

History of monitoring Earth orientation

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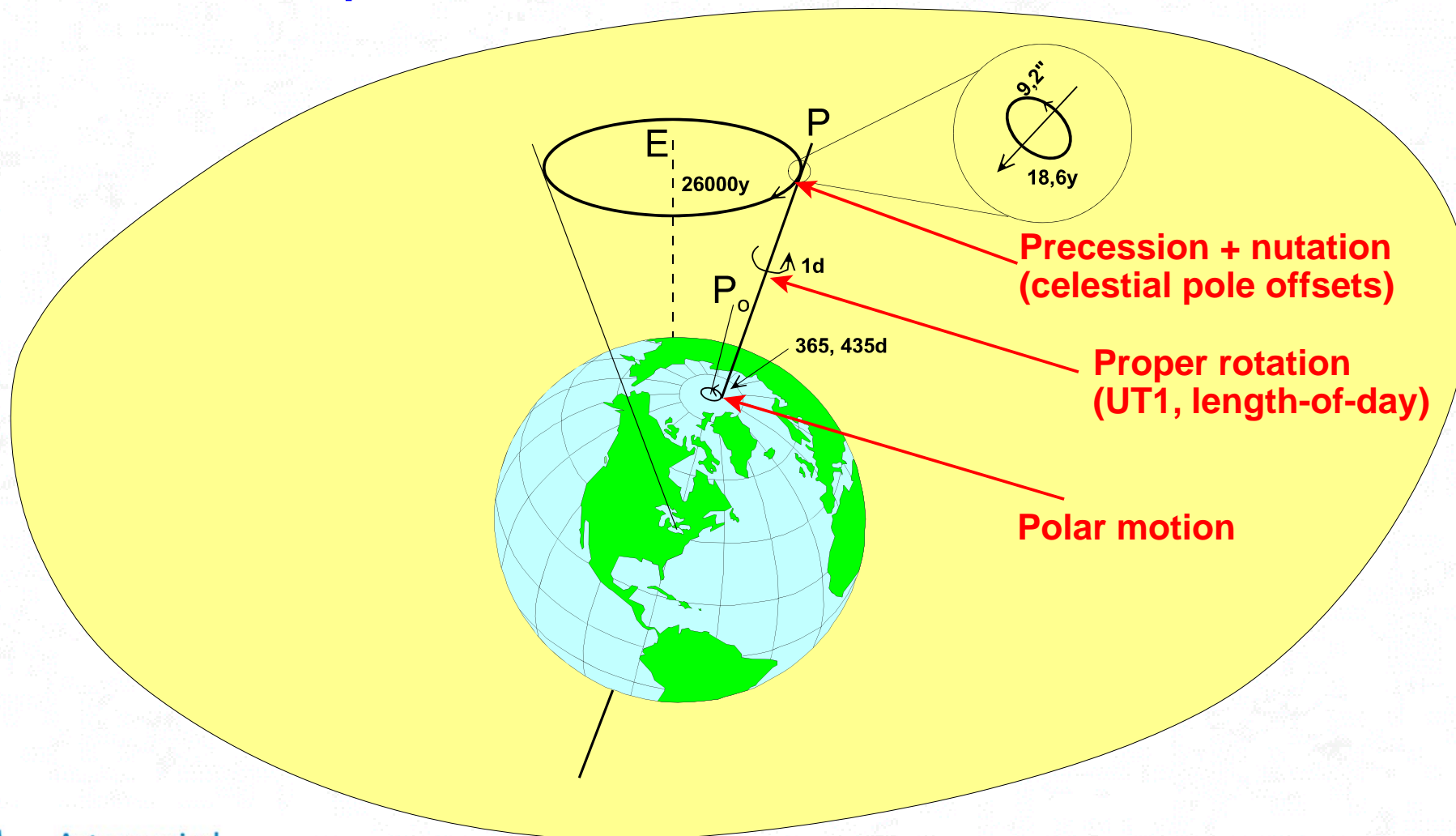
Contents:

- Earth orientation parameters;
- Short historical background;
- Services monitoring Earth orientation;
- Geophysical effects in Earth orientation;
- Re-analyses of historical astrometric observations.

Earth orientation parameters

- Earth rotation **in a wider sense** - total orientation of the body (precession-nutation, polar motion, proper rotation), affected by:
 - ▶ External torques (by the Moon, Sun, planets);
 - ▶ Geophysical influences (internal composition of the Earth, transfer of mass at core-mantle boundary, geomagnetic core-mantle coupling, oceans, hydrosphere, atmosphere...).
- Earth rotation has a fundamental importance in astronomy, especially for transformation between celestial and terrestrial reference systems, but also in other applications:
 - Space navigation;
 - geophysics;
 - geodesy etc...

Earth orientation parameters



Short historical background:

- **precession**

- ▶ known already to Hipparchos (2nd cy BC);

- **polar motion**

- ▶ theoretically predicted by Leonhard Euler (1765) - period=305d;
- ▶ observationally first detected by Karl Friedrich Küstner in Berlin (1884/5);
- ▶ shortly afterwards confirmed by Ladislaus (László) Weinek in Prague;
- ▶ two main components (with periods 430 and 365d) determined by Seth Carlo Chandler (1891);
- ▶ Difference between predicted (305d) and observed (430d) free period explained by Simon Newcomb (1902) by non-rigidity of the Earth.
- ▶ since 1899 polar motion regularly monitored by different services.

Short historical background (cont.):

■ **nutaton**

- ▶ first observed by James Bradley (1728) and theoretically explained by Leonhard Euler (1748);
- ▶ since then systematic improvement of the model took place:
 - Peters 1842, Oppolzer 1882, Newcomb 1898, Woolard 1953, Wahr 1980, Mathews, Herring & Buffet 2000).

■ **changes of speed of rotation**

- ▶ secular deceleration of Moon's motion observed by Edmond Halley (1695);
- ▶ later studied by Pierre Simon de Laplace (18th cy);
- ▶ the Moon's influence on deceleration of Earth rotation implied by George Darwin (end of 19th cy);
- ▶ secular and decadal variations were studied by Simon Newcomb (1882), Willem de Sitter (1927) and Harold Spencer Jones (1939);
- ▶ seasonal (annual, semi-annual) variations detected from observations in the first half of the 20th cy (Nicolas Stoyko, 1950).

Services monitoring Earth orientation

- International Latitude Service (ILS) - set up by IAG to monitor polar motion, active since 1899:
 - ▶ stations located at latitude $39^{\circ} 08'$ (Mizusawa, Tschardjui, Kitab, Carloforte, Gaithersburg, Cincinnati, Ukiah).
- Bureau International de l'Heure (BIH) - set up by IAU in 1919 to unify and maintain Universal Time, later on also polar motion:
 - ▶ astrometric observations, time signals.
- International Polar Motion Service (IPMS) - set up by IAU and IUGG to replace ILS, active since 1962:
 - ▶ astrometric observations with different types of instruments at tens of observatories.

*Some optical astrometric instruments used by ILS, BIH and IPMS
(terrestrial system linked to local plumb-lines, celestial system to stars)*

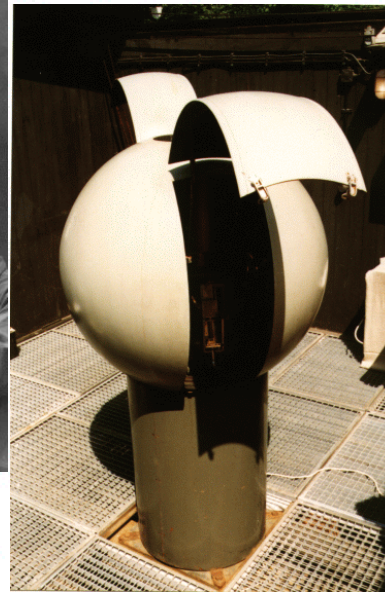


Zenith telescope

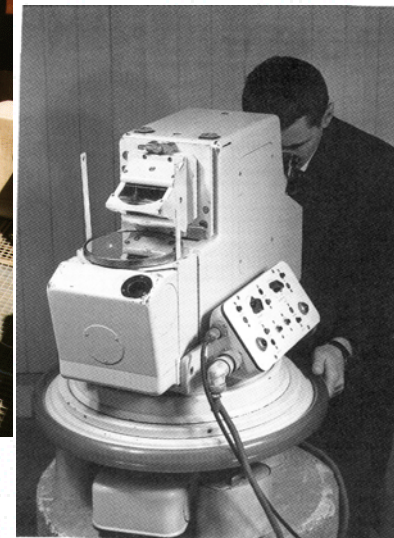


Transit instrument

PZT



Danjon astrolabe



Circumzenithal



Services monitoring Earth orientation

- International Earth Rotation (and Reference Systems) Service (IERS) - set up by IAU and IUGG in 1987 to replace all preceding services to monitor Earth orientation and maintain celestial and terrestrial reference frames:
 - ▶ Space geodesy techniques (SLR, LLR, VLBI, GNSS, DORIS) located all over the world.

Space geodesy techniques used by IERS (terrestrial system linked to station coordinates, celestial system directly to extragalactic objects for VLBI, indirectly through satellite orbits for satellite methods)

SLR
Satellite
Laser
Ranging

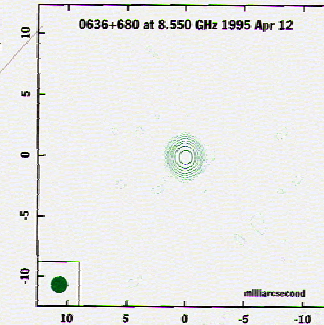
provides the long-term stability for polar motion, for the tie of the ITRS to the Earth's center of mass, and for the monitoring of the gravity field and slow deformations of the Earth. It is the only satellite technique with a passive space segment.



Lageos is the major SLR target used for IERS. It is a 60 cm diameter metallic sphere covered with retroreflectors, cruising at an altitude of 6000 km. It was launched in 1976 by NASA and will remain an excellent geodetic target for tens of thousands years.

VLBI
Very Long
Baseline
Radio
Interferometry

defines and maintains the extragalactic celestial frame. It holds together the International Celestial and Terrestrial Reference Systems. It provides the long-term monitoring of universal time, precession and nutation.



One of the extragalactic radio sources regularly observed with VLBI to maintain the ICRF. The lines show levels of radiated energy. The position of the light centre of this object is measured with an accuracy of 0.0002".

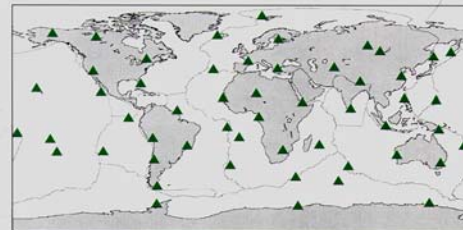
The VLBI antennas used for IERS have diameters ranging from 9 m to 70 m. They are operated in several tens of sites. The precision of observations of the interferometric time delay is 10 picoseconds.



GPS

A worldwide network of GPS stations is operated jointly with the International GPS Service for Geodynamics (IGS) or global applications of interest to IERS. Polar motion and the high-frequency variations of universal time are determined daily. A major strength of GPS for IERS is the capability of fine and accurate densification of the ITRS.

GPS is a radioelectric system operated by the US Department of Defense. It includes 24 satellites at an altitude of 20 000 km. At least four satellites are visible simultaneously at any time from most locations in the world. GPS positioning is used in a wide variety of civil and scientific applications.



DORIS

Doppler Orbit determination
and Radiopositioning
Integrated on Satellite

provides the long term monitoring of the plate motions and of the mean sea level in the ITRS. Among its strengths are a globally distributed and homogeneous network, and the long term commitment of the sponsoring agency.

DORIS is a radioelectric system operated by CNES. The permanent ground segment includes 49 beacons globally distributed. The space segment collects Doppler observations of the beacons. DORIS is the nominal orbitography system of several current and planned space oceanography missions, with altitudes of 1000-2000 km.

Geophysical effects in Earth orientation

- From the theory of Earth rotation it follows that:
 - ▶ External torques (by the Moon, Sun and planets) affect:
 - dominantly precession/nutation;
 - about a half of changes in speed of rotation (tidal deformation);
 - marginally polar motion.
 - ▶ Geophysical influences (motion of the atmosphere, oceans, hydrosphere, geomagnetic torque between mantle and core...) affects:
 - dominantly polar motion;
 - about a half of changes in speed of rotation (winds, oceanic currents);
 - marginally precession/nutation.

Geophysical effects in Earth orientation

- As the accuracy of observing techniques is improving, new theories are required to explain differences between theory and observations;
- Geophysical effects are more and more important; to study these effects in detail, the IERS established
 - ▶ IERS Global Geophysical Fluids Center, consisting of special bureaus for
 - Atmosphere,
 - Oceans,
 - Hydrosphere,
 - ▶ responsible for gathering relevant data and publishing corresponding excitations.

Some re-analyses of old astrometric observations

- Fedorov, Korsun, Mayor, Panchenko, Tarady & Yatskiv 1972:
 - ▶ 75 observatories, groups of stars, polar motion 1890.0-1969.0 with 0.05yr step, original star catalogs.
- Yumi & Yokoyama 1980:
 - ▶ 7 ILS stations, groups of stars, polar motion 1899.9-1979.0 with 0.05yr step, Melchior-Dejaiffe star catalog.
- **Vondrák et al. (1998-2012):**
 - ▶ selected best observatories, Hipparcos Catalog (individual stars), polar motion, celestial pole offsets, Universal time, rheological parameters, ...

Re-analyses made in Astron. Inst. Prague:

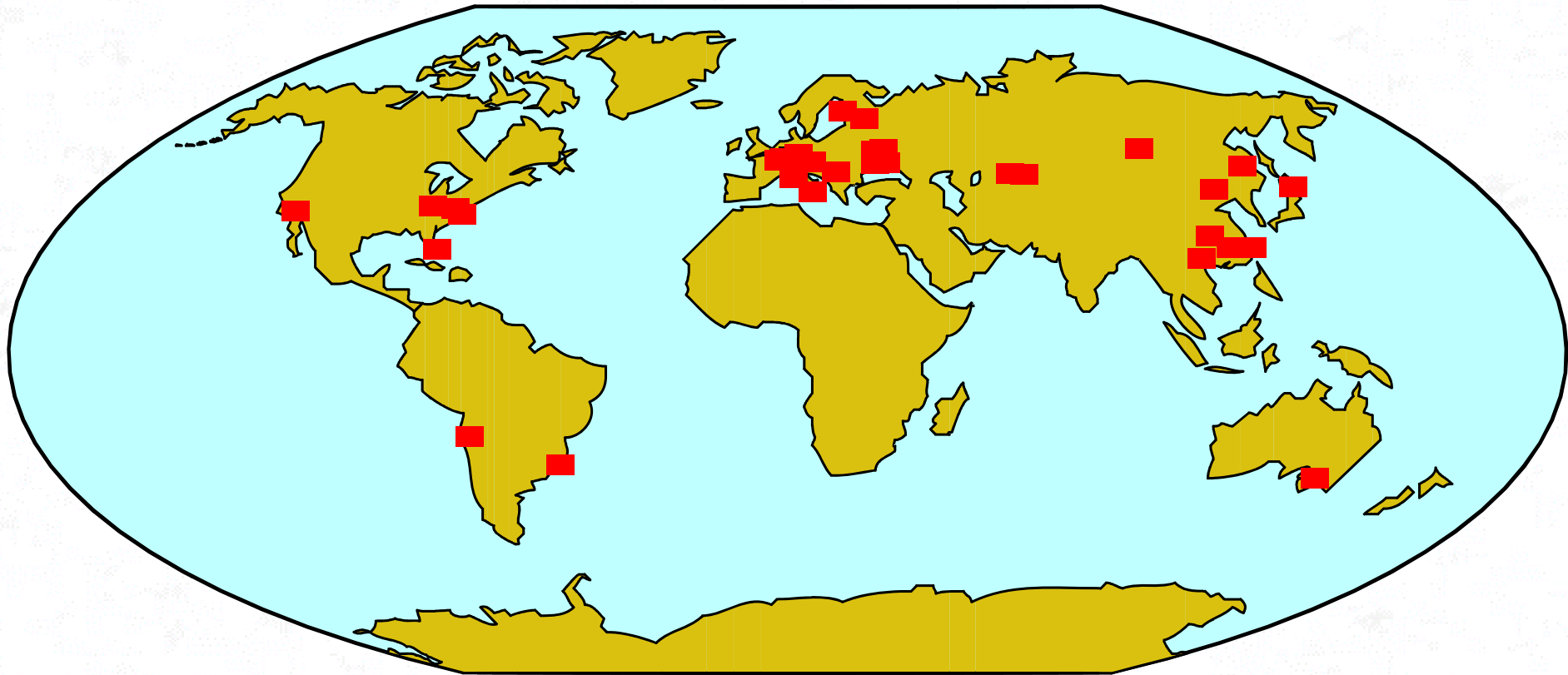
- ▶ Whole project initiated by Martine Feissel, WG on Earth Rotation in Hipparcos Reference Frame was set up by IAU in 1988.
- ▶ In 1991, we selected the best observatories monitoring Earth rotation, according to:
 - Length of observational series;
 - Stability of the results;
 - Quality of observations.
- ▶ Since 1991 we started collecting star by star observations from the selected observatories.
- ▶ The observations were
 - re-calculated with a unique system of astronomical constants/ standards, based on MERIT standards (later on, IERS Conventions),
 - corrected for plate motions (NUVEL-1A), and
 - referred to the same star catalog (Hipparcos, Earth Orientation Catalog).

Re-analyses made in Astron. Inst. Prague:

- The collected and re-reduced observations were used to obtain:
 - ▶ Polar motion in 5-day intervals (1899.7-1992.0);
 - ▶ Universal time in 5-day intervals (1956.0-1992.0);
 - ▶ Celestial pole offsets (1899.7-1992.0):
 - in 5-day intervals, referred to IAU1976 precession and IAU1980 nutation, in the first group of solutions (OA97-OA99);
 - quadratic representation, referred to IAU2006 precession and IAU2000 nutation, in the second group of solutions (OA03-OA10);
 - ▶ rheological parameter $\lambda = l + k - l$ for each instrument;
 - ▶ local seasonal deviations and drifts in latitude/longitude of each instrument.

Re-analyses made in Astron. Inst. Prague:

Participating observatories



Most important solutions:

Name	observat./instr.	Observations [in millions]	Star Catalog	publication
OA97	31/45	4.32	HIP	Vondrák et al., 1998
OA99	33/47	4.45	HIP+corr.	Vondrák, Ron, Pešek, 2000
OA03	27/33 (meridian)	3.26	EOC-1	Ron, Vondrák, 2004
OA04	33/47	4.54	EOC-2	Vondrák, Ron, 2005
OA07	33/47	4.54	EOC-3	Vondrák, Ron, Štefka, 2008
OA09	33/47	4.53	EOC-4	Vondrák, Ron, Štefka, 2010
OA10	33/47	4.51	EOC-4	Vondrák, Ron, Štefka, Chapanov, 2012

Notes: EOC is a combined catalog - observations, HIP, ARIHIP, TYCHO-2, PPM:

1 - meridian observations, 3784 stars, positions + proper motions;

2 - all observations, 4418 stars, positions + proper motions;

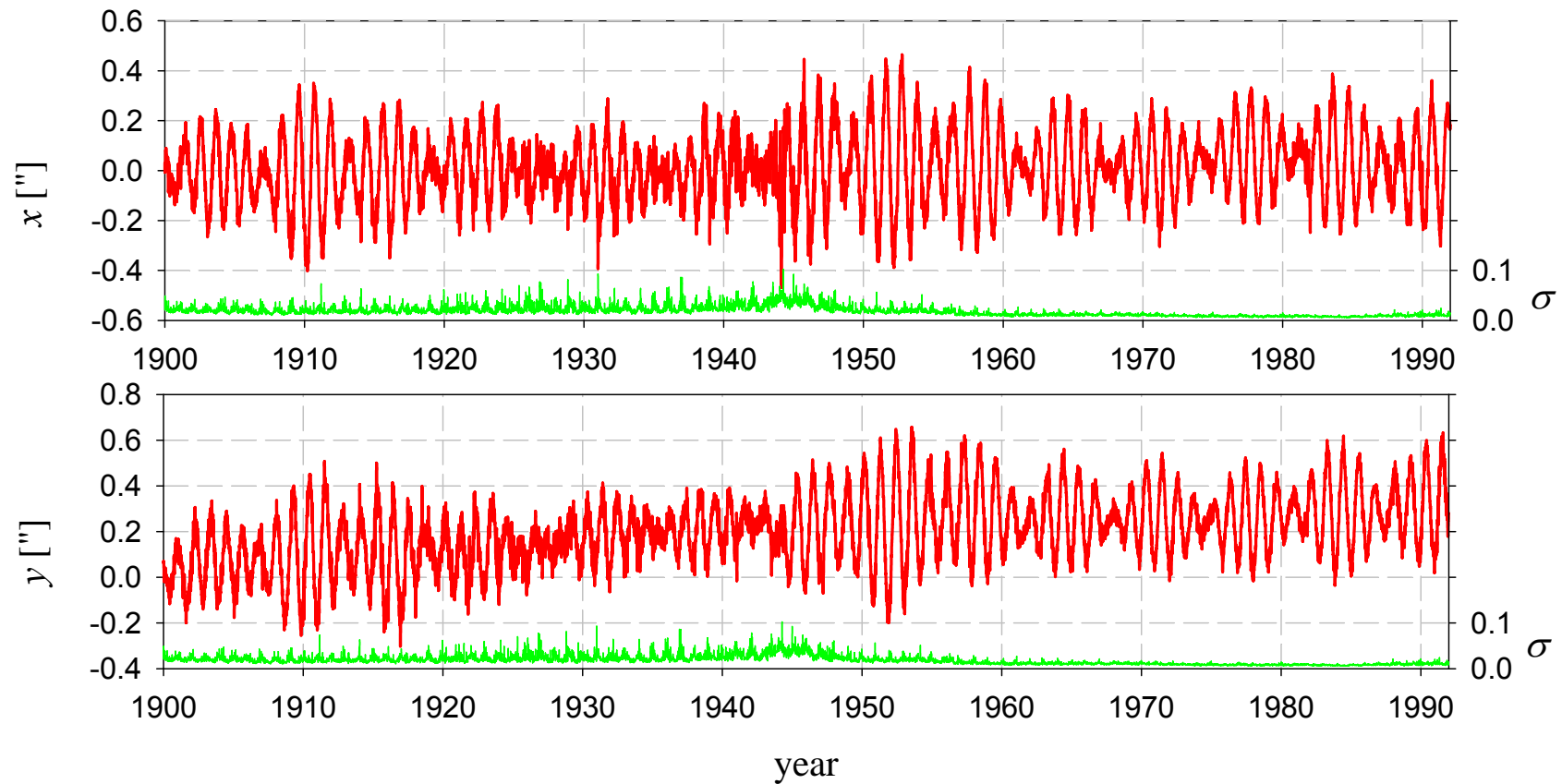
3 - all observations, 4418 stars, positions + proper motions, 585 stars with orbital periodic m.;

4 - all observations, 4418 stars, positions + proper motions, 599 stars with orbital periodic m.;

OA10 is linked to ITRS via IERS solution C04 1978-1992 (constant, linear drift, seasonal).

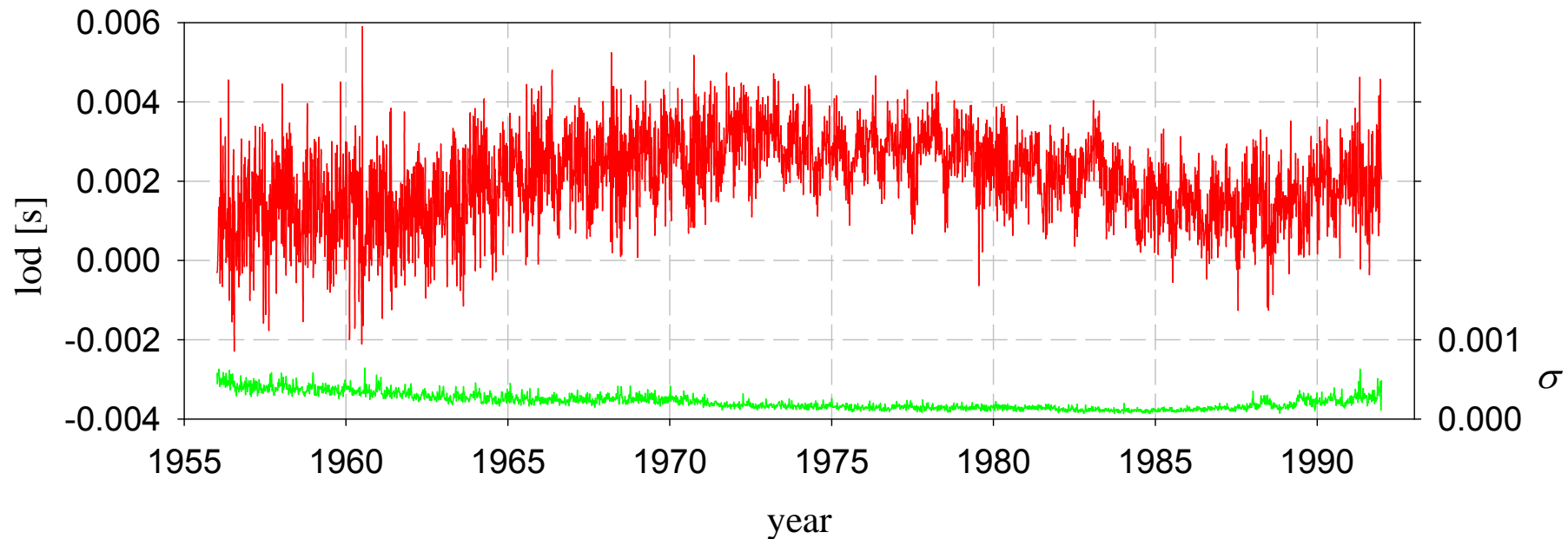
Results of OA10

Polar motion



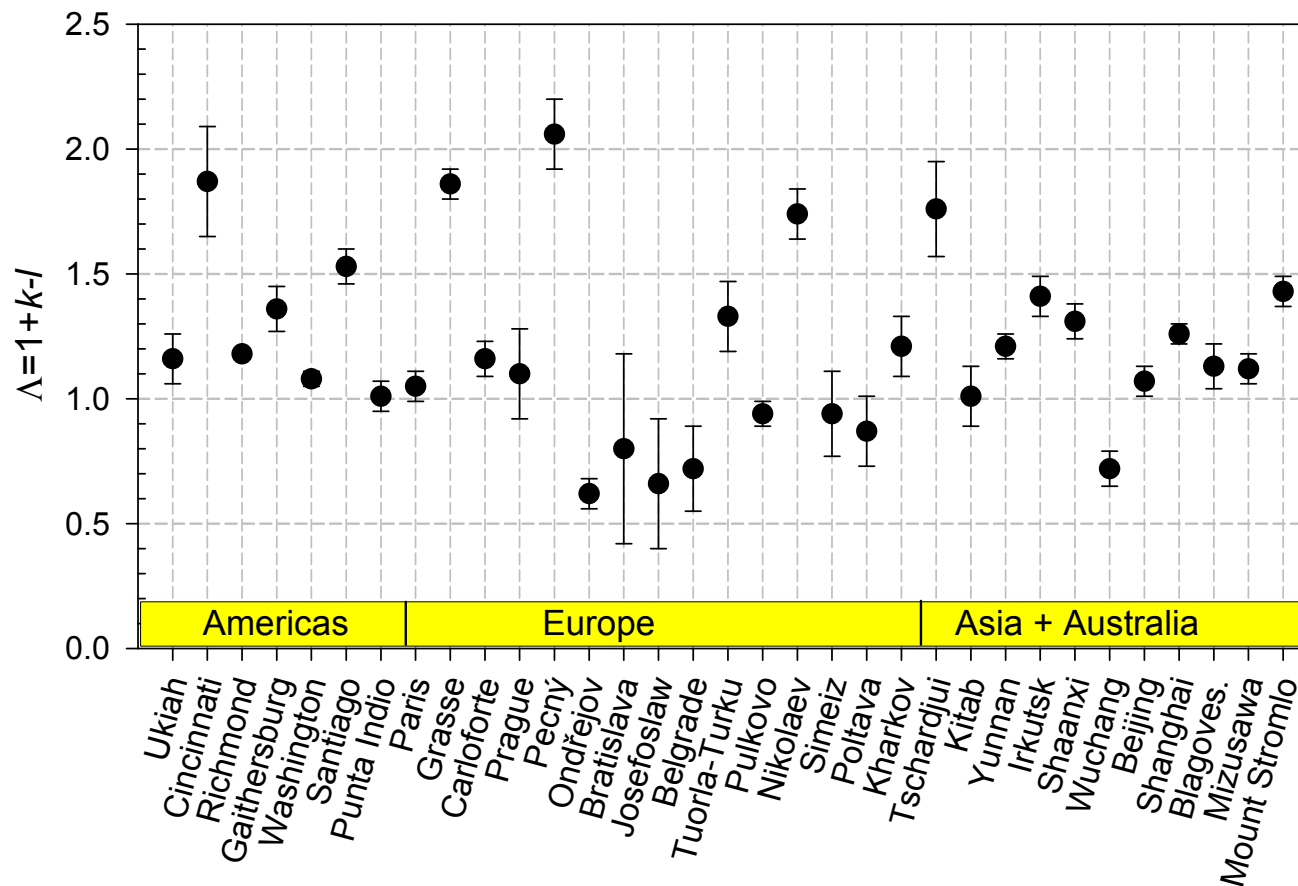
Results of OA10

Length-of-day changes



Results of OA10

Rheological parameter $\Lambda=1+k-l$



Conclusions

- In the most recent re-analysis of historical astrometric observations of Earth orientation covering 1899.7-1992.0:
 - ▶ Almost 5 million observations of individual stars, observed by 47 instruments located at 33 observatories were collected;
 - ▶ They were re-calculated with most recent astronomical constants/standards to be referred to a unique celestial system, based on Hipparcos Catalog;
 - ▶ Based on these observations, Earth orientation parameters plus additional local parameters were obtained;
 - ▶ All these data are archived at the Astronomical Institute of the Czech Academy of Sciences and available for further studies.

**THANK YOU VERY MUCH FOR YOUR
ATTENTION!**
