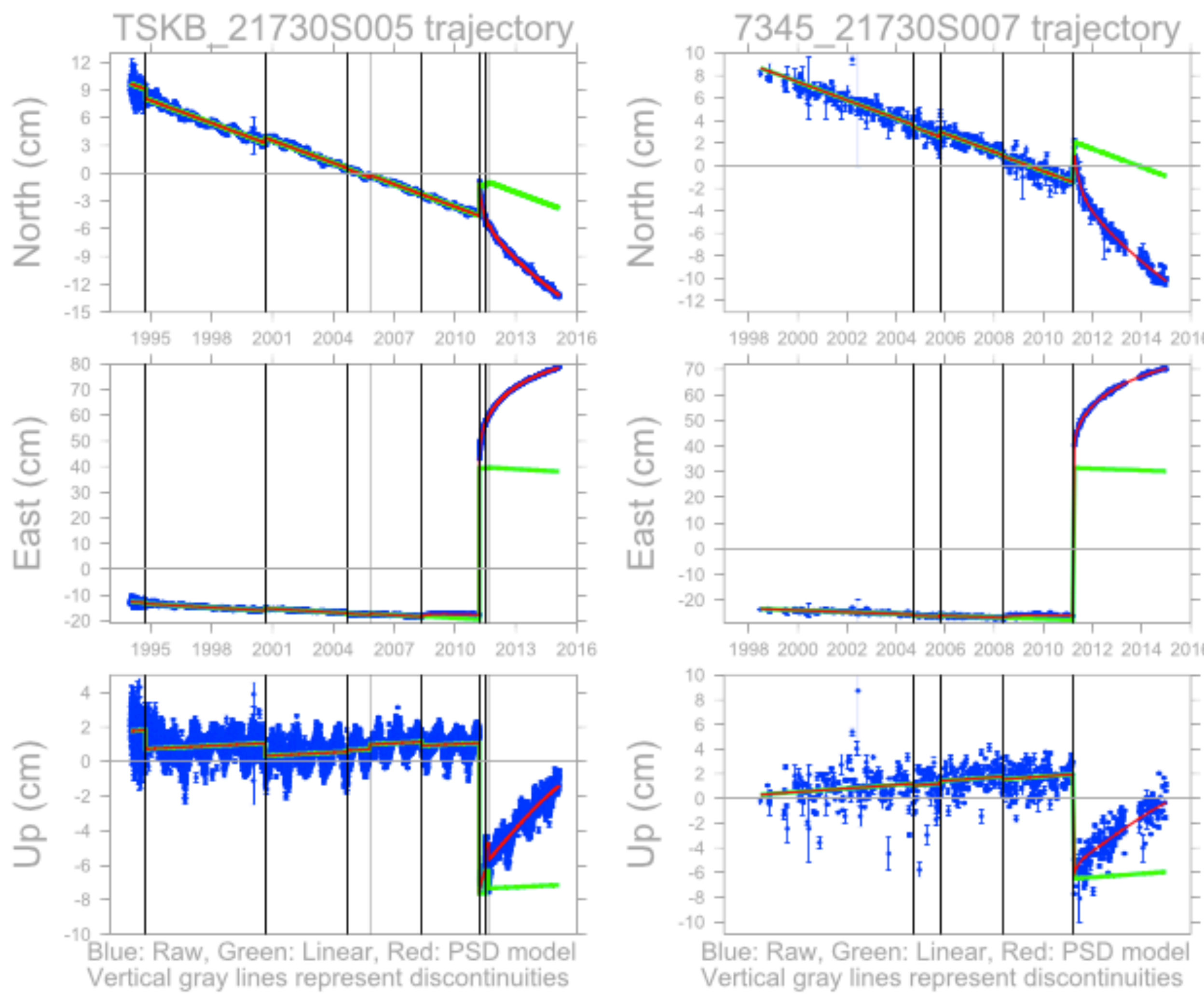
- A precise TRF allows for study/detection of plate tectonic motion, earthquake and episodic motions, regional deformations, post-glacial rebound/subsidence, sea level rise, etc.
- Case of Tsukuba earthquake, March 11, 2011.
- Figure: Trajectory of Tsukuba (Japan) site.

  In blue: raw data;

  In green: the piecewise linear trajectories given by the ITRF2014 coordinates;

  In red: the trajectories obtained when adding the parametric PSD model.

GPS **VLBI**



Source: Altamimi et al. 2016, JGR-SE

PRODUCTS

Celestial Reference Frame

Celestial Reference Frame

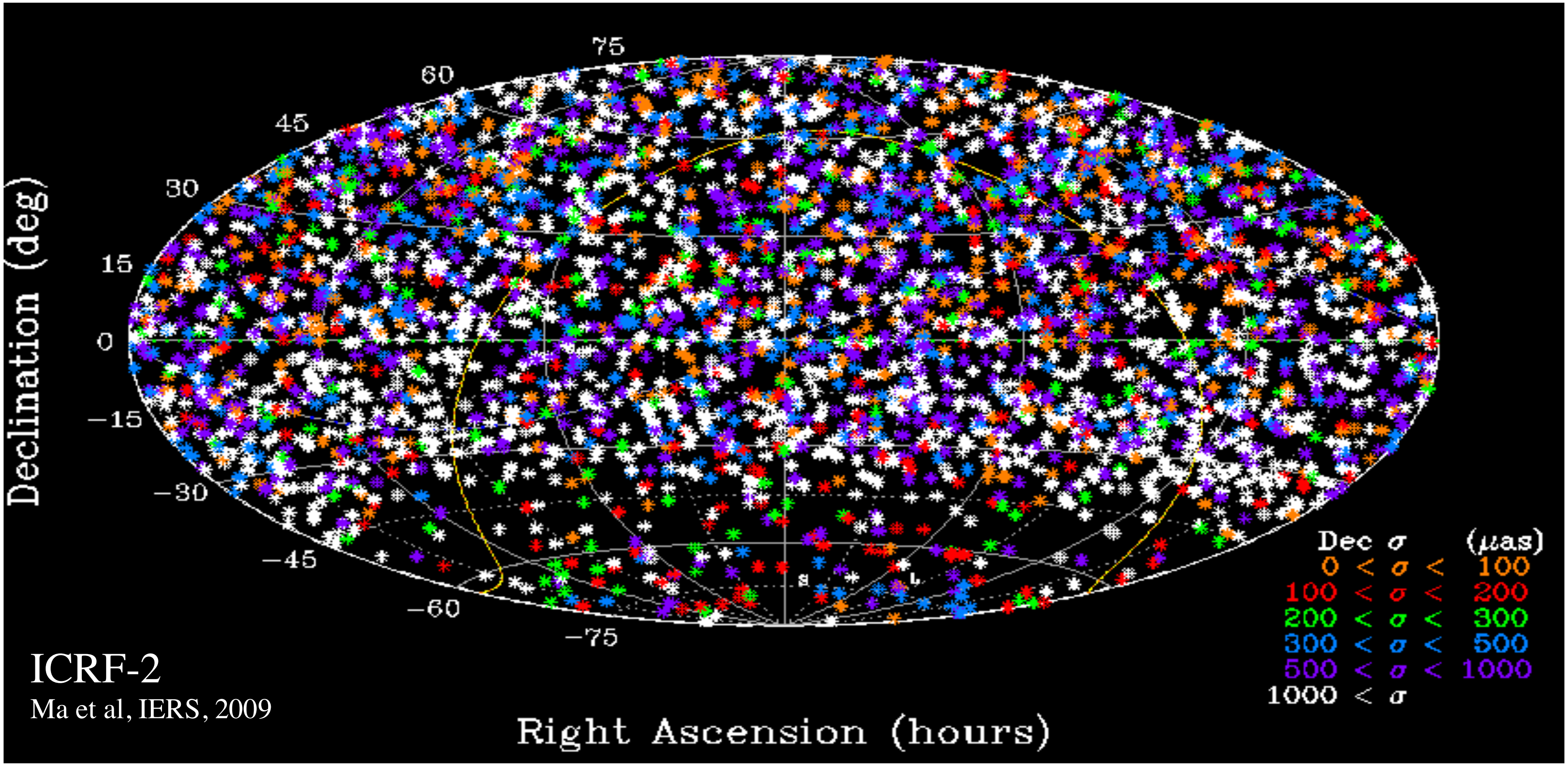
ICRFs

- A Celestial Reference Frame (CRF) is a set of coordinates (RA and Declination) of 'fixed' distant objects (stars, galaxies, quasars, etc).
- The CRF provides the inertial frame for absolute orientation of the Earth in the Universe.

Parameter	ICRF1 (1997) Replace FK5 optical frame	ICRF2 (Jan 1, 2010)	ICRF3 (2018)
Observation Dates	08/1979 – 07/1995 (16 years)	08/1979 – 03/2009 (29.5 years)	08/1979 – 2018 (~38.5 years)
# Observations	1.6M S/X group delays	6.5M S/X group delays	~15M S/X + X/Ka and K delays
# Defining Sources	212	295	200-300
Total Sources	608	3414	4400+ S/X -band 675 X/Ka -band 800 K-band
Noise Floor	~250 μas	~40 μas	20-30 μas
Axis Stability	~20 μas	~10 μas	<10 μas

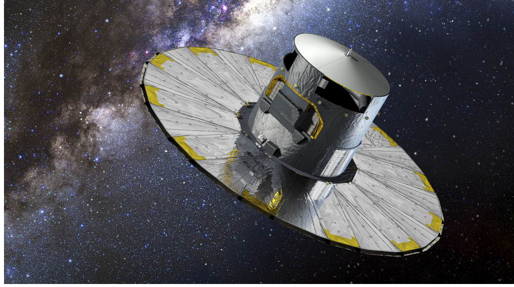
Celestial Reference Frame
ICRFs

ICRF2 : 3414 sources, ~2200 are single session survey sources (VLBA Calibrator Survey) with large formal errors.



Celestial Reference Frame

Gaia CRF



- The ESA mission Gaia was successfully launched on December 19, 2013. For five years, it is expected to observe and map billion of objects, including 500 000 quasars.

⇒ Link current ICRF (VLBI-radio frame) and GCRF (Gaia-optical frame)?

- The Laboratory of Astrophysics of Bordeaux (LAB) identified 195 common sources to link the two frames in the context of the IVS. Proposal approved in 2012:

⇒ All sources included in the IVS monitoring program with a target of 12 successful sessions per year.

⇒ Sources that are poorly observed or with a large position uncertainty are scheduled individually in **R&D and RDV sessions**. These sources are weak (<0.1Jy) or southern sources. Necessary to have a network with **sensitive antennas** and **antennas in the South Hemisphere**.

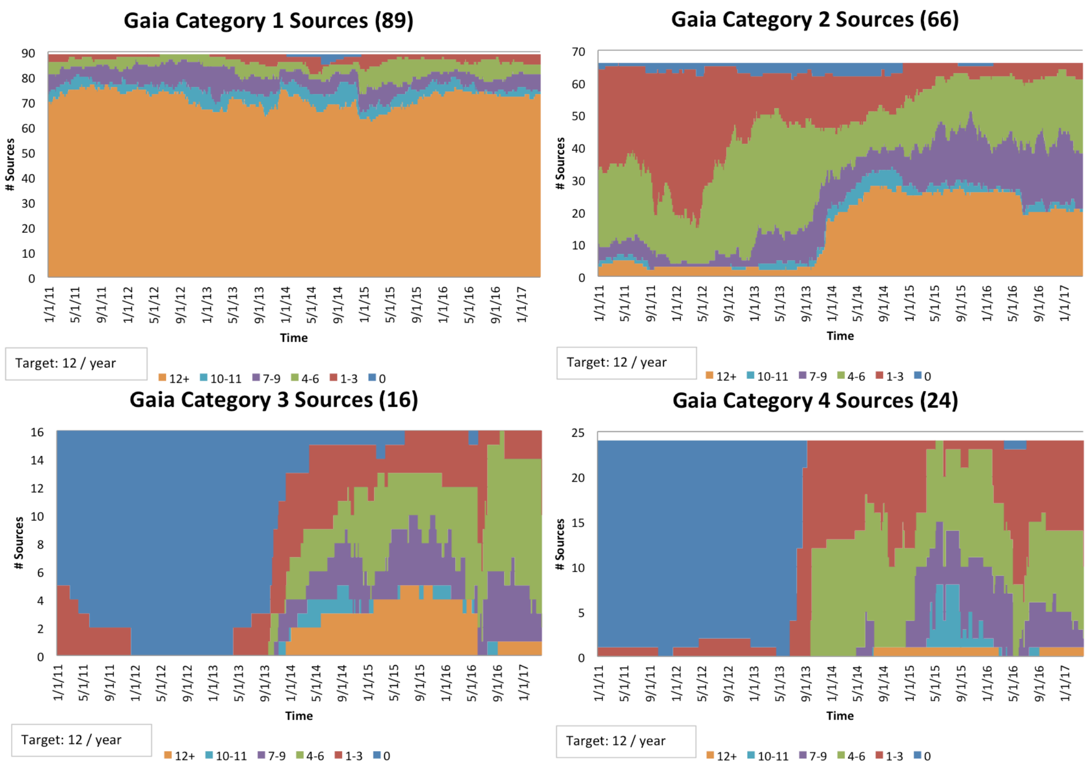


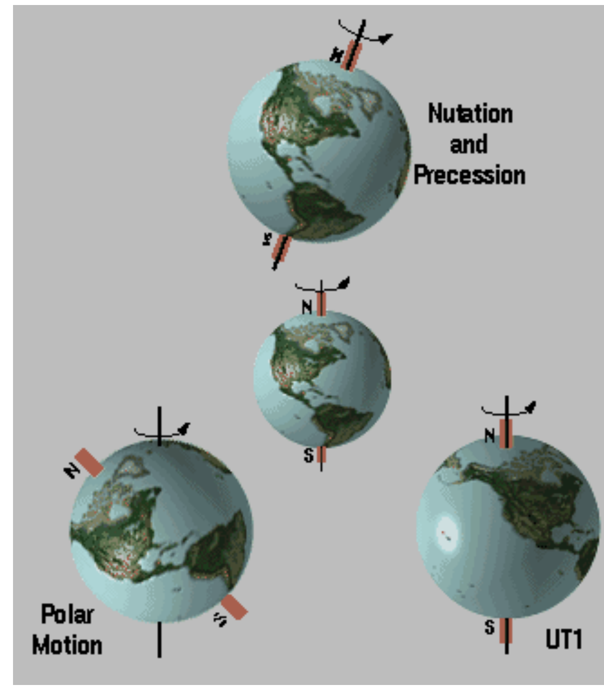
Figure: Number of successful sessions in the past year for each of the 195 ICRF2-Gaia transfer sources in each category determined by LAB.

PRODUCTS

Earth Orientation Parameters

Earth Orientation Parameters (EOP)

- Earth Orientation Parameters (EOP): The IERS Earth Orientation Parameters (EOP) describe the irregularities of the earth's rotation. Technically, they are the parameters which provide the rotation of the ITRS to the ICRS as a function of time.
  - Universal time, UT1;
  - Coordinates of the pole, polar motion;
  - Celestial pole offsets, Nutation/Precession.



- Essential for many applications (Earth navigation, spacecraft navigation…).

Universal Time, UT1

IERS:

Universal time. Universal time (UT1) is the time of the earth clock, which performs one revolution in about 24h. The excess revolution time is called length of day (LOD).

- UT1 is the most critical EOP parameter, since it changes the most rapidly. **VLBI is the only technique that precisely measures UT1**. For this reason, IVS makes 8 weekly 1-hr UT1 measurements and processes them as quickly as possible (***Intensives***). Predicted values of UT1 1 to 4 days in advance are critical for some users.
- UT1-UTC gives the correction to Universal Time due to variations in the Earth's rotation rate. A related parameter, **Length of Day (LOD)** is the difference in (UT1-UTC) from one day to the next, typically ~1-2 milli-seconds. To keep UT1-UTC less than 0.9 seconds, **leap seconds** are occasionally added (usually on Jan. 1 or July 1).

Universal Time, UT1
Length Of Day measured by VLBI

- Length of Day (LOD) is defined as the **excess to 86400 seconds** (24 hours) of the duration of the days.

- It is subject to variations due to zonal tides, to oceanic tides, to atmospheric circulation, to internal effects and to transfer of angular momentum to the Moon orbital motion.

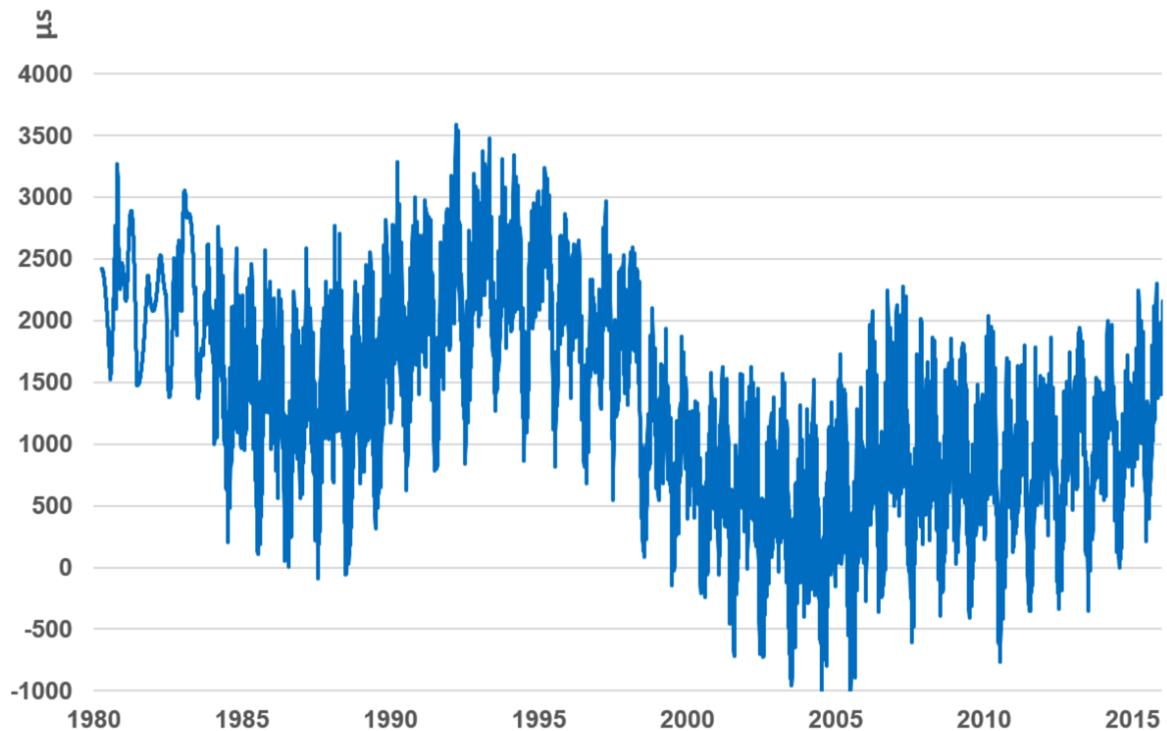


Figure: Length of Day measured by VLBI

Source: Gipson, 2016, IVS GM Proceedings

Universal Time, UT1

Length Of Day measured by VLBI and ENSO

- El Niño/Southern Oscillation (ENSO) is an irregularly periodical variation in winds and sea surface temperatures over the tropical eastern Pacific Ocean. It is the most important coupled ocean-atmosphere phenomenon to cause global climate variability on inter-annual time scales.

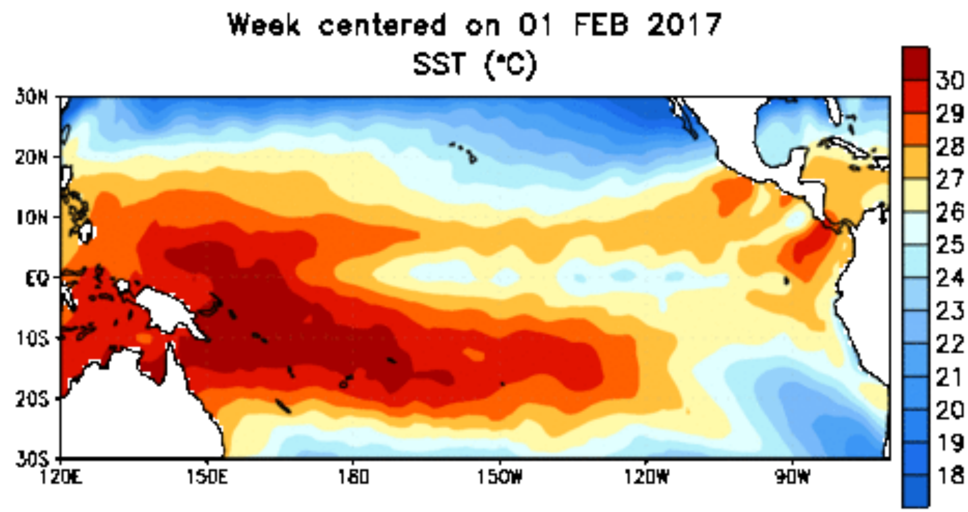


Figure: Sea Surface Temperature (SST) over the tropical Pacific. *Source: http://www.cpc.ncep.noaa.gov/*

- The Multivariate ENSO Index (MEI) is calculated at NOAA. It is the combination of various variables over the tropical Pacific: surface wind, sea surface temperature, surface air temperature, and total cloudiness fraction of the sky.

Universal Time, UT1

Length Of Day measured by VLBI

The residual Length Of Day is the VLBI measured LOD presented previously minus known effects: tidal terms, seasonal terms, and long period terms.

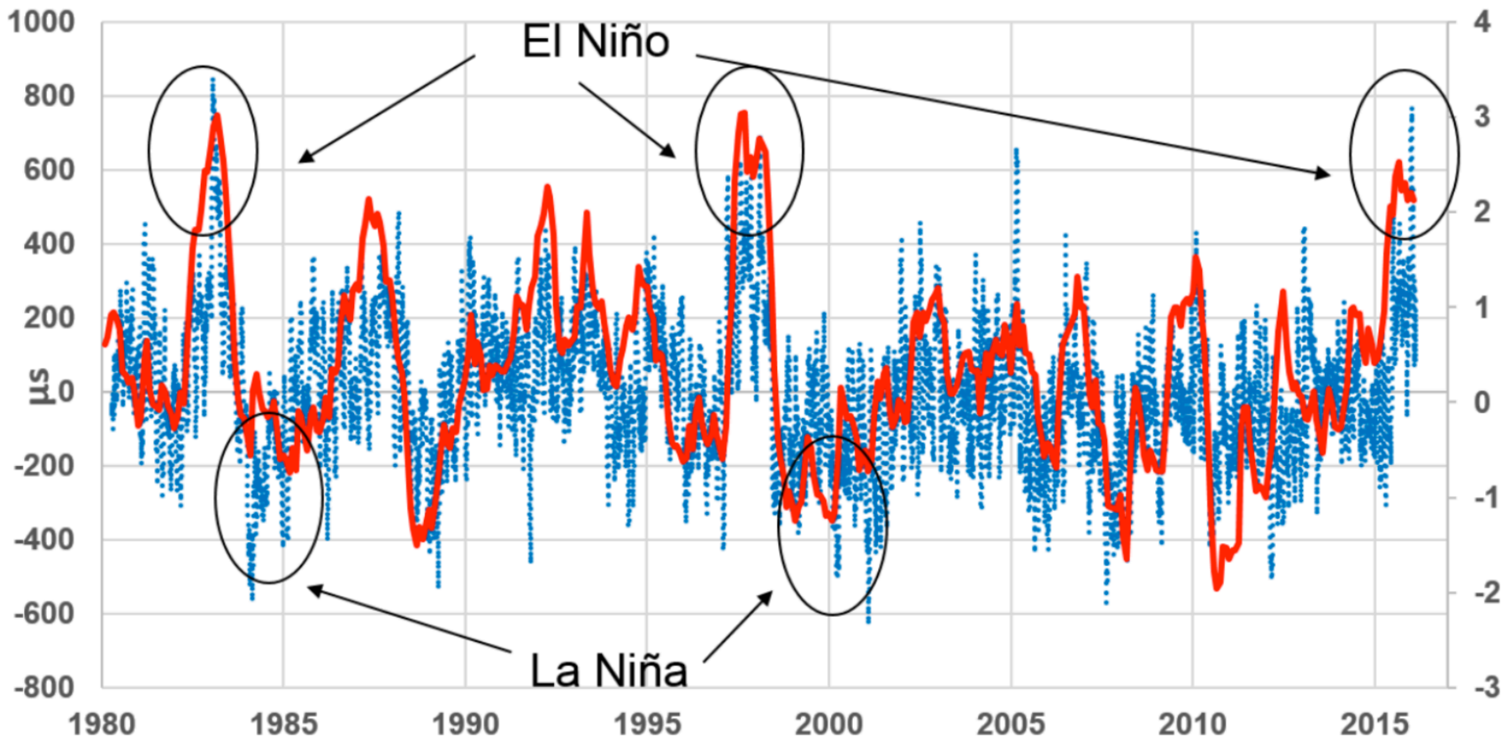


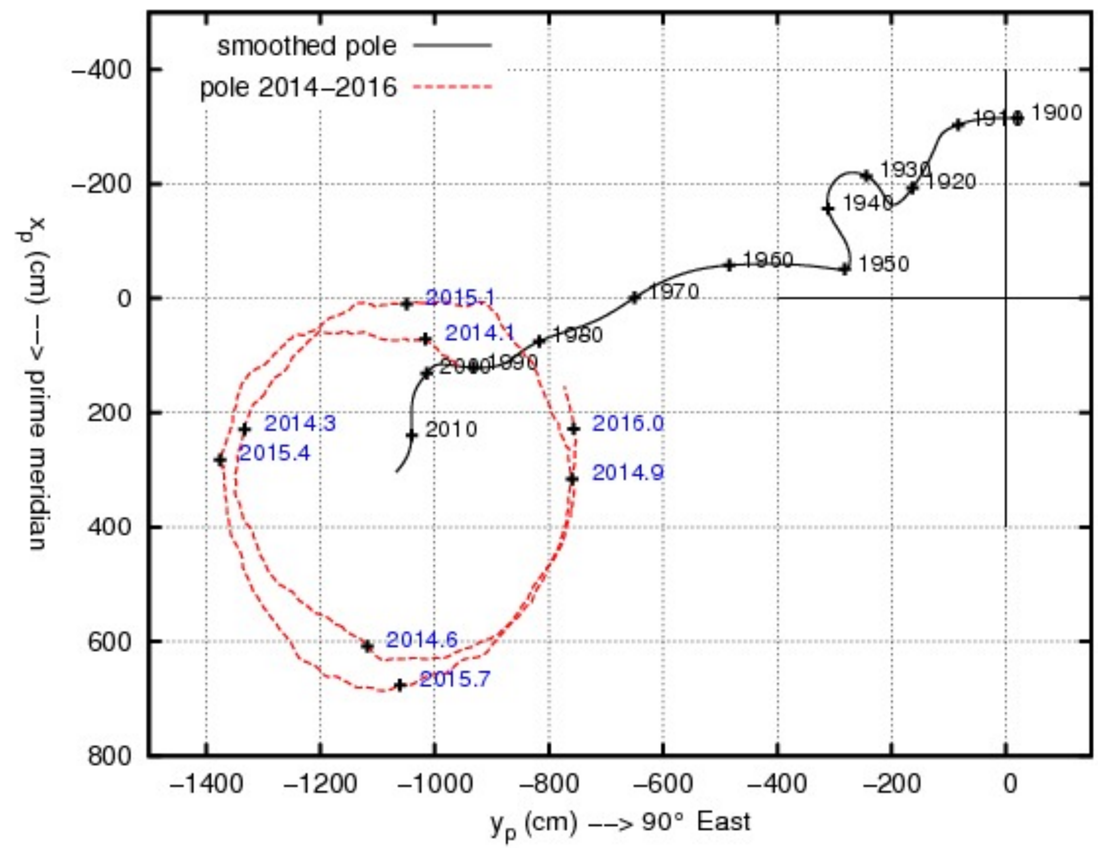
Figure: MEI (red) and residual Length Of Day (blue)

Coordinates of the Celestial Ephemeris Pole (CEP)

IERS:

"Coordinates of the pole. x_p and y_p are the coordinates of the Celestial Ephemeris Pole (CEP) relative to the IERS Reference Pole. The CEP differs from the instantaneous rotation axis by quasi-diurnal terms with amplitudes under 0.01". The x-axis is in the direction of the ITRF zero-meridian; the y-axis is in the direction 90 degrees West longitude."

This is the imaginary point in the sky where the Earth's axis of rotation intersects the celestial sphere.



Source: SYRTE/Obs Paris website

Celestial Pole Offsets

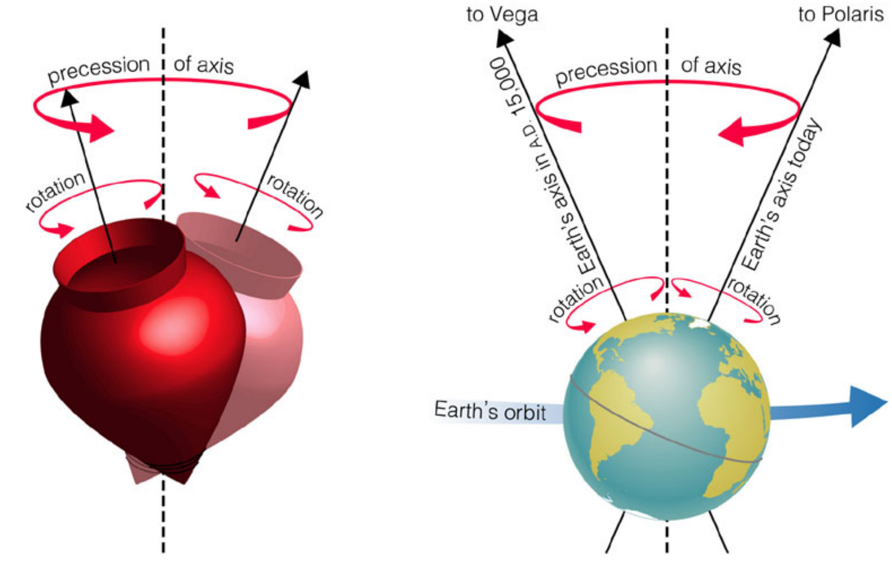
Precession and nutation

IERS:

Celestial pole offsets are described in the IAU Precession and Nutation models. The observed differences with respect to the conventional celestial pole position defined by the models are monitored and reported by the IERS.

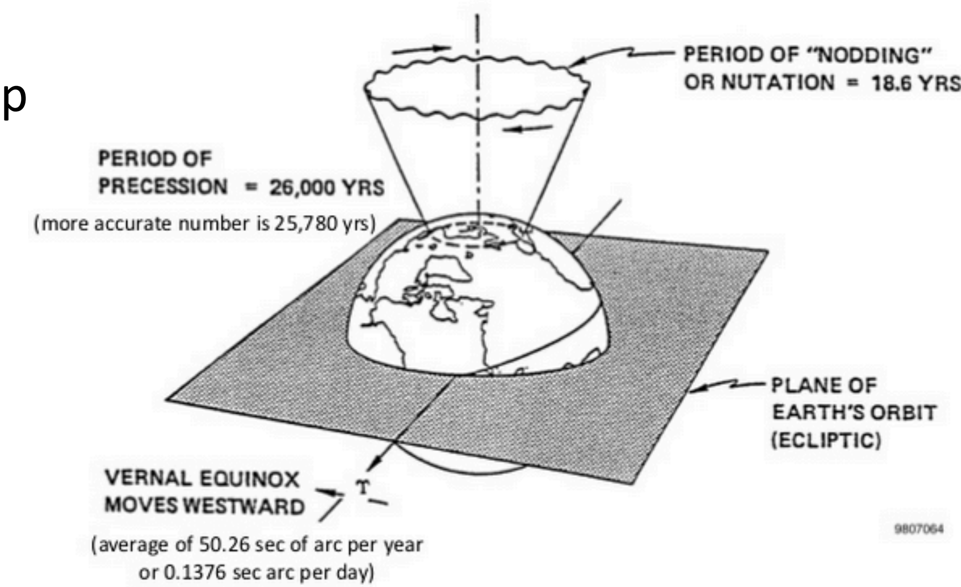
- Caused by torques exerted on the Earth and its equatorial bulge by the Moon, the Sun, and the planets.
- Described very well by the IAU models. However there are residual effects of up to 1 milli-arc-second due to the free-core nutation, the inner free-core nutation, and other small effects, that cannot be predicted by the models.

VLBI makes the **most accurate measurements of Precession/Nutation** in IVS sessions (such as the R1's, R4's, RDV's, etc).



CELESTIAL MOTION

Principal Motion of the Celestial Ephemeris Pole



Why the VLBI data is important?

- **Better understanding of our planet**:
  - El Niño causes the Earth's rotation to speed up or slow down. One of the effects of the 1997 El Niño weather system was to lengthen our day by 0.6 milliseconds.
  - Our continents are in constant motion. North America and Europe are drifting apart at a rate of about 1 cm per year.
- VLBI is used at USNO to determine reference frames for stars and the Earth, and to predict the variable orientation of the Earth in three-dimensional space. Knowing CRF and TRF is important to the Department of Defense in order to maintain the accuracy of the GPS upon which much of the world depends for **navigation**. VLBI is the only technique that can make the precise celestial position measurements required to produce meaningful EOP needed to **calibrate the GPS system**.
- The EOP are also essential for performing orbit controls of spacecraft, as well as deciding to insert or delete a **leap seconds** in the Coordinated Universal Time (UTC), which is the primary time standard by which the world regulates clocks.
- ... A lot more!

- Thanks for your hard work.