TIME IN ASTRONOMY, ROTATION OF THE EARTH - THEORY AND OBSERVATIONS

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- **PART 2:**
  - **Development of observational techniques used to monitor Earth orientation;**
  - **Observed variations of Earth orientation during the last 2700 years.**

Development of observational techniques

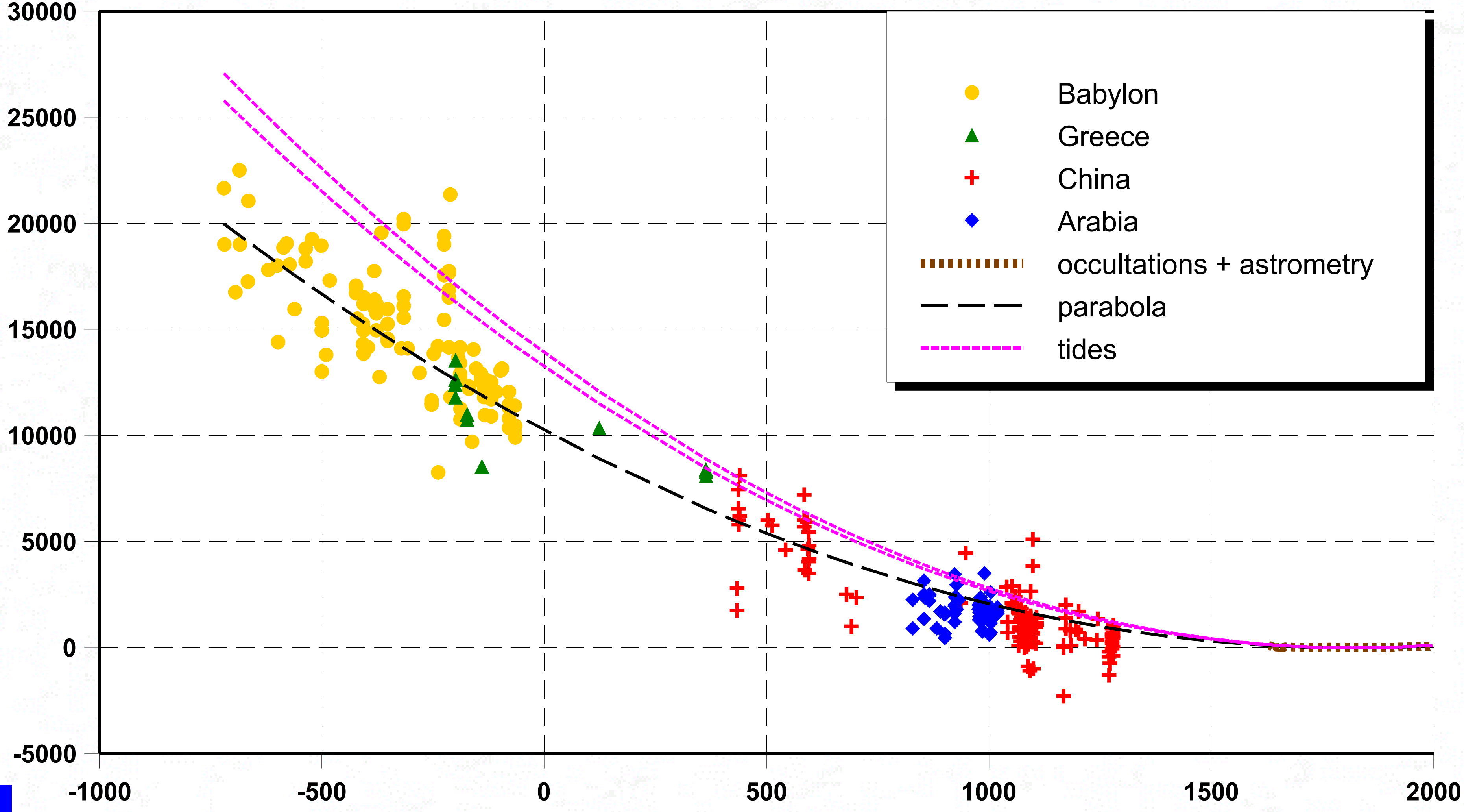
- **Main observational technique before the invention of the telescope (i.e., from 7th century BC to first half of 17th century):**
  - ♦ **naked eye ⇒ old records (with and without precise time data) of eclipses of the Sun and Moon;**
- **Since first half of 17th cent. telescopes started to be used:**
  - ♦ **⇒ occultations of the stars by the Moon;**

only one component - proper rotation

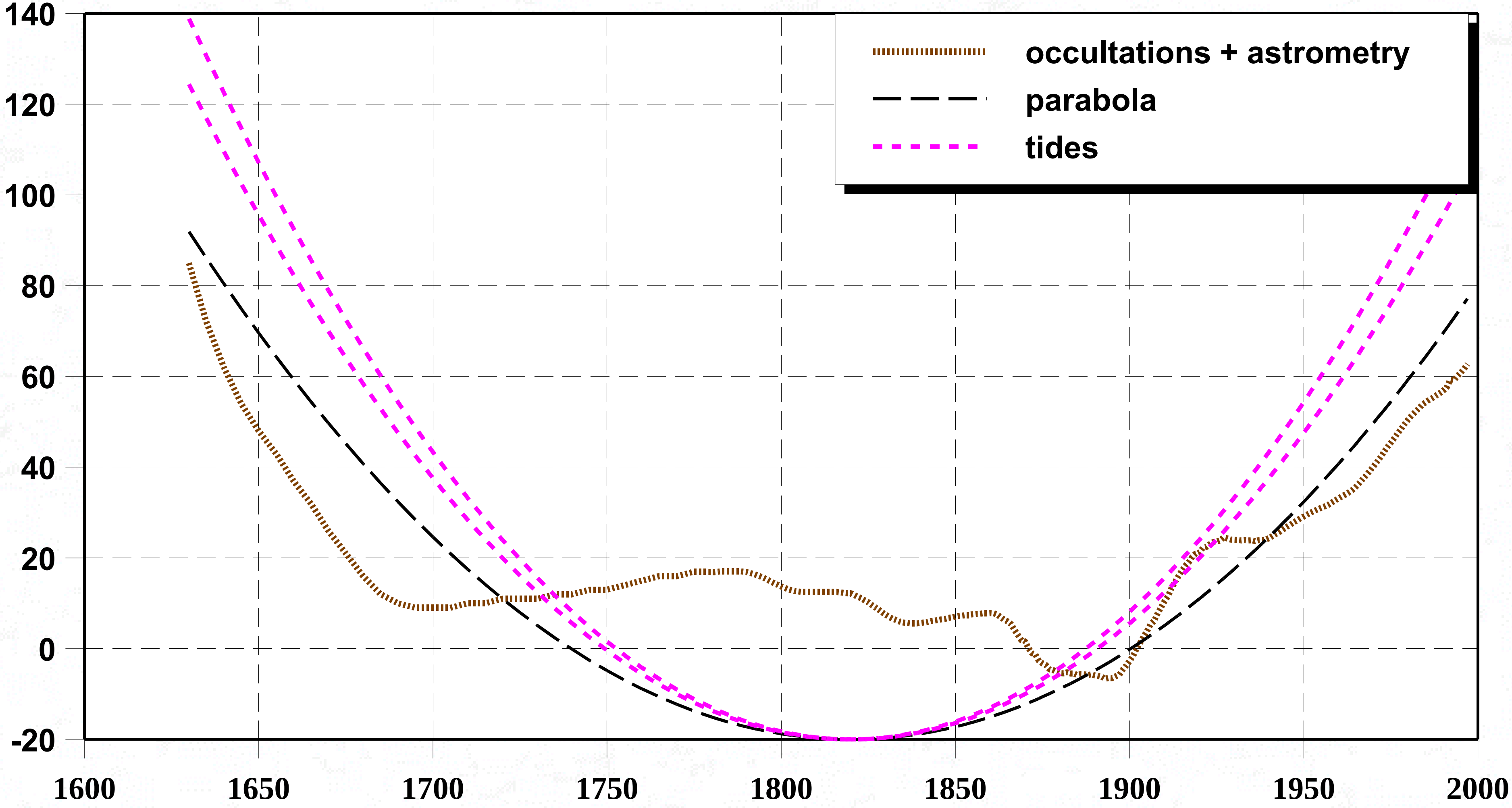
- Since the end of 19th century, specialized instruments of optical astrometry:
  - ⇒ observation of changes of geographic latitudes and Universal Time, internationally coordinated by:
    - International Latitude Service since 1899;
    - Bureau International de l'Heure since 1911;
    - International Polar Motion Service since 1962;
- Since 1988 modern space techniques:
  - ⇒ observation of orientation of intercontinental baselines by VLBI, GPS observations, satellite and lunar laser ranging, DORIS observations, all coordinated by:
    - International Earth Rotation Service, in 2003 re-named to International Earth Rotation and Reference Systems Service.

all five components of Earth orientation

ET-UT [s] from observation of eclipses (after Stephenson 1997), occultations of stars by the Moon, and astrometric observations



ET-UT [s] from occultations and optical astrometry



Conclusions from pre-telescope observations (confirmed by later observations)

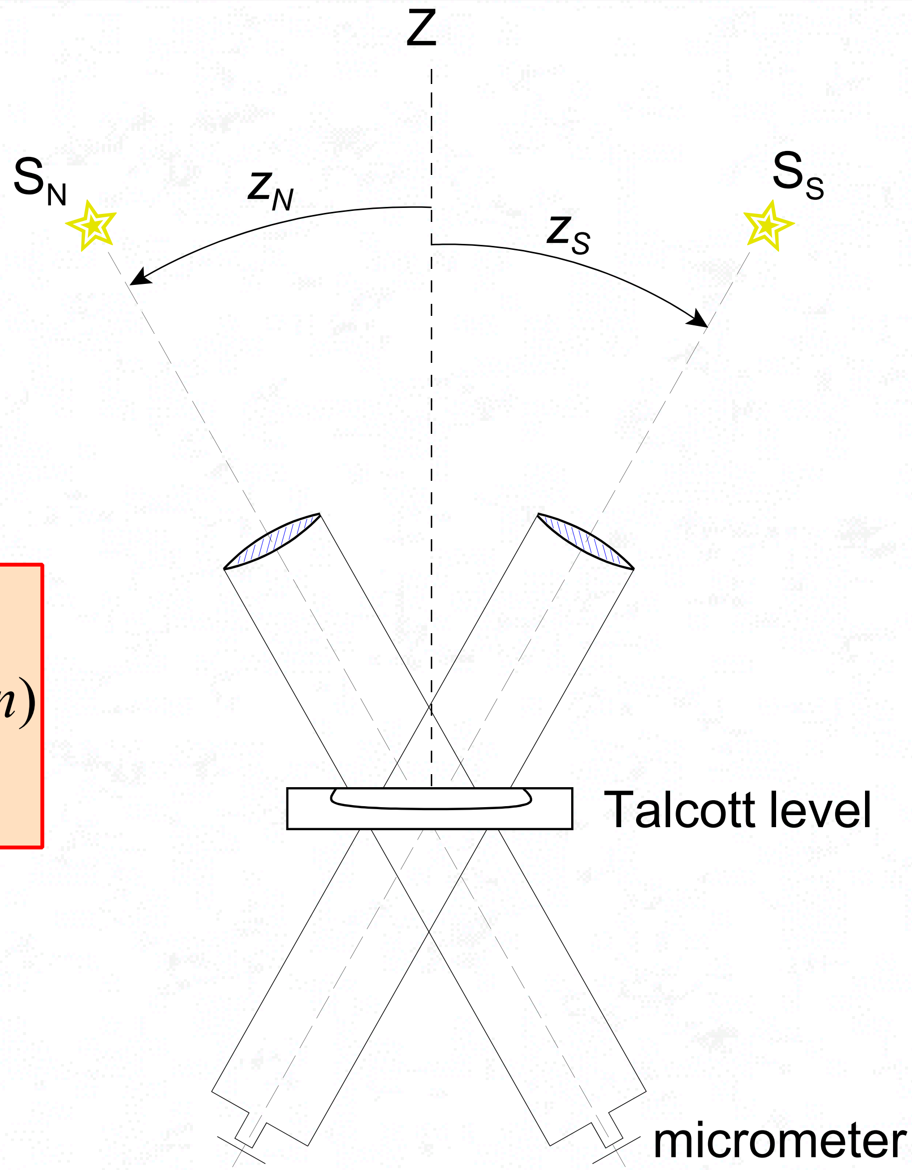
- **Slow deceleration of rotation, caused by tidal friction;**
  - **We observe slower deceleration than one would expect from tidal effects;**
  - **Additional effect - a slow decrease of the Earth's flattening (principal moment of inertia), which, in turn, accelerates the rotation. This is confirmed by SLR observations during the past 20-30 years.**
    - **'post glacial rebound' - reaction to deglaciation of polar regions of the Earth.**
- **Decade quasi periodical changes in speed of rotation:**
  - **Changes on core-mantle boundary - changing topography, electromagnetic coupling ...**

Classical astrometric instruments, used in 20th century to monitor Earth orientation

- Visual zenith-telescopes;
- Transit instruments (visual, photoelectric);
- Photographic Zenith Tubes;
- Instruments for the method of equal altitudes (astrolabe, circumzenithal).

ZT - Visual zenith-telescope (Horrebow-Talcott method; measuring the difference of zenith distance z_S - z_N between two stars when transiting over local meridian).

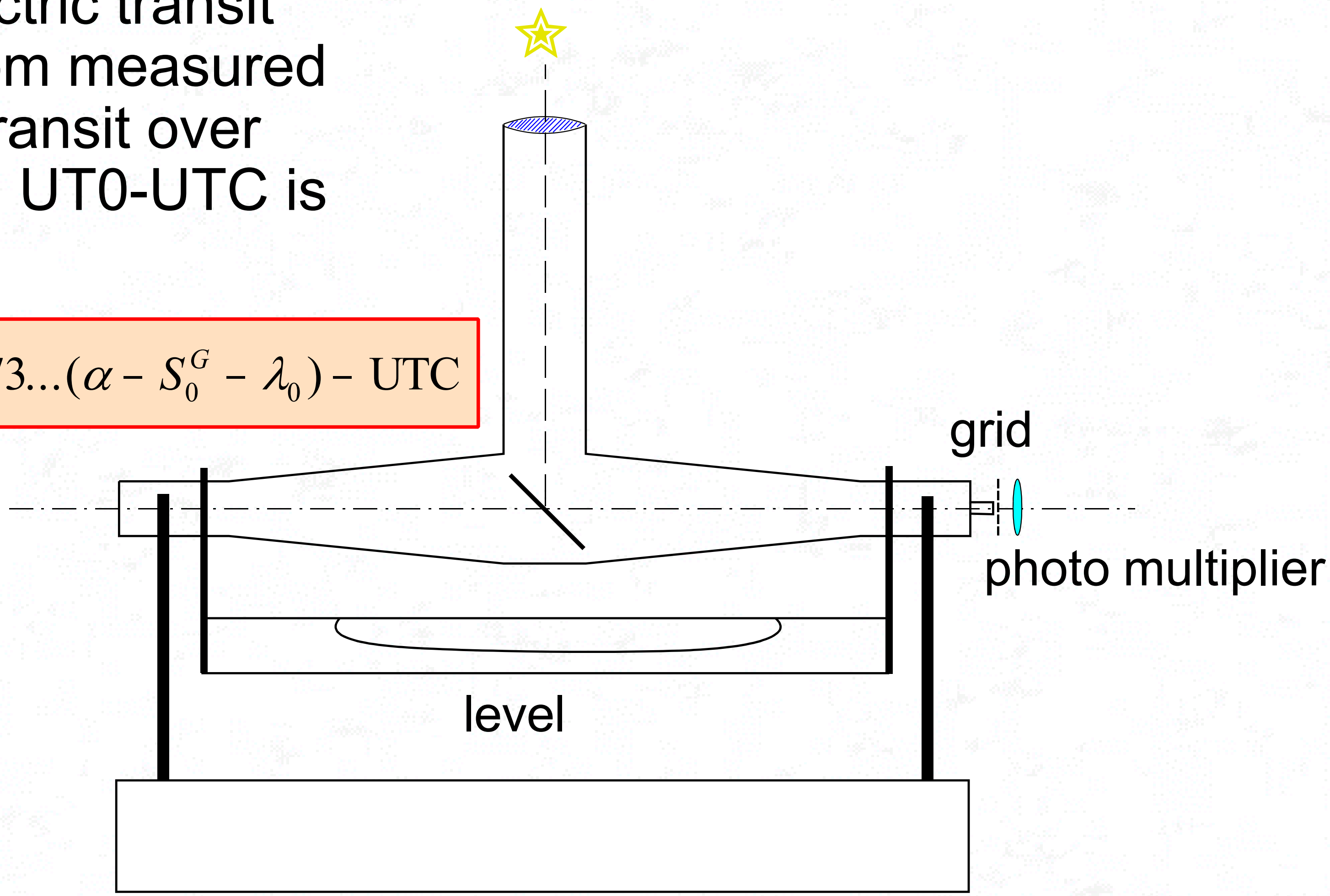
$$z_S - z_N = (D_S - D_N)M +$$
$$+ corr.(level, curvature, diff.refraction)$$
$$\varphi = \frac{1}{2}(\delta_S + \delta_N + z_S - z_N)$$



Visual zenith-telescope
(ILS station - Carloforte)

PTI - photoelectric transit instrument (from measured time of star's transit over local meridian, UT0-UTC is determined).

$$UT0 - UTC = 0.9973...(\alpha - S_0^G - \lambda_0) - UTC$$

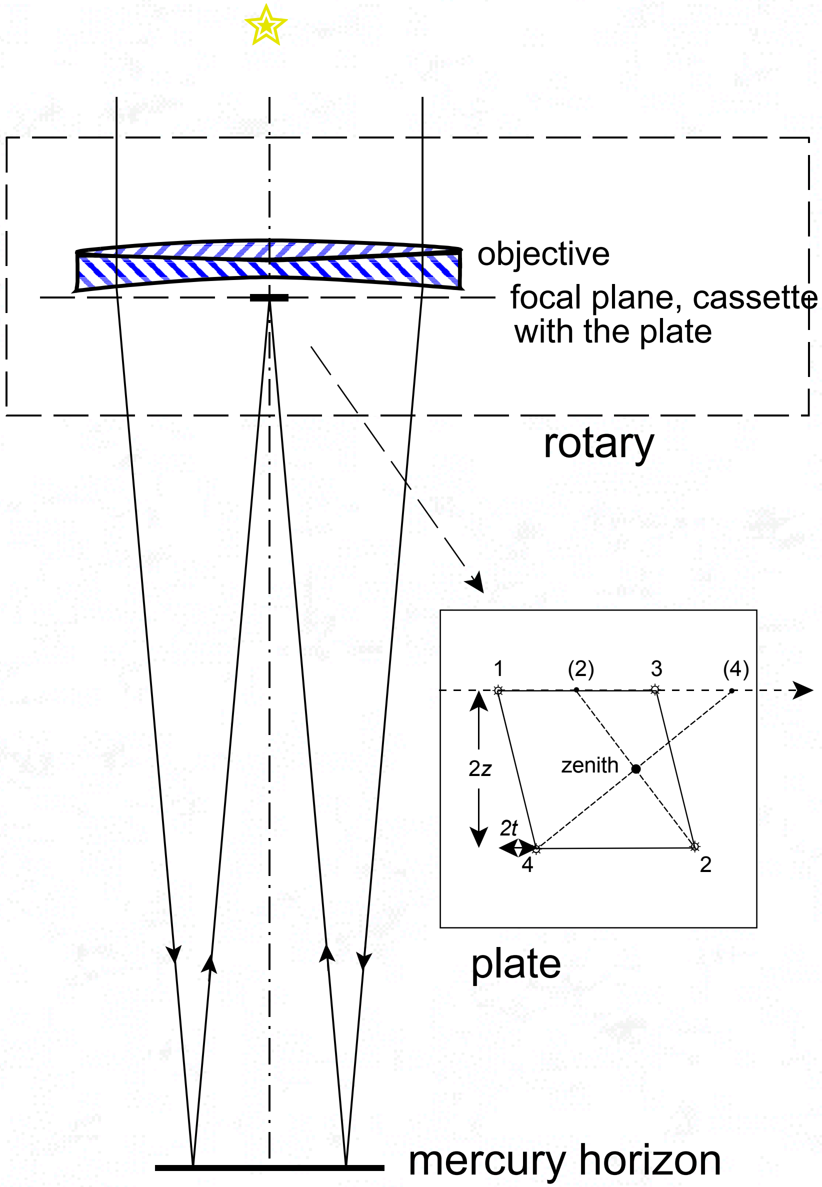


Visual transit instrument Zeiss 100/1000mm (GO Pecný, Ondřejov)

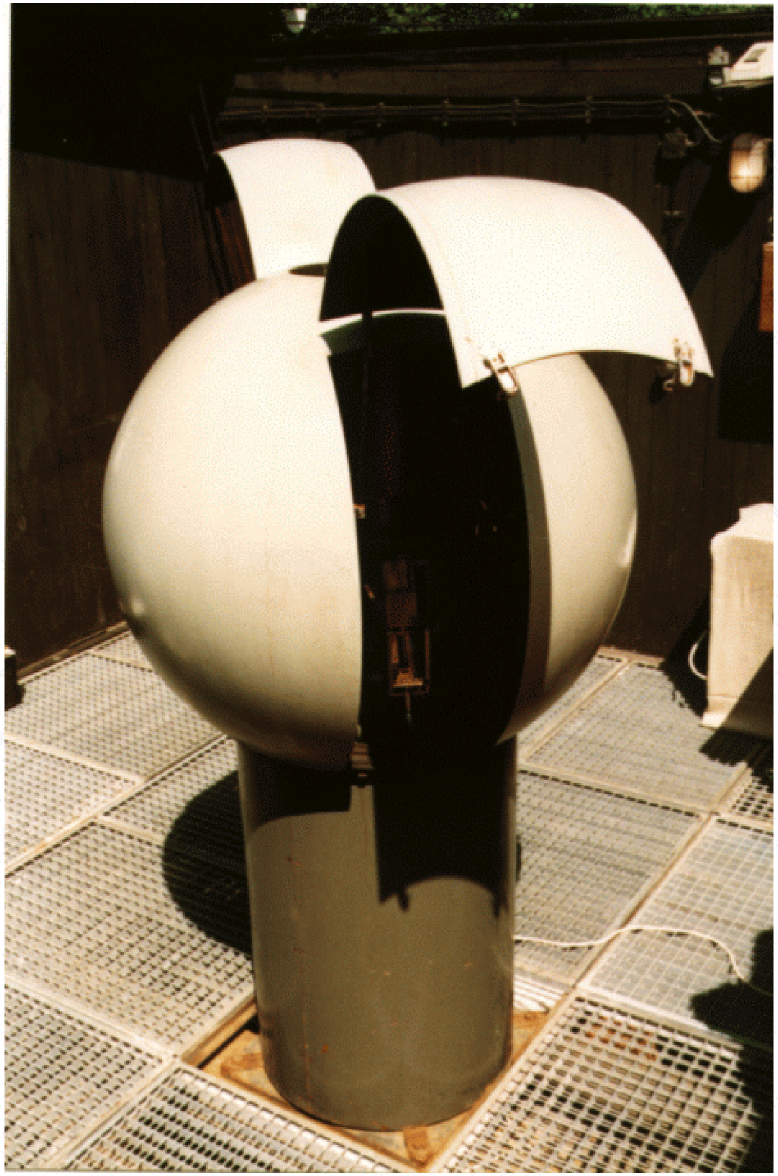
PZT - Photographic Zenith Tube (from measured plate coordinates, zenith distance *z* and hour angle *t* of the star is computed).

$$\varphi = \delta - z$$

$$\mathrm{UT0} - \mathrm{UTC} = 0.9973\ldots(t + \alpha - S_0^G - \lambda_0) - \mathrm{UTC}$$

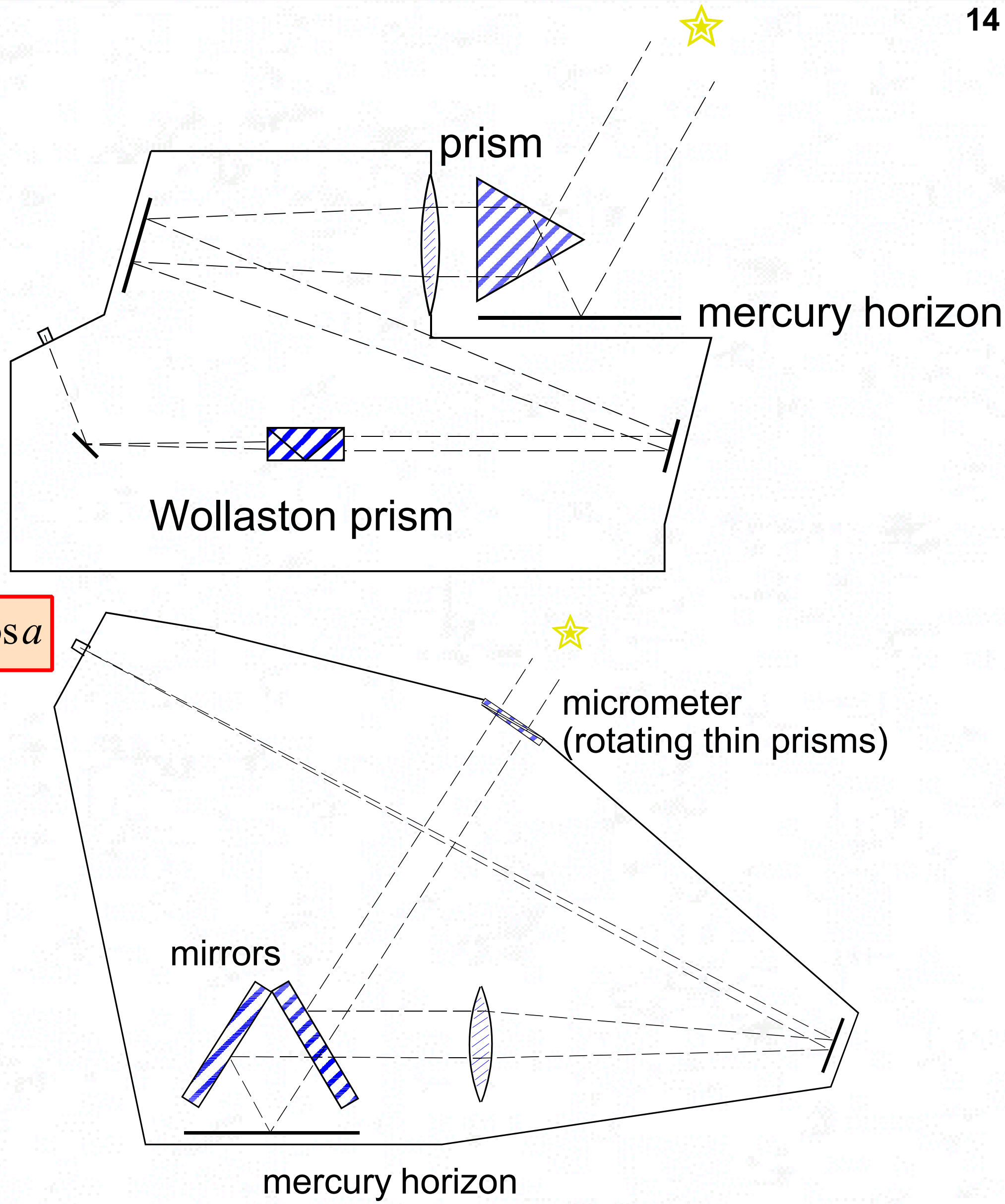


PZT Zeiss (250/3780mm)
Ondřejov Observatory

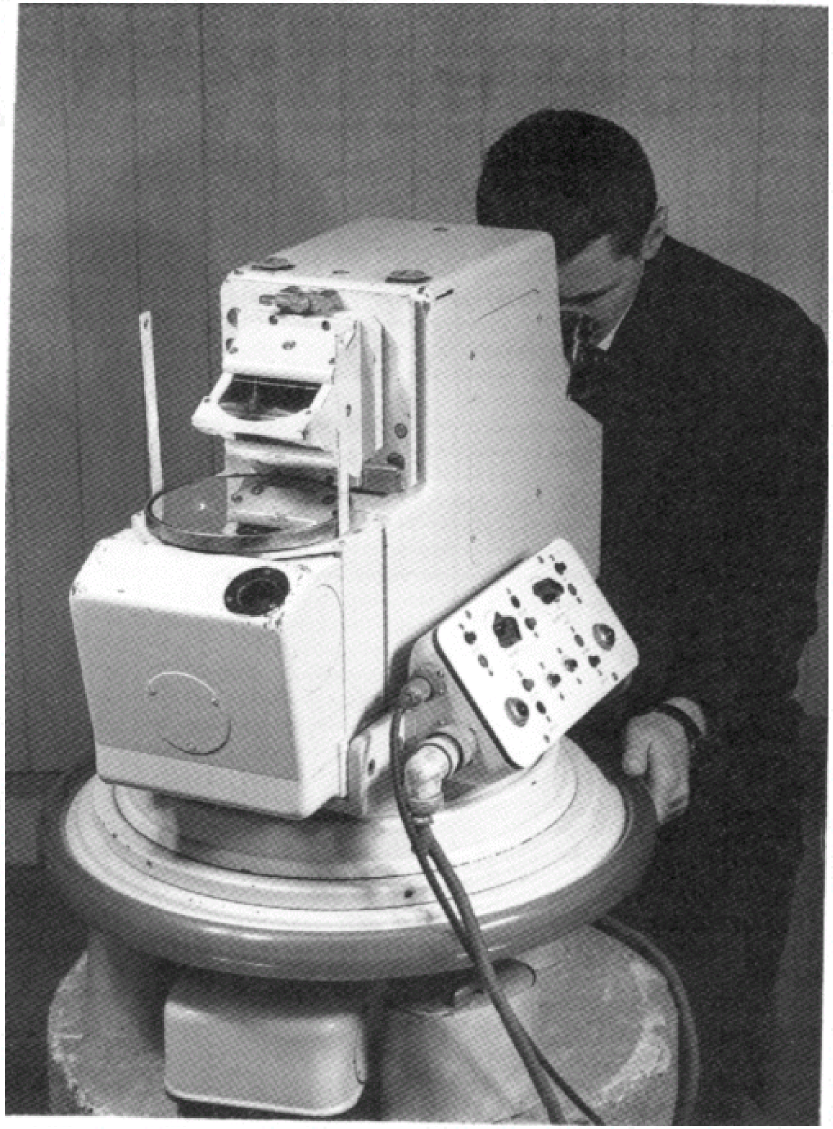


AST - Danjon astrolabe and
CZ - circumzenithal
(from measured time of transit over local almucantar, the difference δh between observed and calculated altitude of the star is determined).

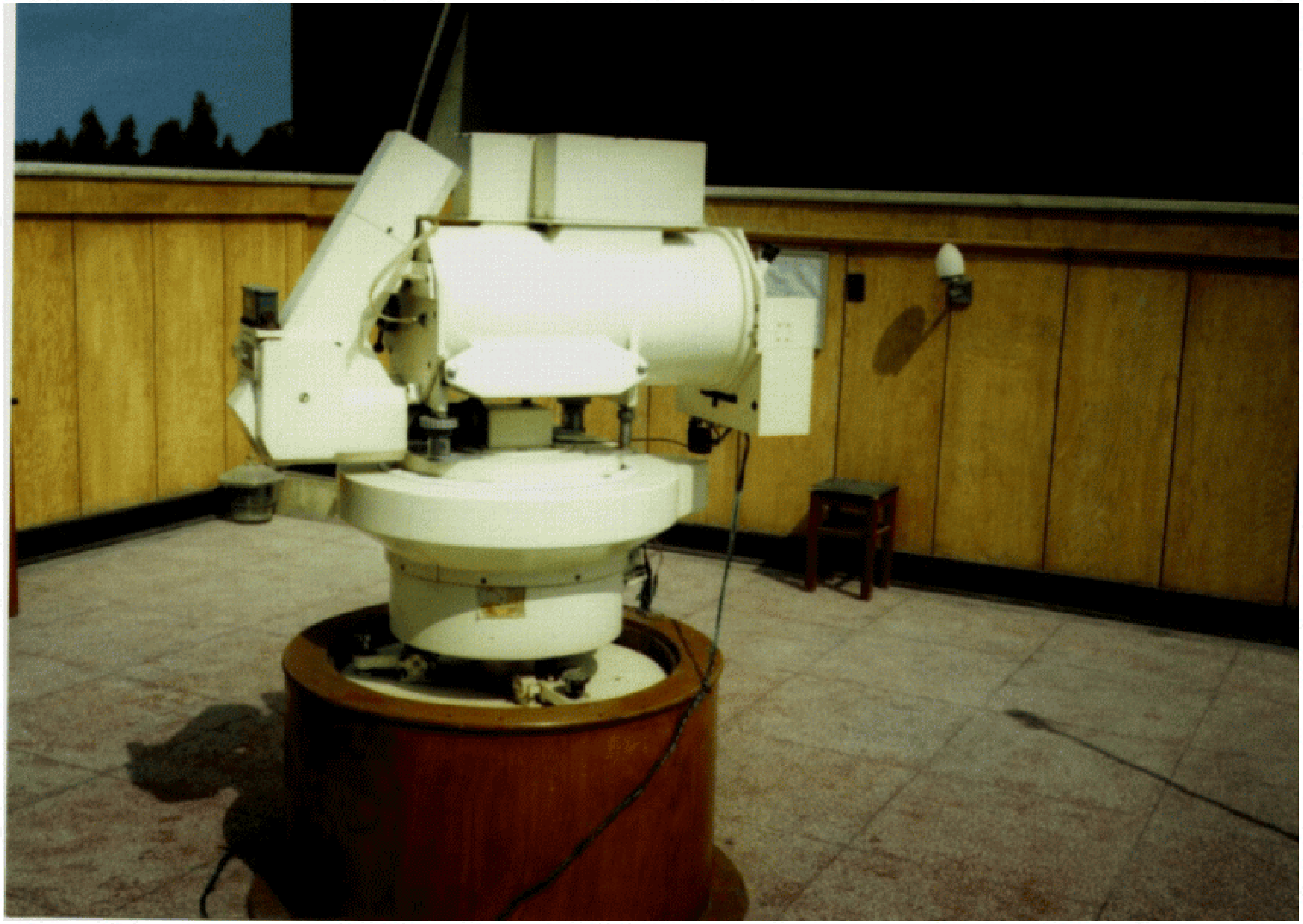
$$\delta h = 15.041\ldots(\mathrm{UT0} - \mathrm{UTC})\cos\varphi_0 \sin a - (\varphi - \varphi_0)\cos a$$



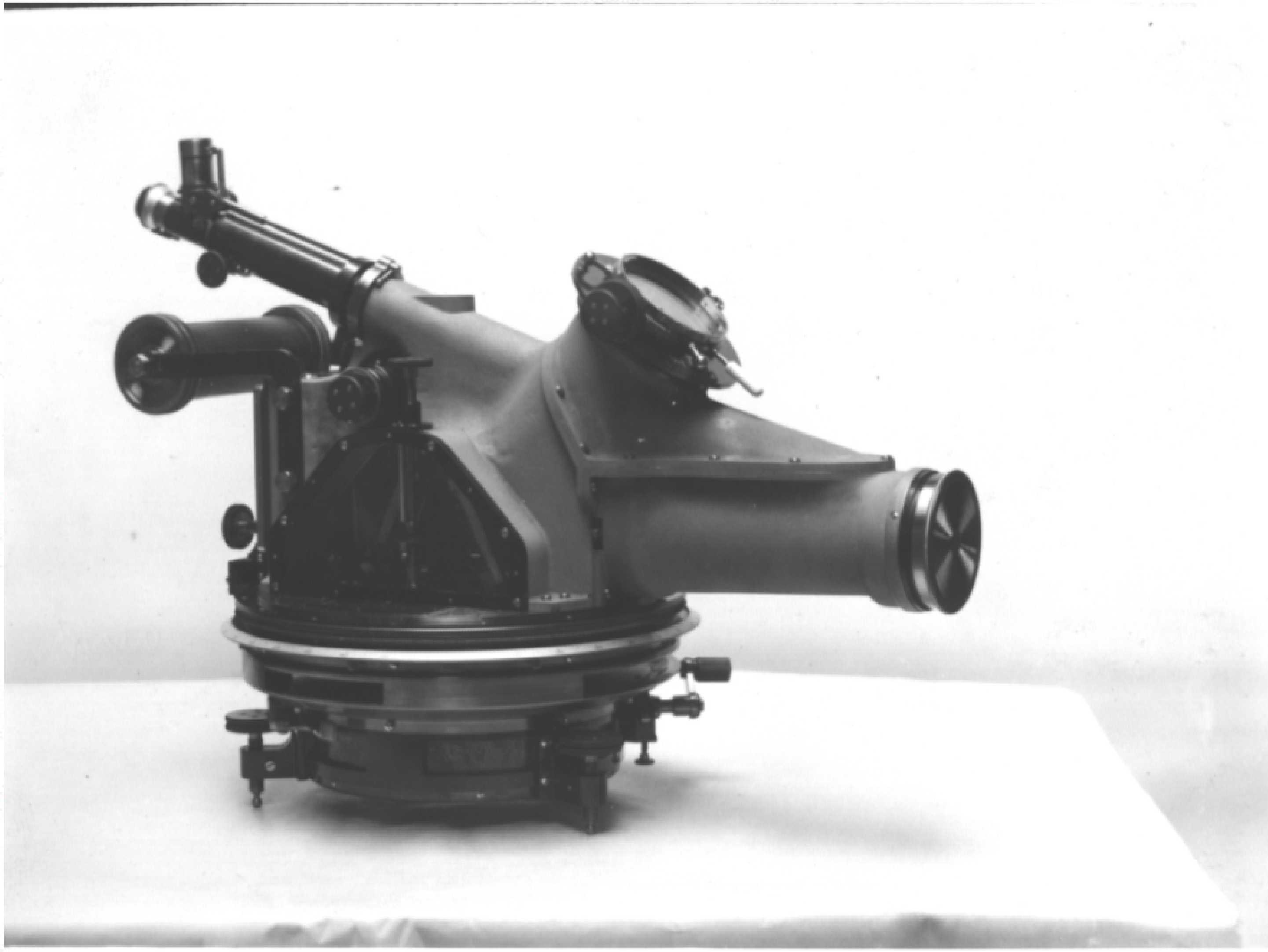
Danjon astrolabe of 1956
(Observatoire de Paris)



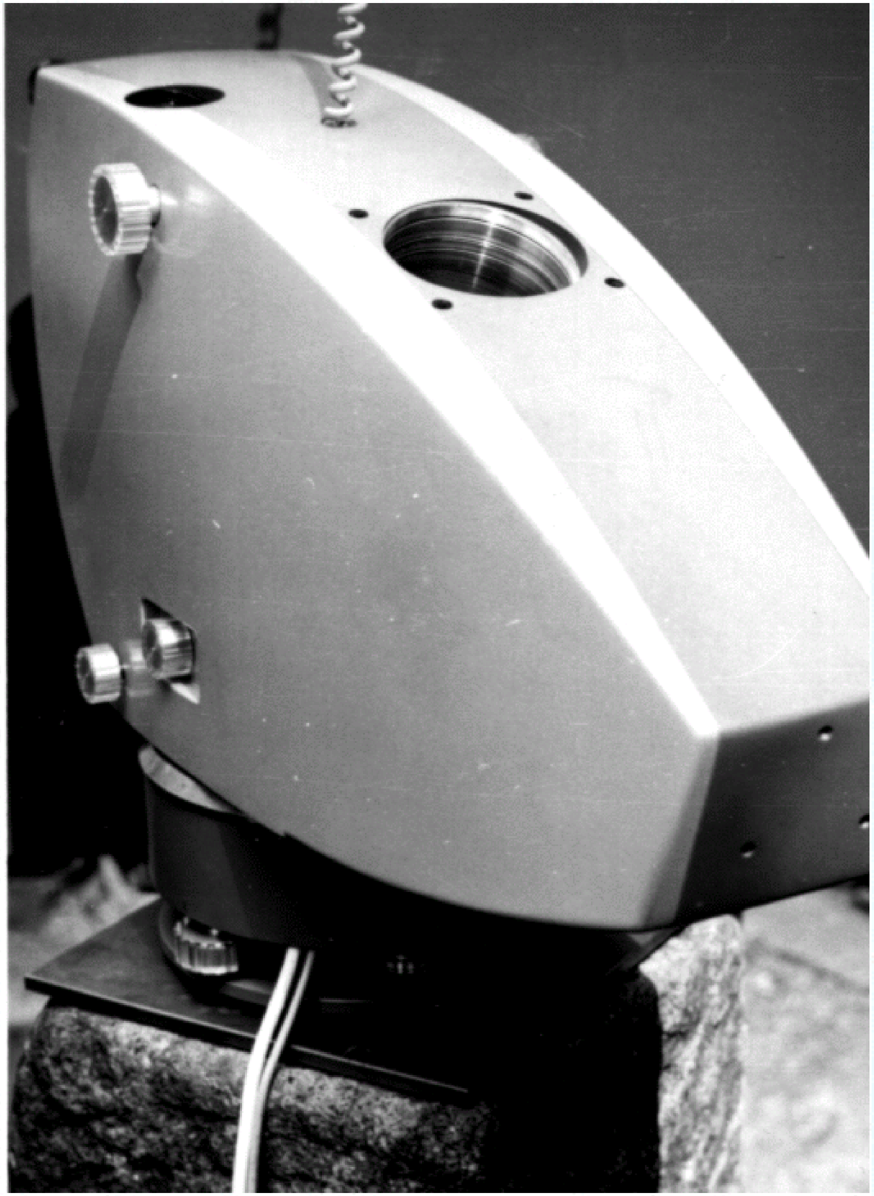
Chinese photoelectric astrolabe (Yunnan Observatory)



Cirkumzenithal Nušl-Frič, model 1922



Cirkumzenithal VÚGTK of 1967 (100/1000mm)



Results of observing EOP by optical astrometry in 1899.7 - 1992.0

- **In AI ASCR observational material was collected from:**
  - 33 observatories, 47 instruments of different types, about 4.5 million individual observations;
- **The instruments can be divided into 3 groups:**
  - Observations of latitude variations;
  - Observations of Universal Time UT0-TAI;
  - Observations by the method of equal altitudes,
- **The following Earth Orientation Parameters are determined:**
  - Polar motion (*x, y*);
  - Universal Time (UT1-TAI);
  - Celestial pole offsets ($\delta\psi$, $\delta\varepsilon$, or δX, δY).

Observation equations (for 3 types of observations):

Simplified

$$v_\varphi = \Delta\varphi - (x\cos\lambda - y\sin\lambda) + \Delta\varepsilon\sin\alpha + \Delta\psi\sin\varepsilon\cos\alpha$$

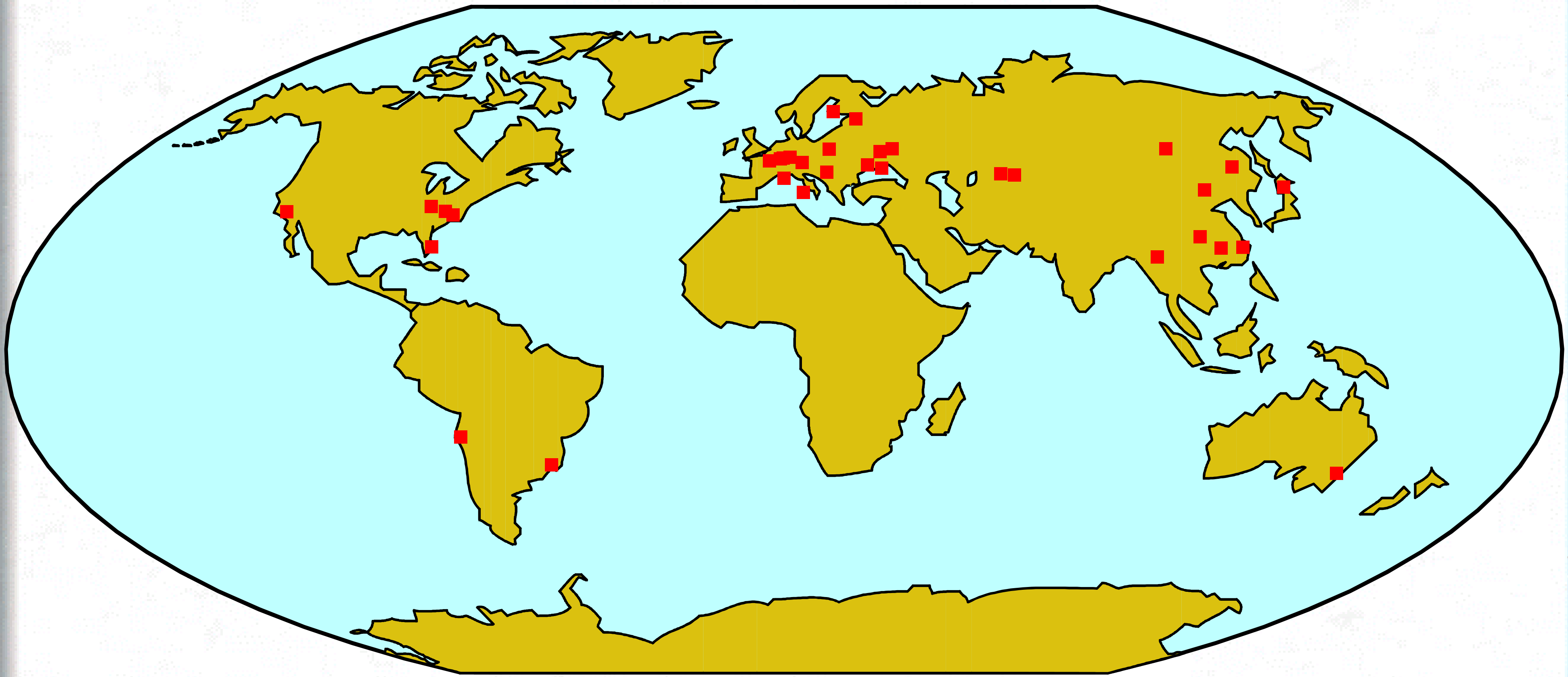
$$v_T = 15(\mathrm{UT0} - \mathrm{UTC})\cos\varphi - 15\cos\varphi(\mathrm{UT1} - \mathrm{UTC}) + \sin\varphi(x\sin\lambda + y\cos\lambda) -$$
$$- \cos\varphi\tan\delta(\Delta\varepsilon\cos\alpha - \Delta\psi\sin\varepsilon\sin\alpha)$$

$$v_h = -\Delta h + 15\cos\varphi\sin a(\mathrm{UT1} - \mathrm{UTC}) +$$
$$+ x(\cos\lambda\cos a + \sin\varphi\sin\lambda\sin a) - y(\sin\lambda\cos a - \sin\varphi\cos\lambda\sin a) +$$
$$+ \Delta\varepsilon(\sin q\sin\delta\cos\alpha - \cos q\sin\alpha) - \Delta\psi\sin\varepsilon(\sin q\sin\delta\sin\alpha + \cos q\cos\alpha)$$

$\Delta\varphi$, UT0-UTC, Δh are the observations

x, y, UT1-UTC, $\Delta\varepsilon$, $\Delta\psi$ are the unknown EOP's

Geographic distribution of observatories



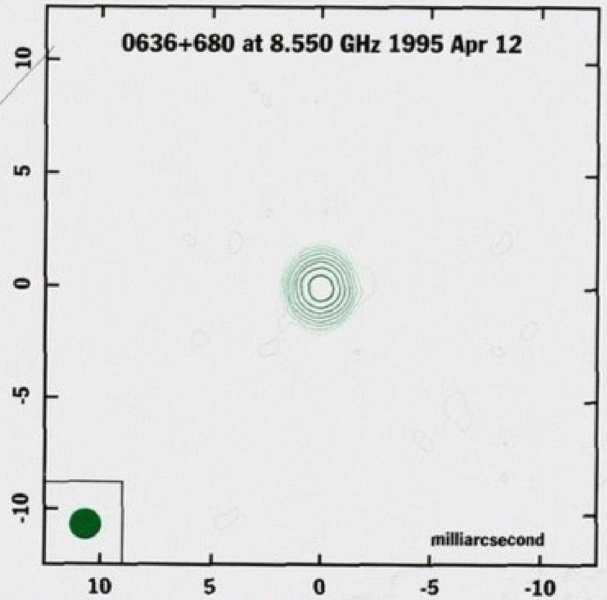
Modern space techniques for monitoring Earth orientation

- Very long baseline interferometry (VLBI);
- Global positioning system (GPS);
- Satellite (SLR) and lunar (LLR) laser ranging;
- DORIS.

VLBI

Very Long Baseline radio Interferometry

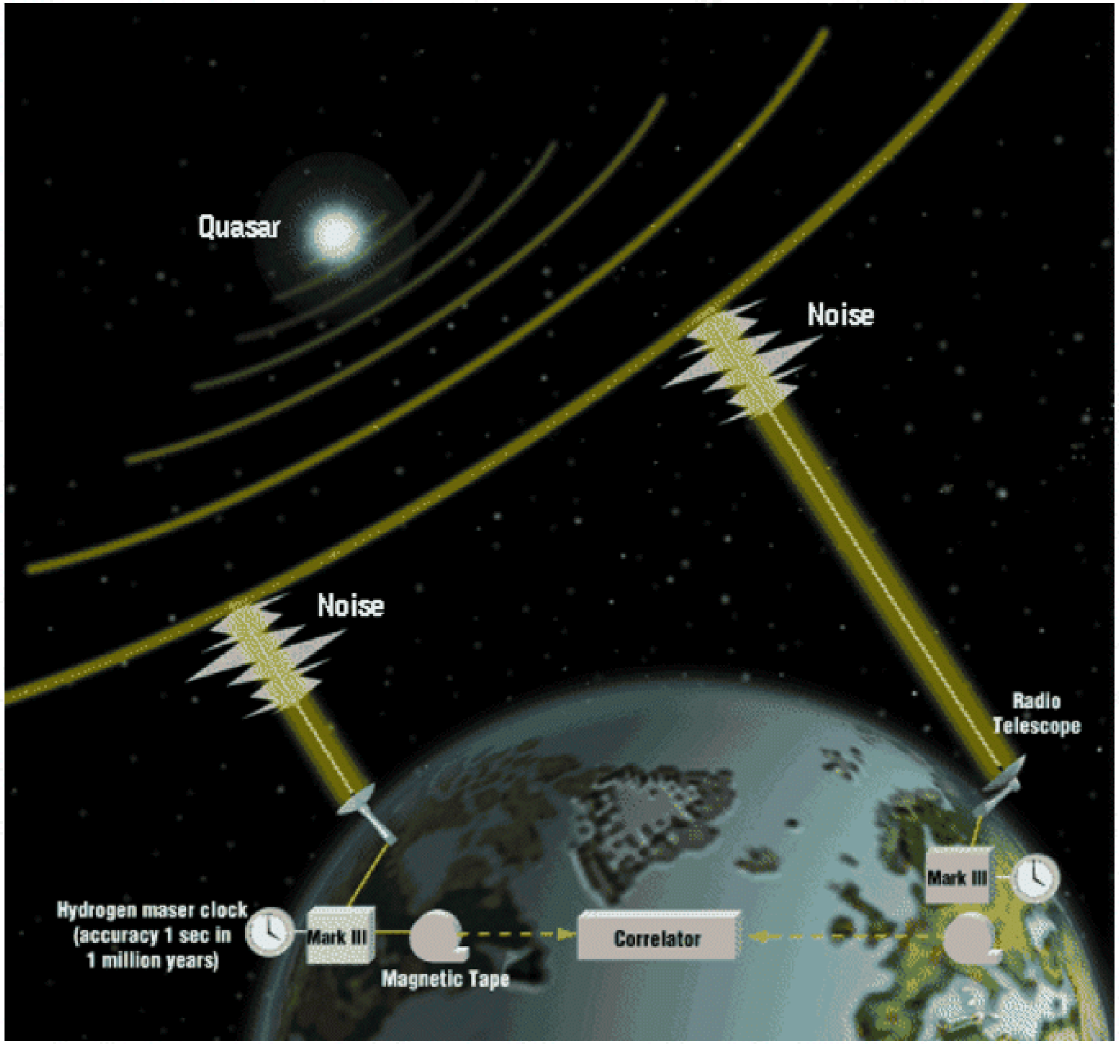
defines and maintains the extragalactic celestial frame. It holds together the International Celestial and Terrestrial Reference Systems. It provides the long-term monitoring of universal time, precession and nutation.



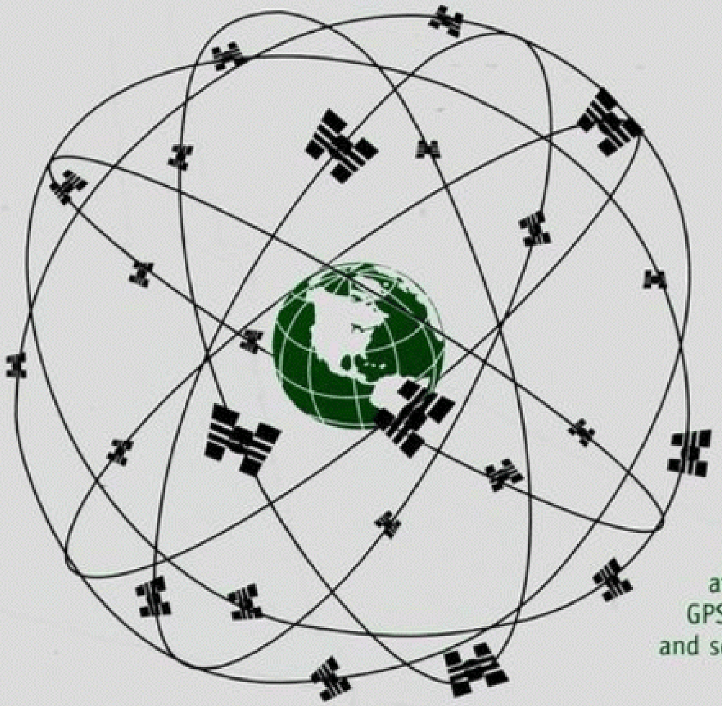
One of the extragalactic radiosources regularly observed with VLBI to maintain the ICRF. The lines show levels of radiated energy. The position of the light centre of this object is measured with an accuracy of 0.0002 ".

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.

Principle of VLBI



VLBI antenna



GPS

Global Positioning System

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.

GPS antennas

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.

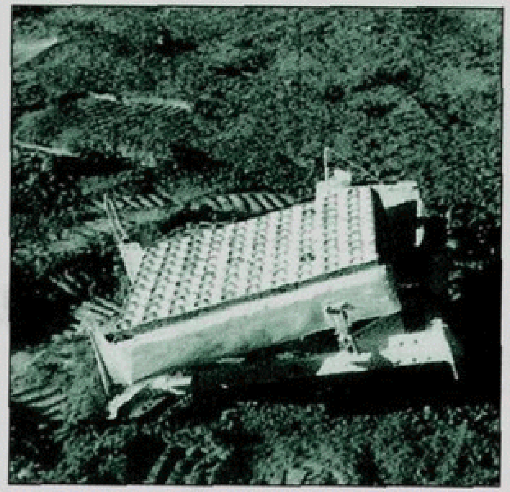
Lageos is the major SLR target used for IERS. It is a 60 cm diameter metallic sphere covered with retroreflectors, cruising at an altitude of 6000 km. It was launched in 1976 by NASA and will remain an excellent geodetic target for tens of thousands years.

Mobile SLR station

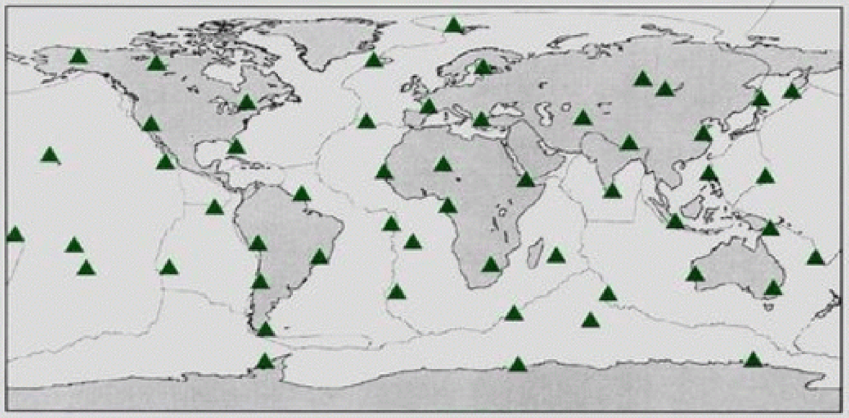
LLR

Lunar
Laser
Ranging

In addition to its value for lunar sciences and the theory of gravitation, LLR is a key IERS technique to determine the orientation of the dynamical frame of the Solar System in the ICRS.



Laser reflector arays were deposited on the Moon by the Apollo and Lunakhod missions. Their areas are about 1 m². Four of them are ranged regularly.



DORIS

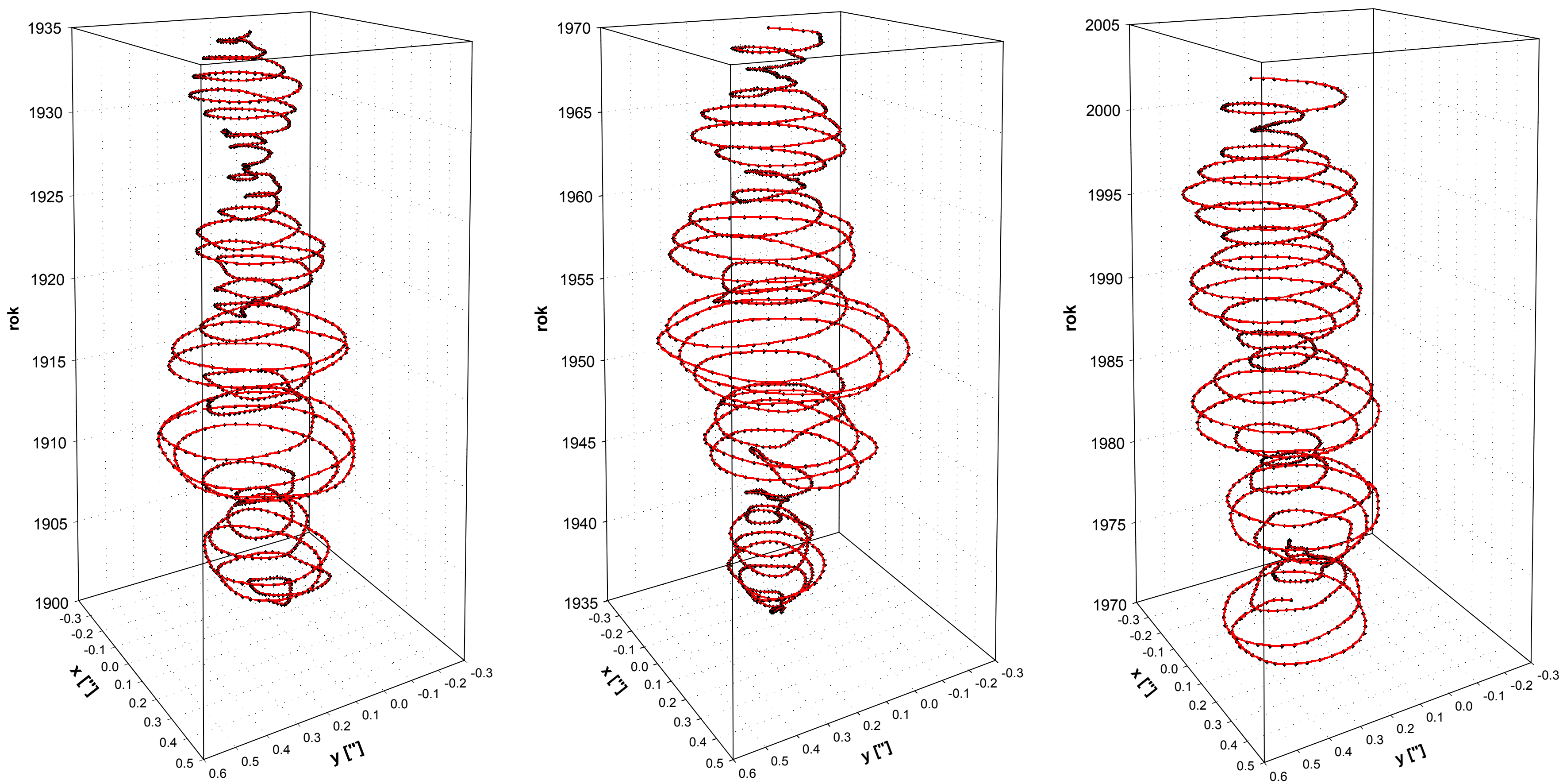
Doppler Orbit determination and Radiopositionning Integrated on Satellite

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.

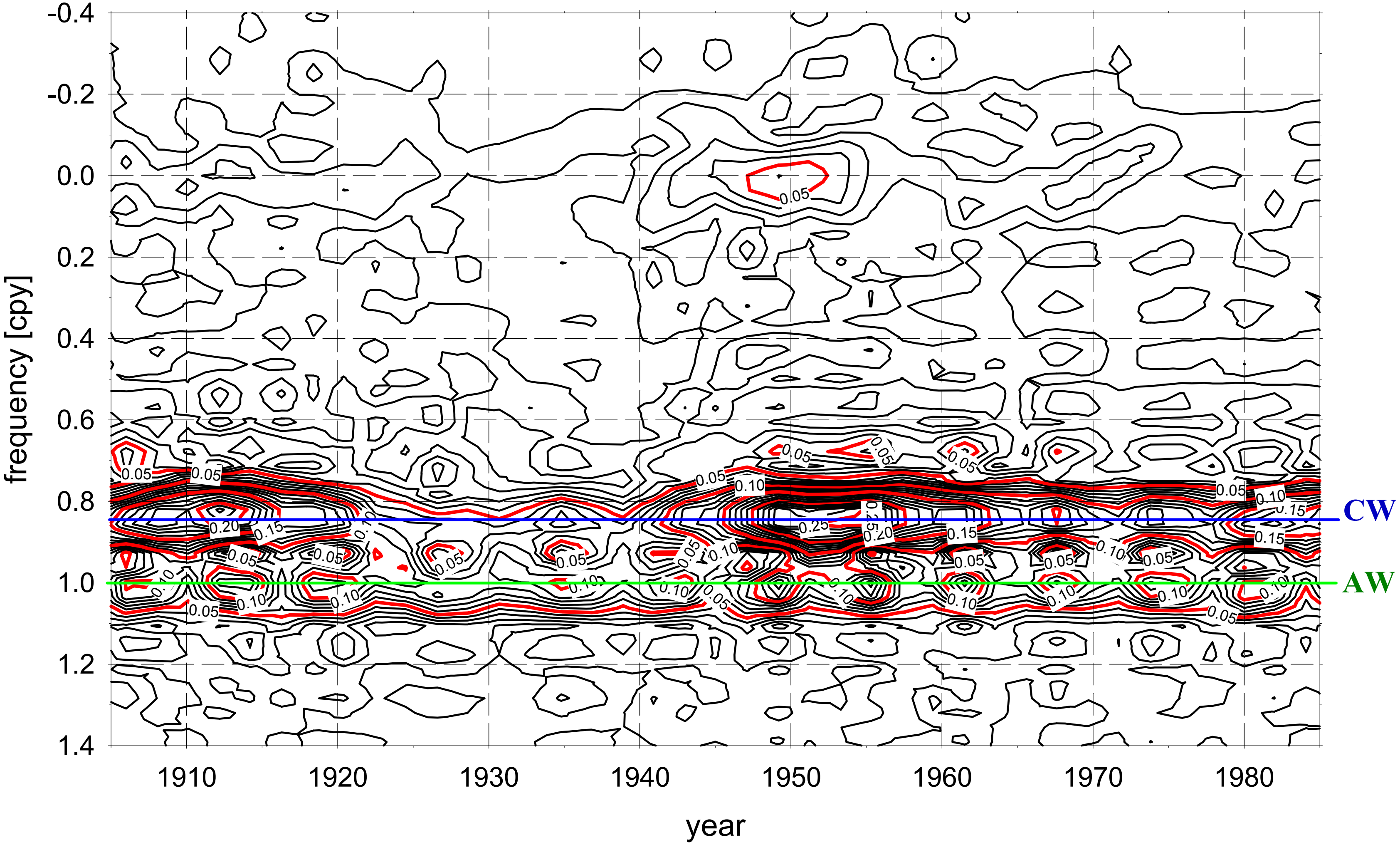
DORIS is a radioelectric system operated by CNES. The permanent ground segment includes 49 beacons globally distributed. The space segment collects Doppler observations of the beacons. DORIS is the nominal orbitography system of several current and planned space oceanography missions, with altitudes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

DORIS beacon

Polar motion from astrometric (1899,7-1992,0) and modern space observations



Evolution of spectrum of polar motion



Estimation of annual and Chandler wobbles:

$$x = a_x + b_x t + c_{ax}\cos 2\pi t + s_{ax}\sin 2\pi t + c_{cx}\cos 2\pi f t + s_{cx}\sin 2\pi f t$$

$$y = a_y + b_y t + c_{ay}\cos 2\pi t + s_{ay}\sin 2\pi t + c_{cy}\cos 2\pi f t + s_{cy}\sin 2\pi f t,$$

(f=0.845 cpy is constant Chandler frequency),
from which we calculate semi-major and -minor axes A, B,
phase φ and orientation of major axis ψ :

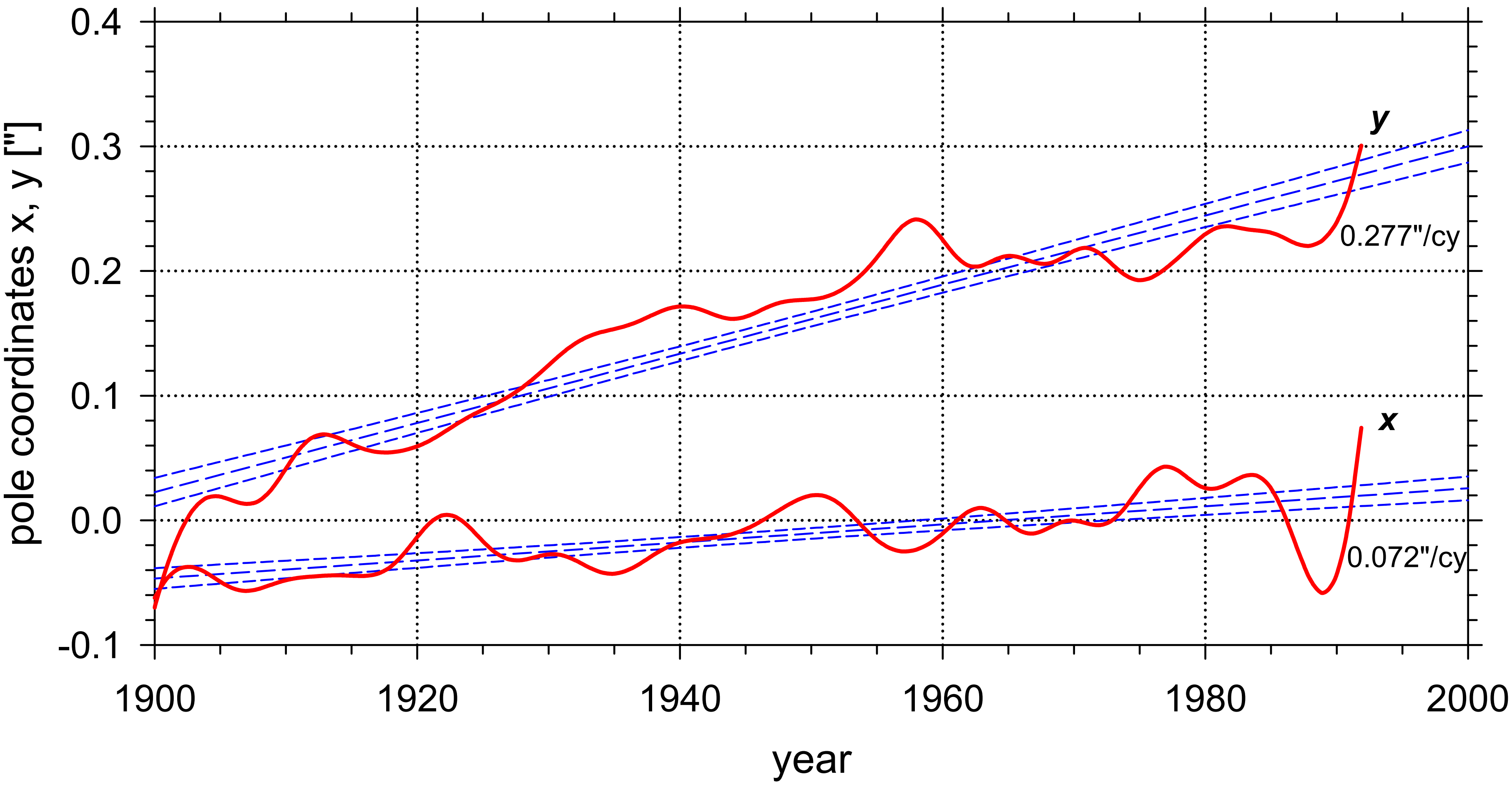
$$(A - B)\cos(\varphi - 2\psi) = c_x + s_y$$

$$(A - B)\sin(\varphi - 2\psi) = s_x - c_y$$

$$(A + B)\cos\varphi = c_x - s_y$$

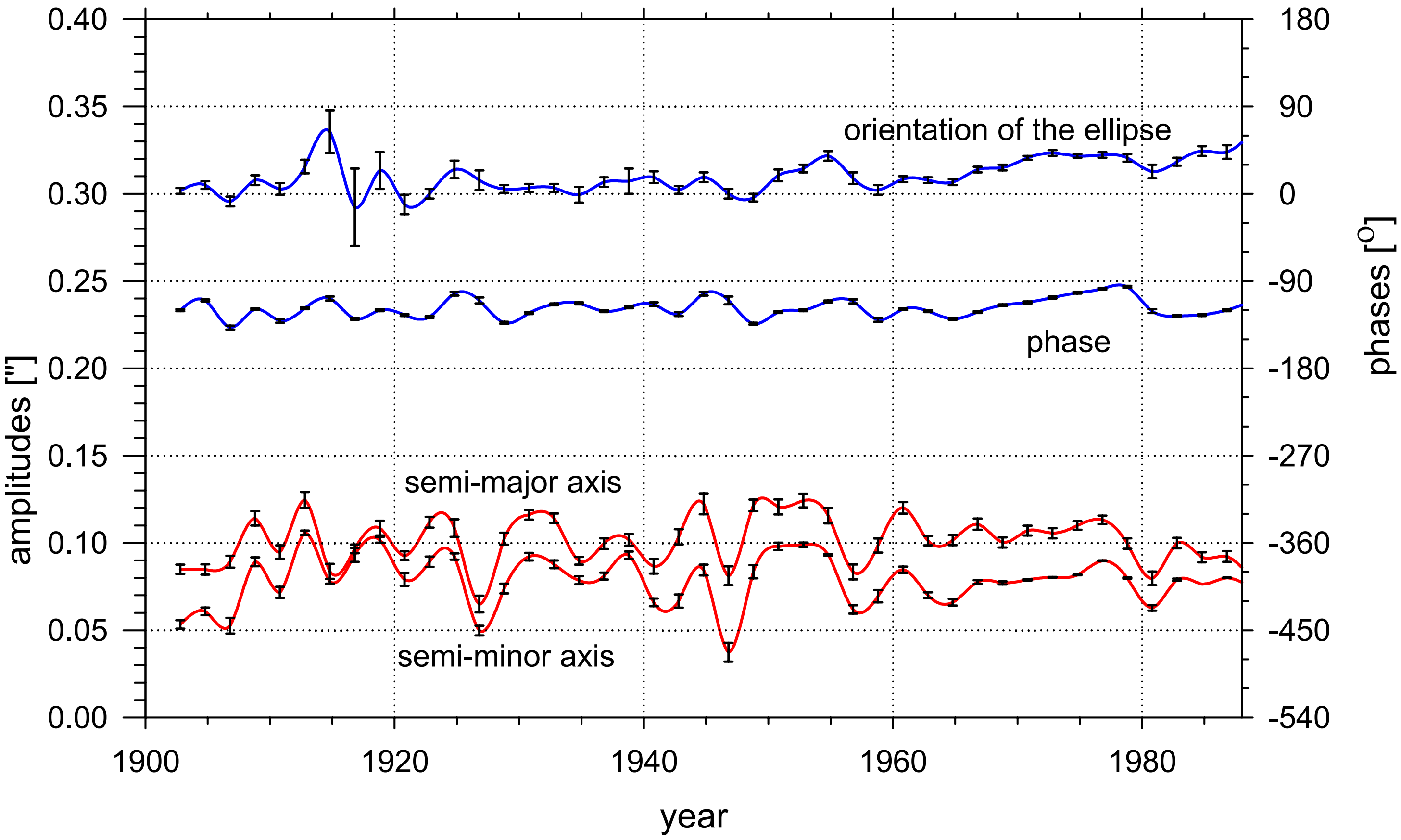
$$(A + B)\sin\varphi = s_x + c_y$$

Secular and long-periodic polar motion

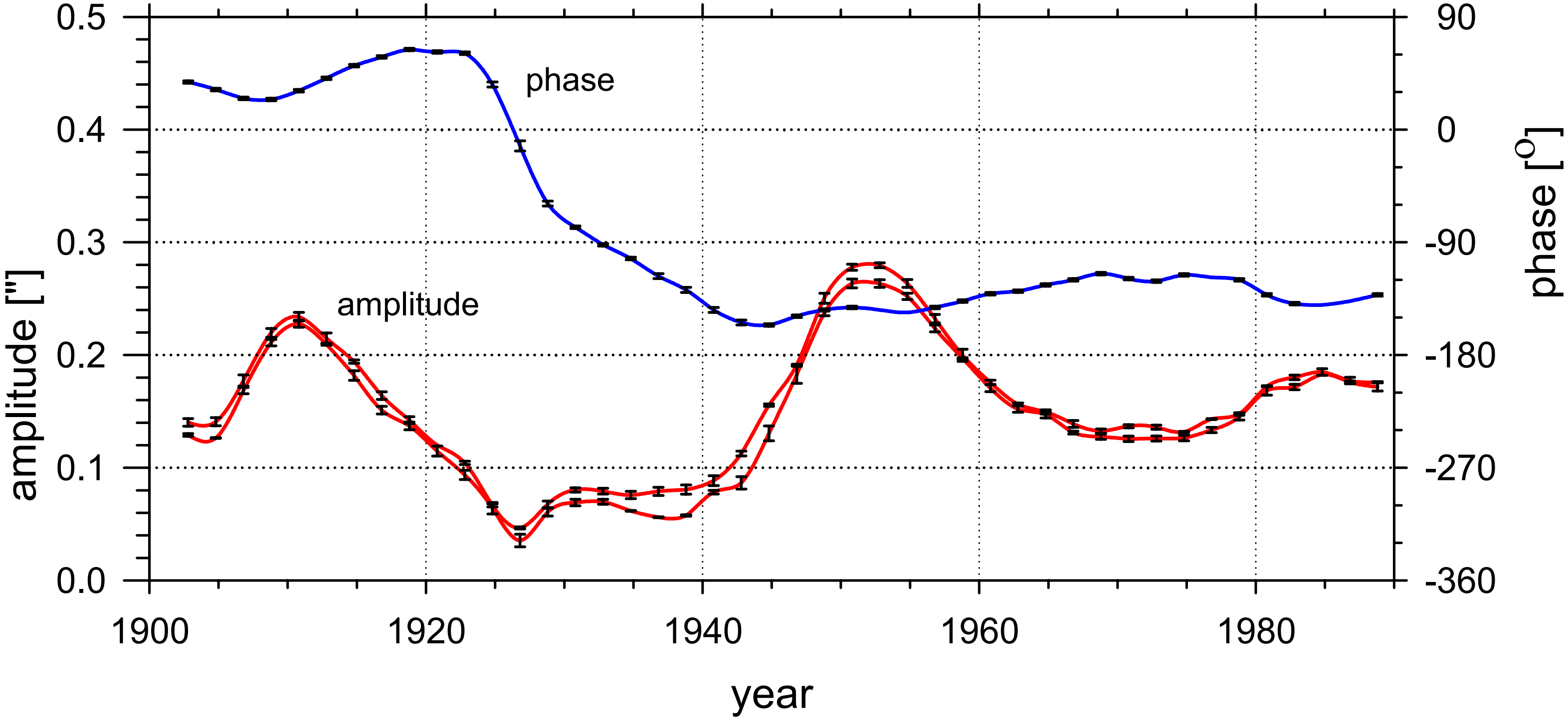


Parameters of annual wobble

(computed at 6y intervals)



Parameters of Chandler wobble
(computed at 6y intervals)

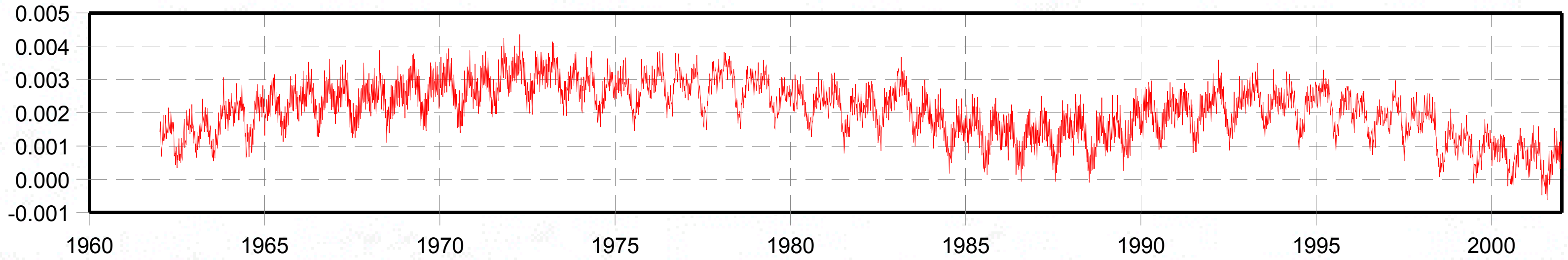


Polar motion - conclusions

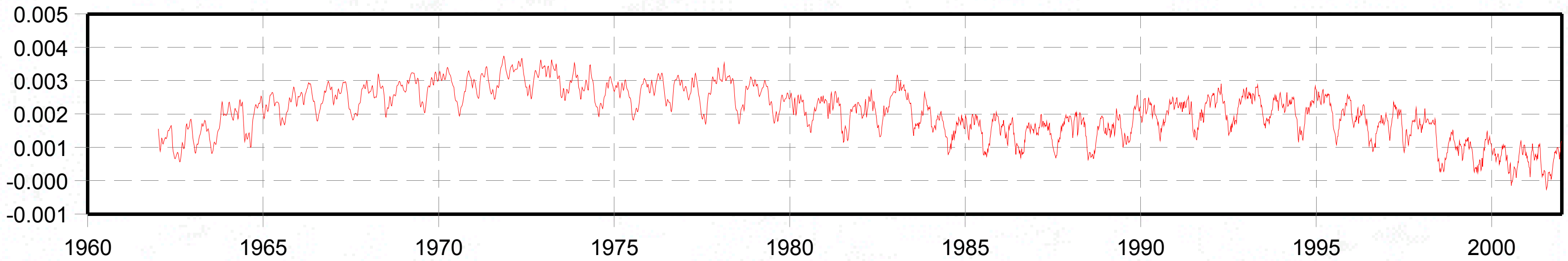
- **Secular/long-periodic component:**
  - Postglacial rebound.
- **Annual wobble:**
  - More stable than Chandler wobble;
  - Forced by air pressure changes and ocean motions with frequency 1 year.
- **Chandler wobble (*P*=435 days):**
  - Not stable, both amplitude and phase variable;
    - Damped by viscosity of the mantle;
    - Excited by combined influence of the atmosphere and ocean, with period close to 14 months.

Variation of length of day from astrometric and modern space observations

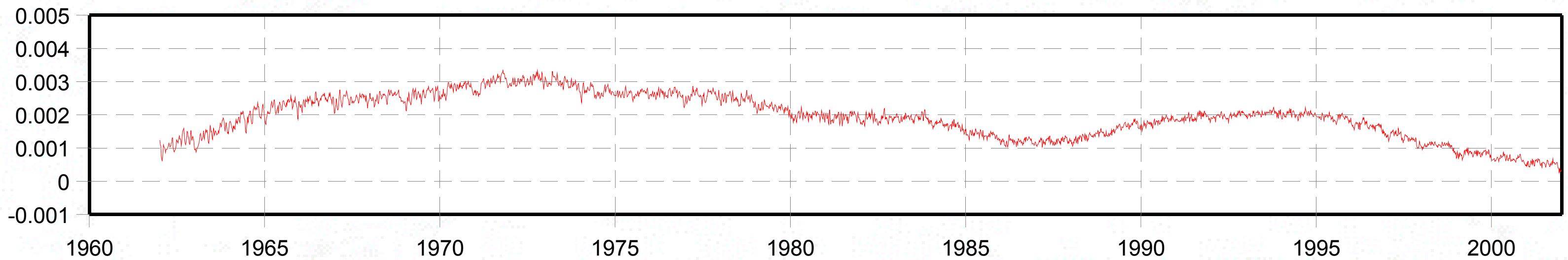
Length-of-day changes: observed



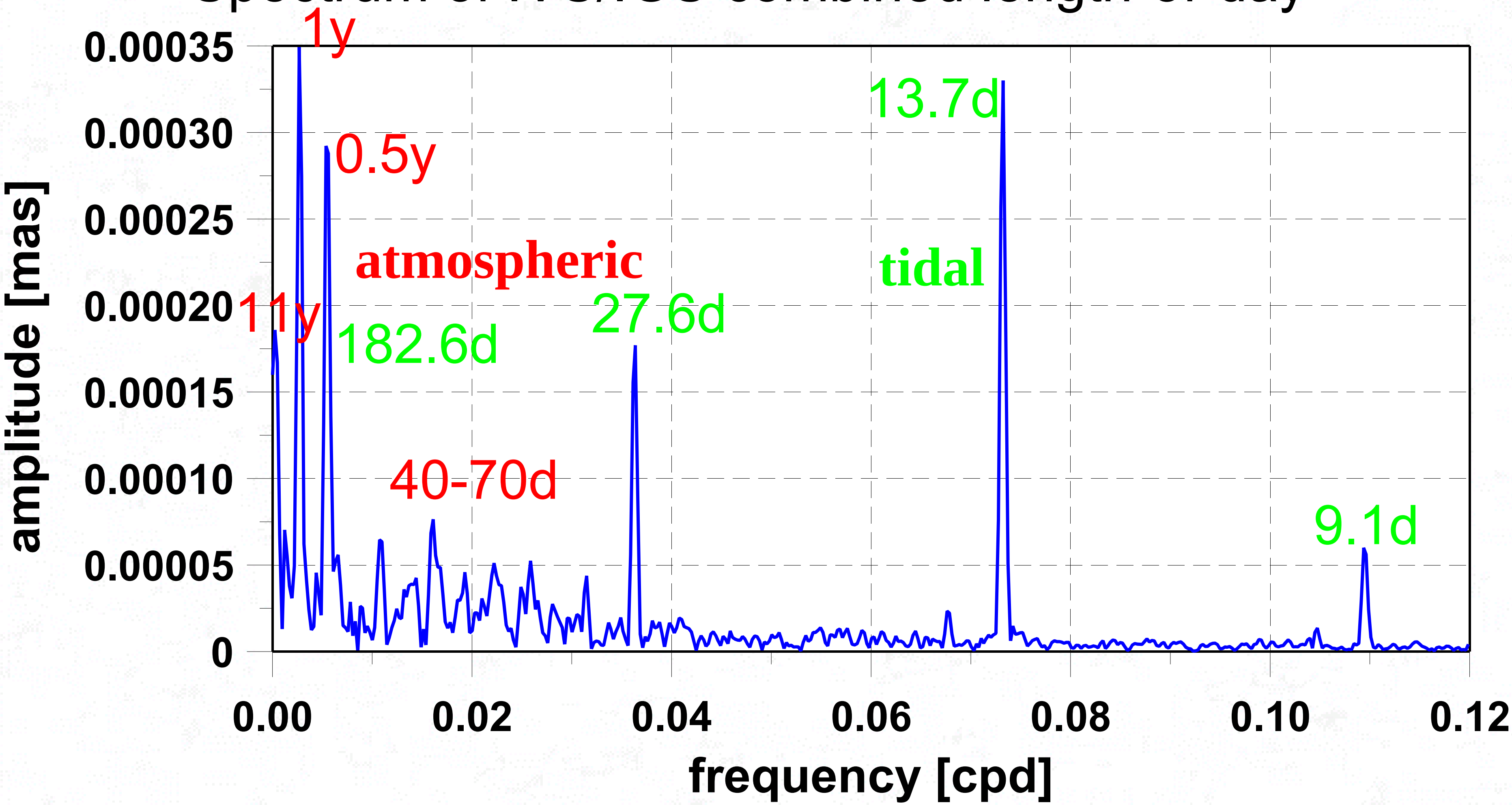
Length-of-day changes: observed - tidal changes



Length-of-day changes: observed - (tidal changes + atmospheric effects)



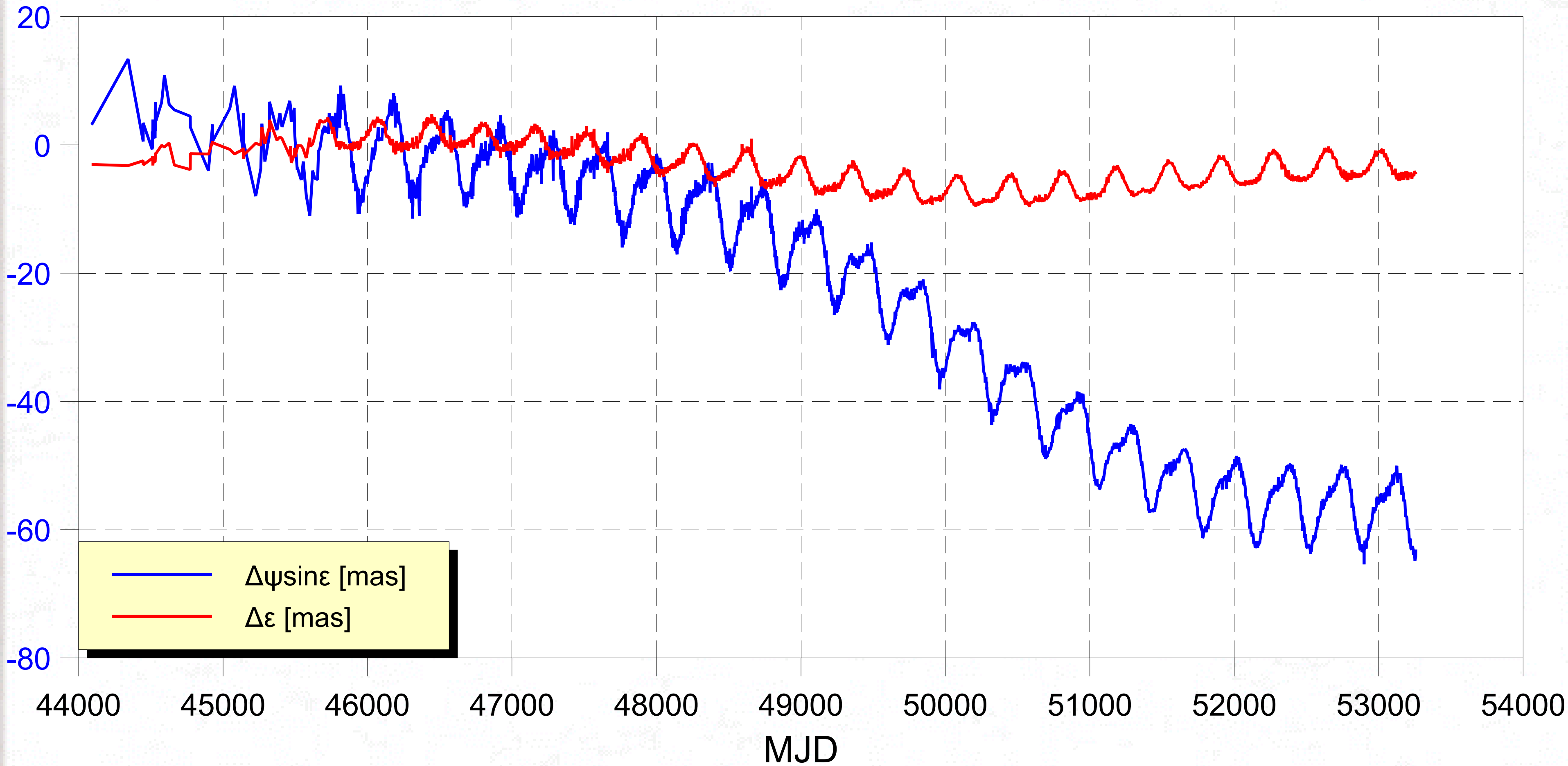
Spectrum of IVS/IGS combined length-of-day



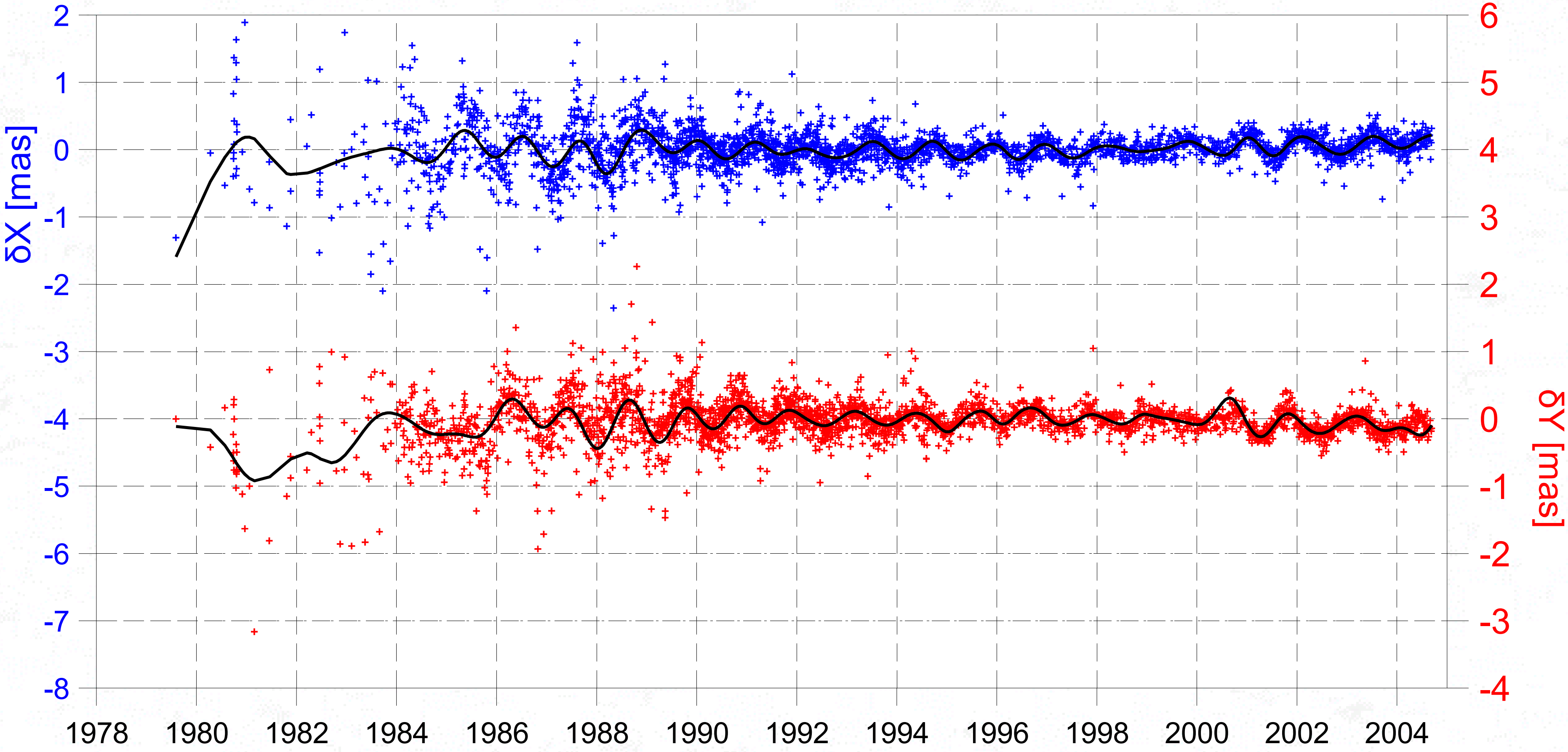
Variations of the speed of rotation - conclusions:

- **Secular deceleration of rotation:**
  - Tidal friction, secular decrease of Earth's flattening.
- **Decade quasi periodical variations:**
  - Core-mantle boundary changes (topography, electromagnetic coupling).
- **Variations with periods from several days to ten years:**
  - Zonal winds (longer periods);
  - Tidal changes of the principal moment of inertia of the Earth (shorter periods).

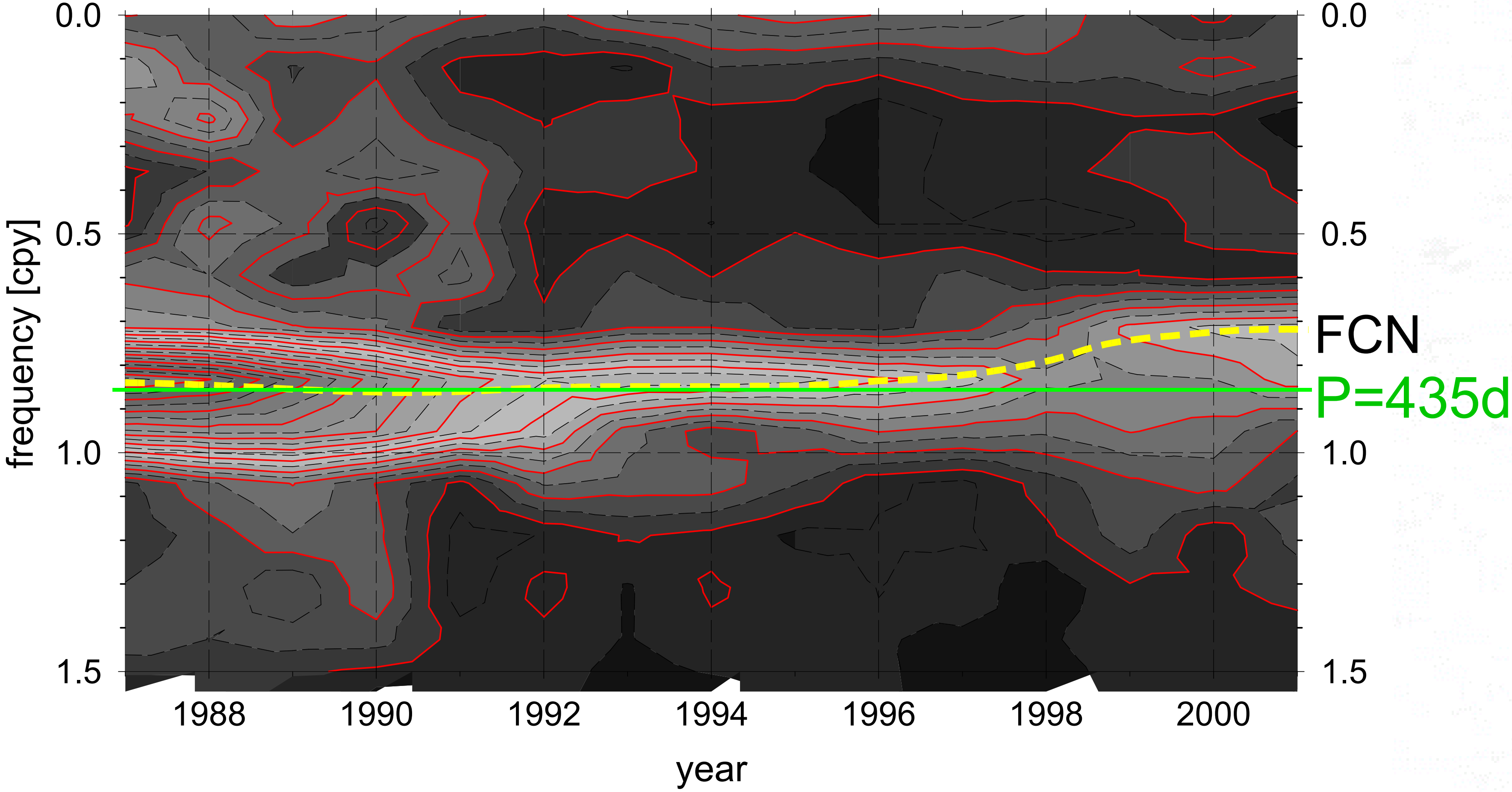
Celestial pole offsets with respect to IAU1980



Celestial pole offsets with respect to IAU2000



Time evolution of IVS celestial pole offset spectrum
(FFT with moving Parzen window 6 years wide)



Resonance (Mathews-Herring-Buffet transfer function):

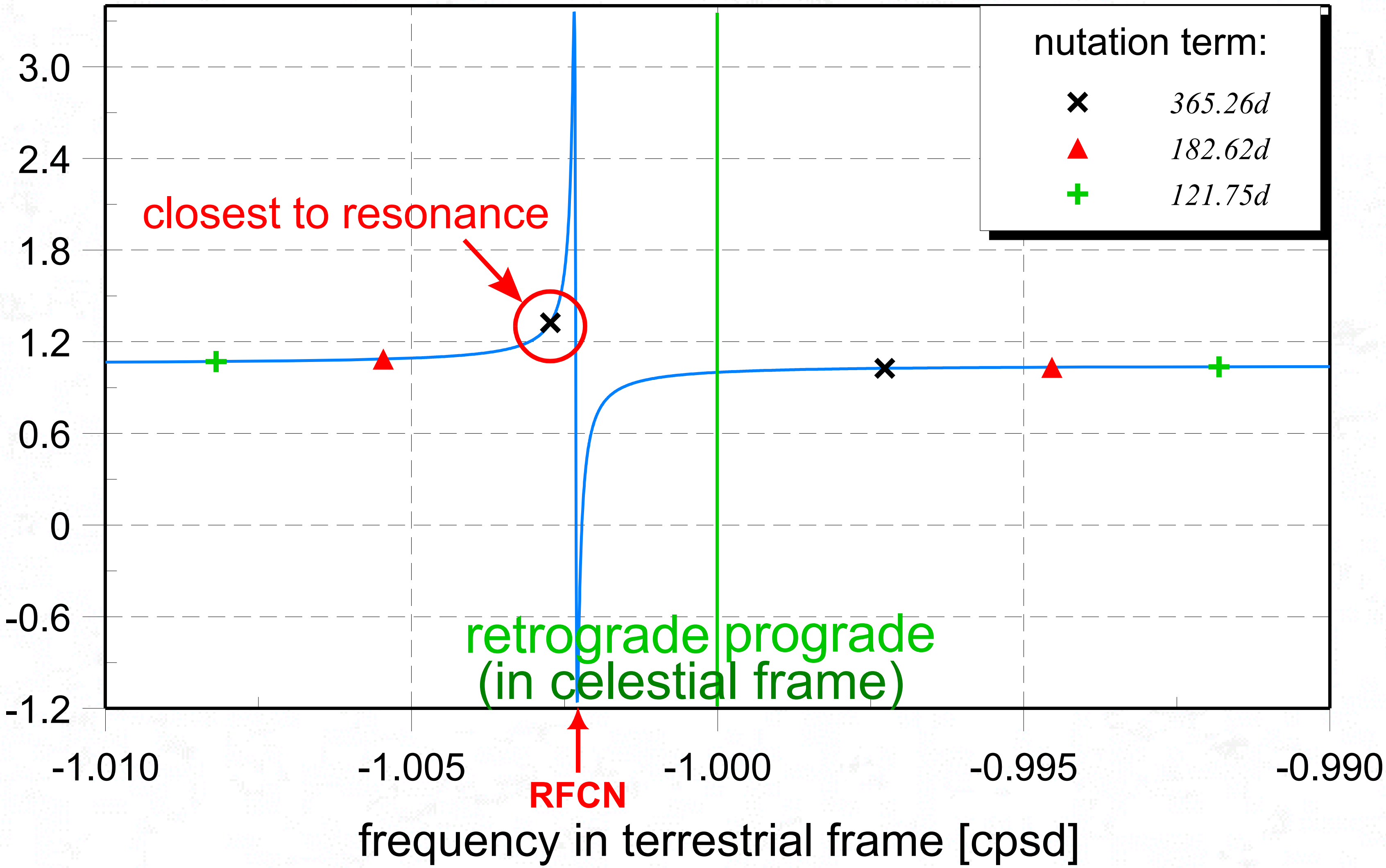
amplitude ratio of non-rigid/rigid Earth model:

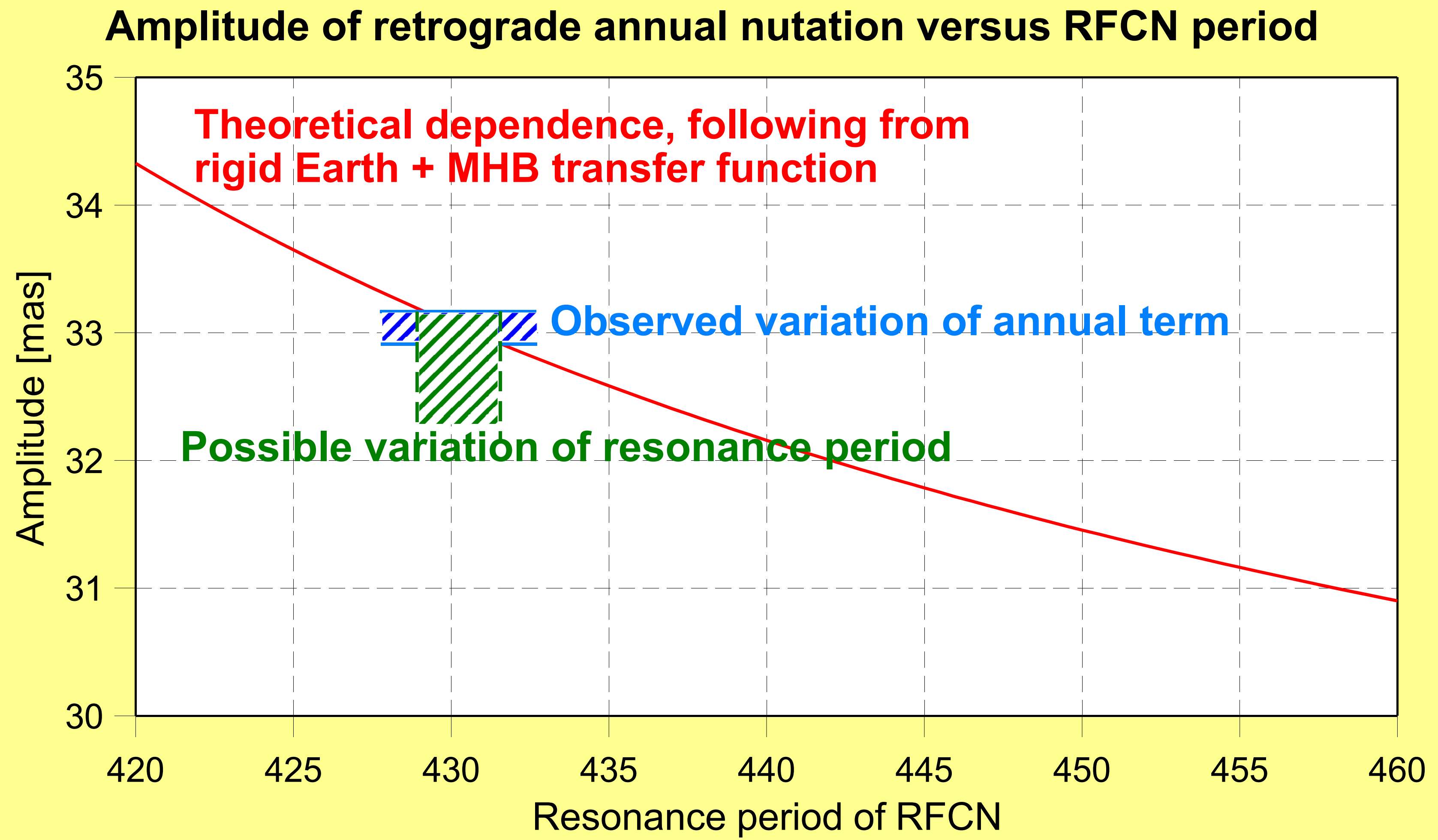
$$T(\sigma) = \frac{e_R - \sigma}{e_R + 1} N_0 \left[1 + (1 + \sigma) \left(Q_0 + \sum_{j=1}^{4} \frac{Q_j}{\sigma - s_j} \right) \right]$$

where e_R is dynamical ellipticity of rigid Earth, σ is the frequency of nutation (in ITRF), *N, Q* are constants, and s_j are resonance frequencies:

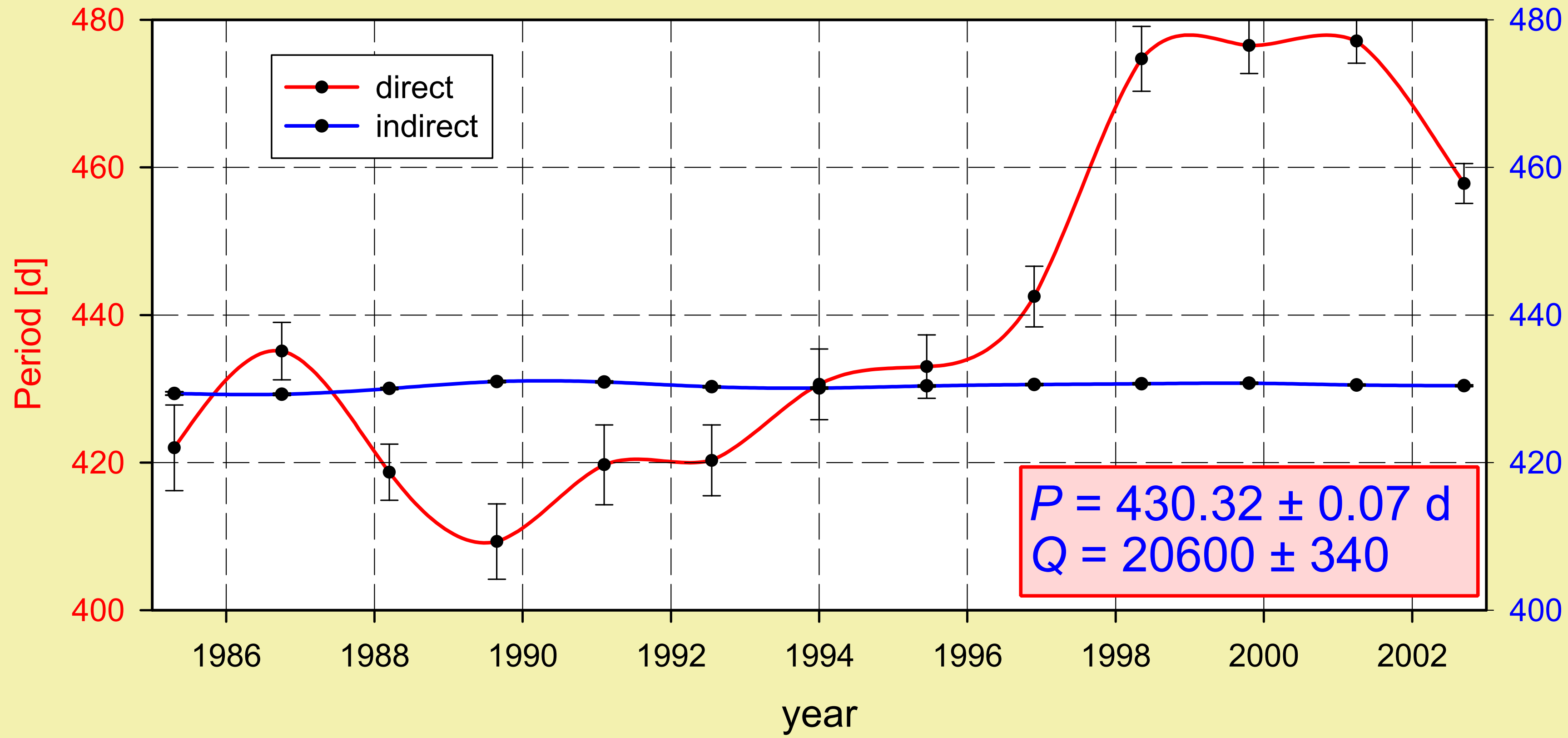
1. Chandler Wobble - CW ($P_{ter.}$ = 435 d);
2. Retrograde Free Core Nutation - RFCN ($P_{cel.}$ = 430 d);
3. Prograde Free Core Nutation - PFCN ($P_{cel.}$ = 1020 d);
4. Inner Core Wobble - ICW ($P_{ter.}$ = 2400 d).

Transfer function MHB2000 - real part




Amplitude of retrograde annual nutation versus RFCN period
Theoretical dependence, following from
rigid Earth + MHB transfer function
Observed variation of annual term
Possible variation of resonance period
Amplitude [mas]
35
34
33
32
31
30
420
425
430
435
440
445
450
455
460
Resonance period of RFCN

Period of RFCN - direct and indirect determination



Celestial pole offsets from the model IAU2000A - conclusions

- New model of nutation agrees with observations on the level ±0.1mas;
- Dominant deviation has a retrograde period, apparently changing in range 430-460 days, and a variable amplitude ≈ 0.1 mas (FCN);
- The resonance period, given by internal structure of the Earth, is close to 430 days and relatively stable, its temporal variation is very small (a few tenths of a day);
- The observed change of the period, obtained from direct analysis of celestial pole offsets, can be most probably ascribed to excitation by external parts of the Earth.