

# ASTRONOMICAL REFERENCE SYSTEMS AND FRAMES, ASTROMETRIC TECHNIQUES AND CATALOGS

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## ■ PART 1:

- ◆ Reference systems and frames used in astronomy:
  - Historical outline, from the oldest ones to the most recent;
- ◆ Transformation between terrestrial and celestial systems.



# REFERENCE SYSTEMS USED IN ASTRONOMY

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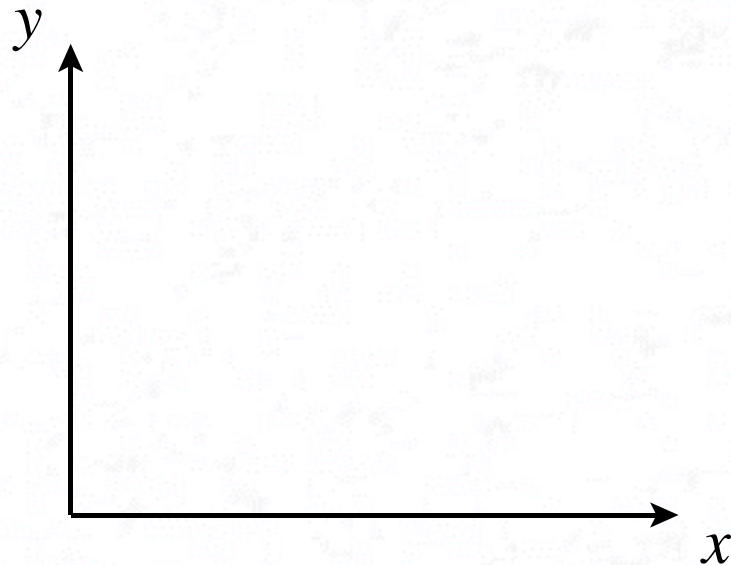
- **We must distinguish between system and frame:**
  - ◆ **Reference system - the idea, definition;**
  - ◆ **Reference frame - realization of reference system by means of real physical objects.**



# Examples:

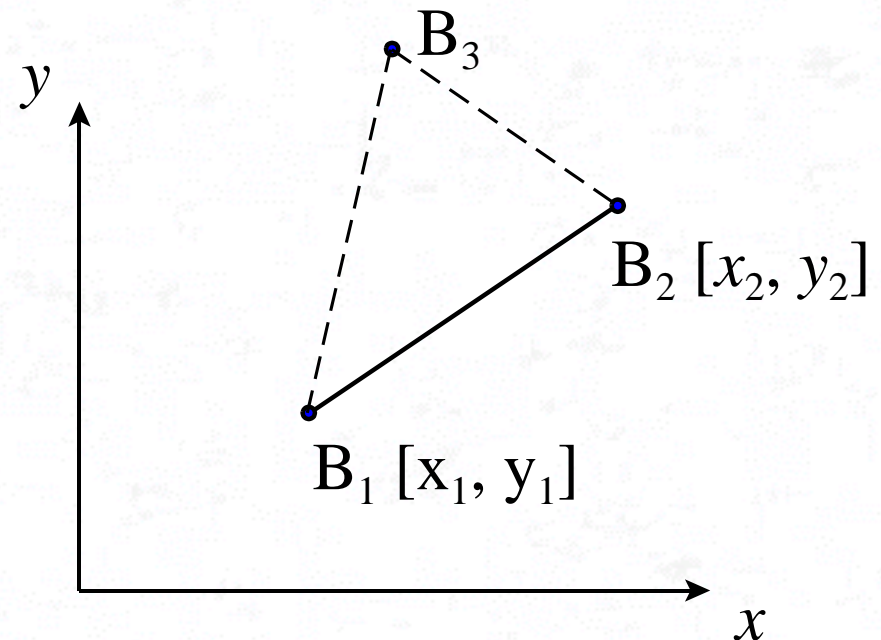
## System

RECTANGULAR PLANAR  
SYSTEM



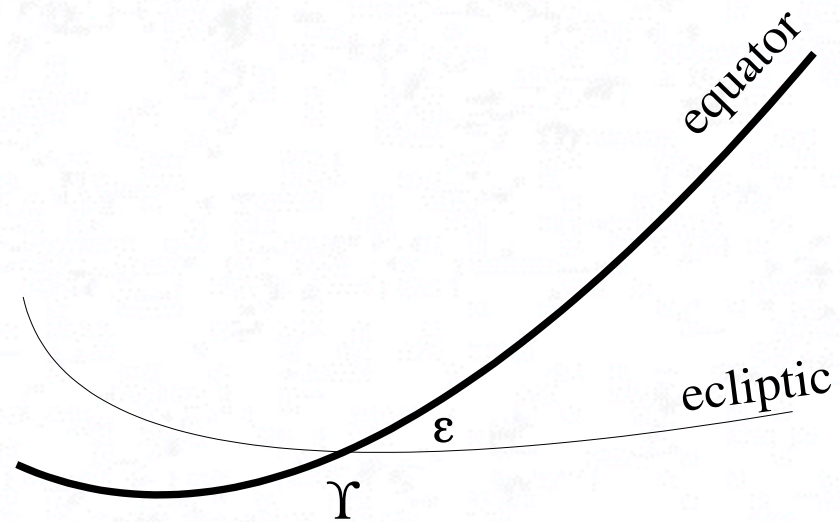
## Frame

AT LEAST TWO POINTS WITH  
KNOWN COORDINATES



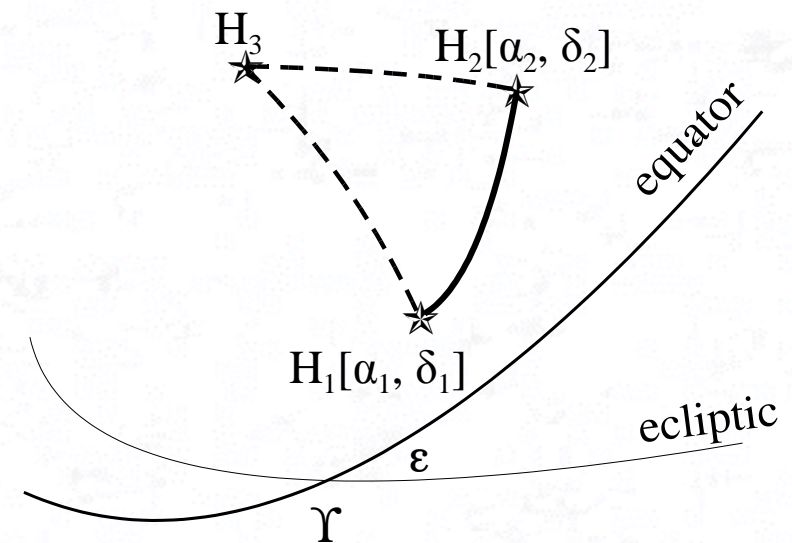
## System

EQUATORIAL SPHERICAL  
SYSTEM



## Frame

AT LEAST TWO STARS WITH  
KNOWN COORDINATES



# GLOBAL COORDINATE SYSTEMS:

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## ■ A. Celestial reference system

- ◆ serves to describe positions and motions of celestial bodies; it should be inertial in Newtonian sense, i.e., such that Newton laws hold in it; it is fixed with respect to the rest of universe - it should be nonrotating, its origin having no acceleration.
- ◆ It is possible to be realized:
  - kinematically (by means of adopted coordinates and proper motions of the stars, resp. extragalactic objects);
  - dynamically (by means of adopted theories of motion of solar system bodies).



## ■ B. Terrestrial reference system

- ◆ serves to describe positions and motions on the Earth, astronomical observations are made mostly from the surface of the rotating Earth.
- ◆ It is possible to be realized:
  - by means of adopted positions of selected observatories, and their temporal changes.

## ■ C. Intermediary (precession-nutation) system

- ◆ serves for transformation between the celestial and terrestrial system.
- ◆ It is defined by:
  - conventionally chosen axis (close to instantaneous spin axis of the Earth) – until recently Celestial Ephemeris Pole (CEP);
  - adopted origin on the equator, corresponding to the adopted axis – until recently equinox, but:
    - ★ since 2003 important change!! - Celestial Intermediate Pole (CIP), Celestial Ephemeris Origin (CEO), Terrestrial Ephemeris Origin (TEO), since 2006 renamed to CIO & TIO.



- Reference systems were developed in agreement with observational techniques used and their precision
  - ◆ human eye, telescope, divided circles, photographic and photoelectric registration, CCD...;
- Reference frame of the celestial system ⇒ stellar catalogs
  - ◆ two-dimensional, the third dimension added only since 19th century, when Bessel determined the first annual parallax;
- **Ecliptic system** (until 17th cent.):
  - ◆ only a very slow rotation of the basic plane (0.5" per year), fast motion of the origin of longitudes (50" per year); Sun, Moon and bright planets move in its vicinity;
    - observations with a low precision, without telescopes, instruments held in hand.

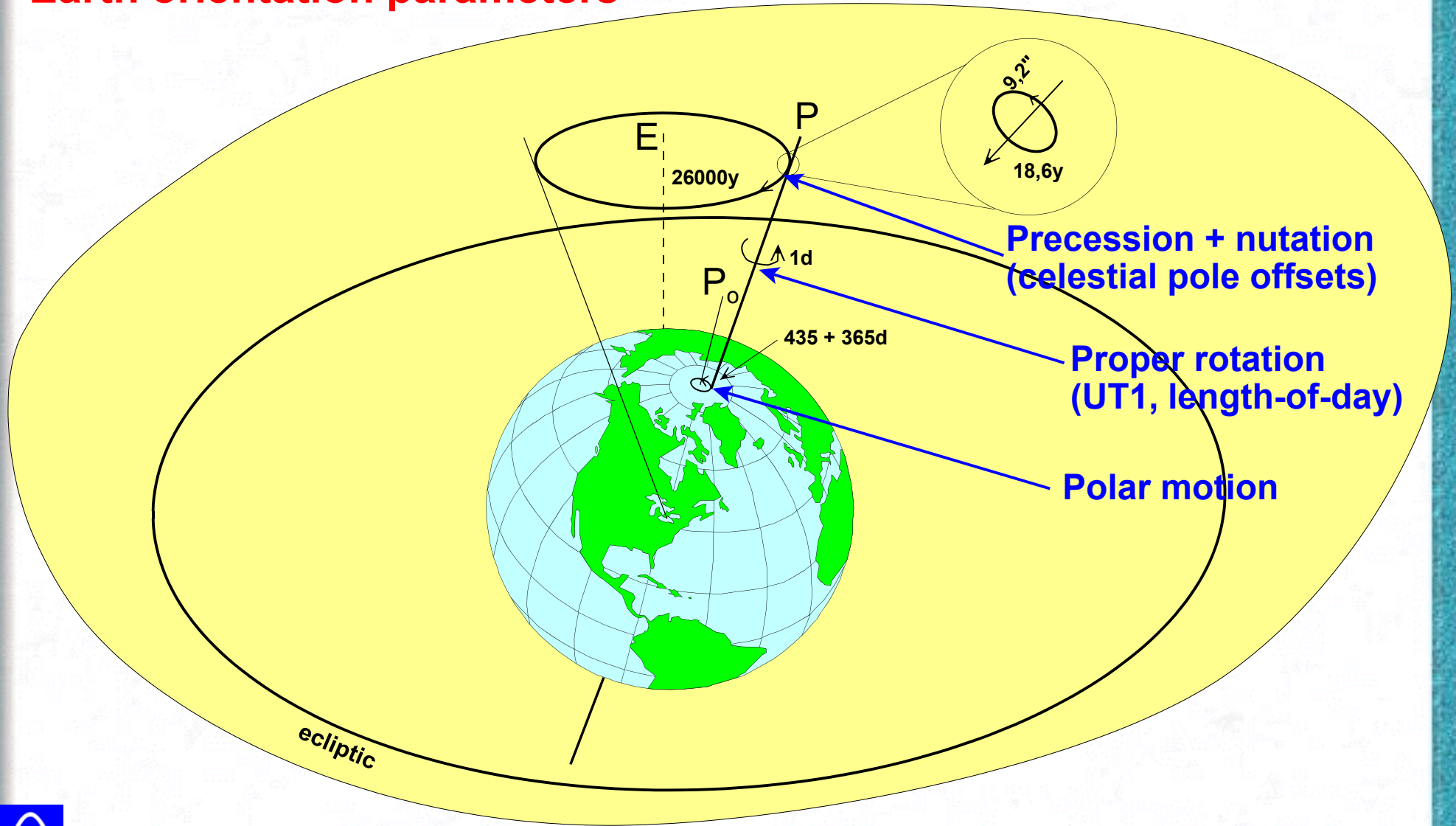


- **Equatorial system** (since the beginning of 18th cent.):
  - ◆ Relatively fast rotation of the basic plane ( $20''$  per year), fast motion of the origin of right ascensions ( $40''$  per year),
    - when observing in local meridian, the determination of declination is made independently of right ascension (zenith distance, time of transit);
    - instruments with telescopes, firmly connected with the rotating Earth, precise pendulum clocks - 1655 Huygens, electric registration of time with chronographs and contact "impersonal" micrometer - 2nd half of 19th cent.
- **Terrestrial reference equatorial system** (origin of longitudes from Ferro, since 1911 from Greenwich), transformation between celestial and terrestrial ref. syst. defined by Earth orientation parameters:
  - ◆ Polar motion  $x, y$  (position of CIP in terrestrial syst.),
  - ◆ Proper rotation UT1-UTC (angle between the origins of celestial and terrestrial ref. syst.),
  - ◆ Celestial pole offsets  $d\varepsilon, d\psi$  (position of CIP in celestial syst.)





# Earth orientation parameters



## Transformation between terrestrial and celestial systems:

- $[CRS] = PN(t).R(t).W(t).[TRS]$ ,
  - ◆ where  $PN$  is precession-nutation matrix,
  - ◆  $R$  is proper rotation matrix,
  - ◆  $W$  is polar motion matrix.
- Reference frame of terrestrial system  $\Rightarrow$  catalog of coordinates of selected points (geographic coordinates in the past, rectangular coordinates now), and their temporal changes - ITRF.
- Problems:
  - ◆ polar motion,
  - ◆ irregular speed of rotation,
  - ◆ plate tectonic motion.



# RESOLUTIONS IAU 2000/2006 AND THEIR PRACTICAL IMPLEMENTATION

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- **Overview of some IAU resolutions 2000 and the reasons, leading to their adoption;**
- **A detailed explanation of resolutions IAU2000 (B1.6-B1.8) and IAU2006 (1-3):**
  - ◆ **New precession-nutation;**
  - ◆ **New definition of the pole and origins;**
  - ◆ **New transformation between terrestrial and celestial reference systems.**



## The resolutions were closely linked with the past decisions adopted at IAU General Assemblies:

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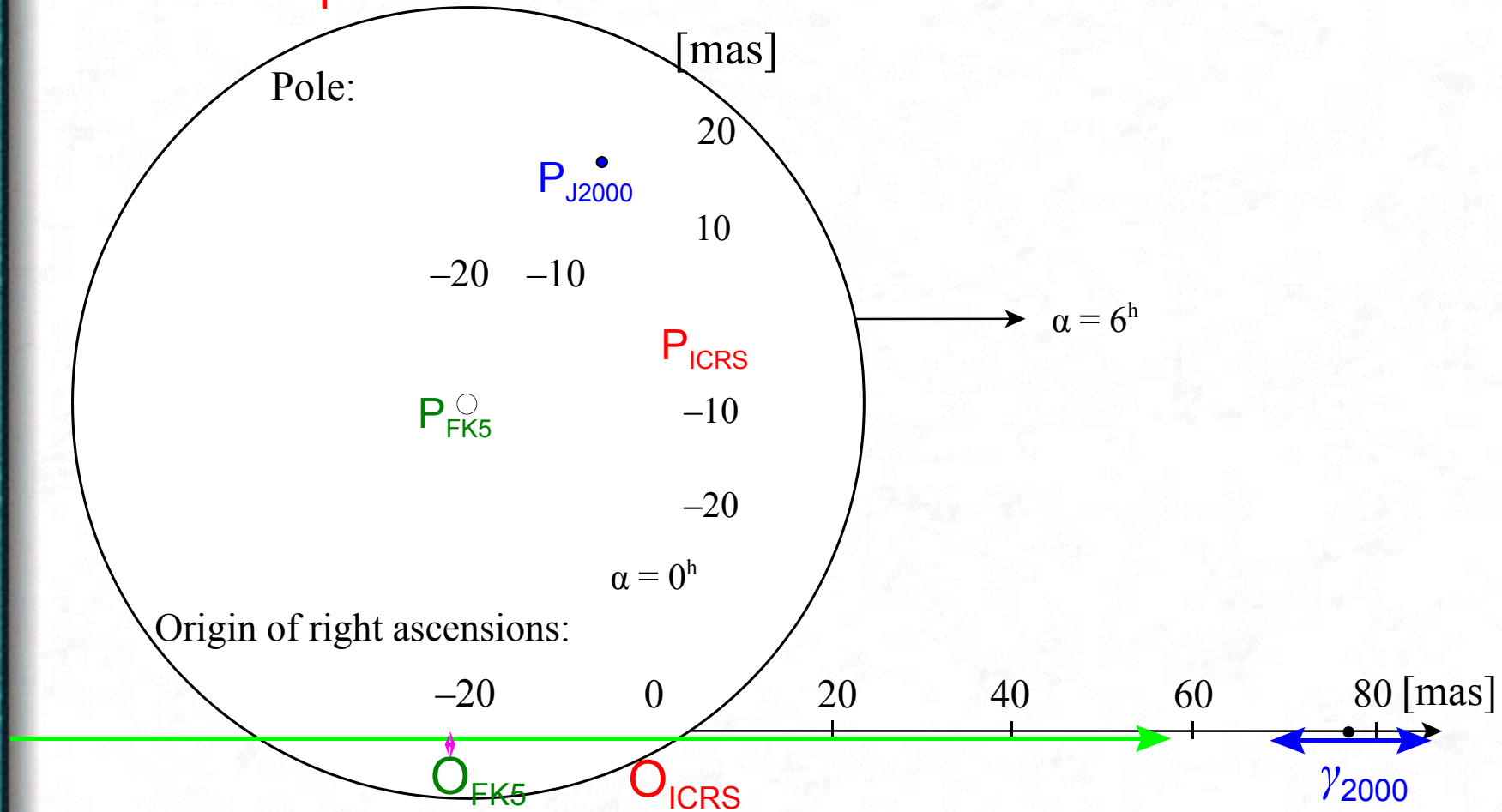
- In 1991 - concepts of a new definition of celestial reference system and of time scales in general relativity frame were adopted;
- In 1994 - a list of extragalactic radio sources was adopted, defining conventional reference frame, and a joint IAU/IUGG Working Group was set up to prepare new model of non-rigid Earth nutation model;



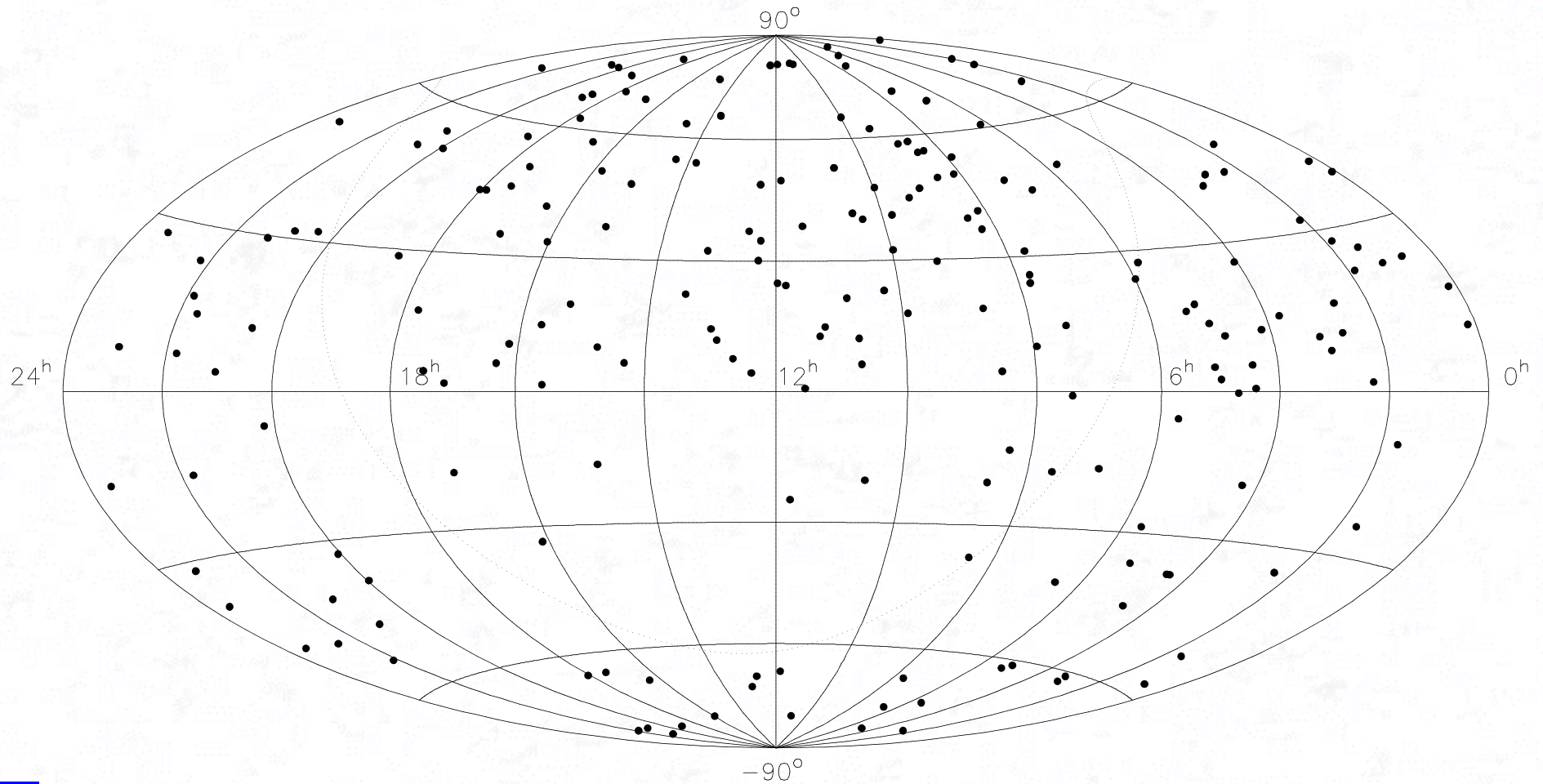
- **In 1997 - new International Celestial Reference System (ICRS) and International Celestial Reference Frame (ICRF) were adopted:**
  - ◆ **kinematically fixed system;**
  - ◆ **ICRS - barycentric rectangular system, axes fixed with respect to extragalactic objects;**
  - ◆ **ICRF - realization of ICRS (adopted values of coordinates);**
  - ◆ **New system is close to equatorial system for the epoch J2000.0 (i.e., to FK5 frame);**
  - ◆ **New system and frame have no epoch!!**



# Mutual orientation of ICRS, FK5 a mean equator + equinox for the epoch J2000.0



# Defining sources of ICRF



# REASONS LEADING TO ADOPTION OF RESOLUTIONS IAU2000 and IAU2006:

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*Resolutions IAU2000 - 'packet' of nine closely linked resolutions (B1.1-B1.9) plus additional two (B2, B3).*

*Resolutions IAU2006 (1-3) - supplements to preceding ones*

*In the following only some of the resolutions IAU2000 (B1, B2) and IAU2006 (1-3) will be discussed  $\Rightarrow$  transformations of space-time coordinates.*





## Resolution IAU2000 B1.1 (ICRS + ICRF)

- International Celestial Reference System (ICRS) and International Celestial Reference Frame (ICRF) are, since January 1, 1998, defined by means of **adopted positions** of extragalactic objects, emitting in radio wavelengths. At present, there are 212 **defining**, 294 **candidate** and 102 **additional** radio objects;
- Although their proper motions are negligible, these objects have different **shapes, which are often changing in time**. Therefore, it is necessary to maintain these systems and frames regularly. It is also necessary to densify and expand them to other wavelengths (optical, infrared ...).



- Hipparcos Celestial Reference System (HCRF) was established, as a primary realization of ICRF at optical wavelengths:
  - ◆ All Hipparcos stars **with the exception** of those flagged C, G, O, V and X (double or multiple systems).



# Resolutions IAU2000 (B1.6) and IAU2006 (1) (new precession + nutation)

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- The past model of precession-nutation, adopted by IAU in 1980, was based on:
  - ◆ Kinoshita's solution for a rigid Earth (external torques only by the Moon and Sun);
  - ◆ Wahr's transfer function for non-rigid Earth, computed for elastic stratified Earth with fluid core (without atmosphere and oceans).



- Observations by VLBI made after 1980 proved that this model is no more adequate, at today's level of observational accuracy (better than 1mas). Therefore a new model is adopted, based on:
  - ◆ More precise solution for the rigid Earth (Souchay et al. 1999), which takes into consideration also external torques by the planets;
  - ◆ Transfer function for non-rigid Earth (Mathews, Herring and Buffet 2002) that considers also:
    - Non-elasticity of the Earth,
    - Electromagnetic couplings between outer fluid core and the mantle and inner solid core,
    - Annual atmospheric tides,
    - Geodetic nutation (impact of general relativity),
    - Influence of oceanic tides.

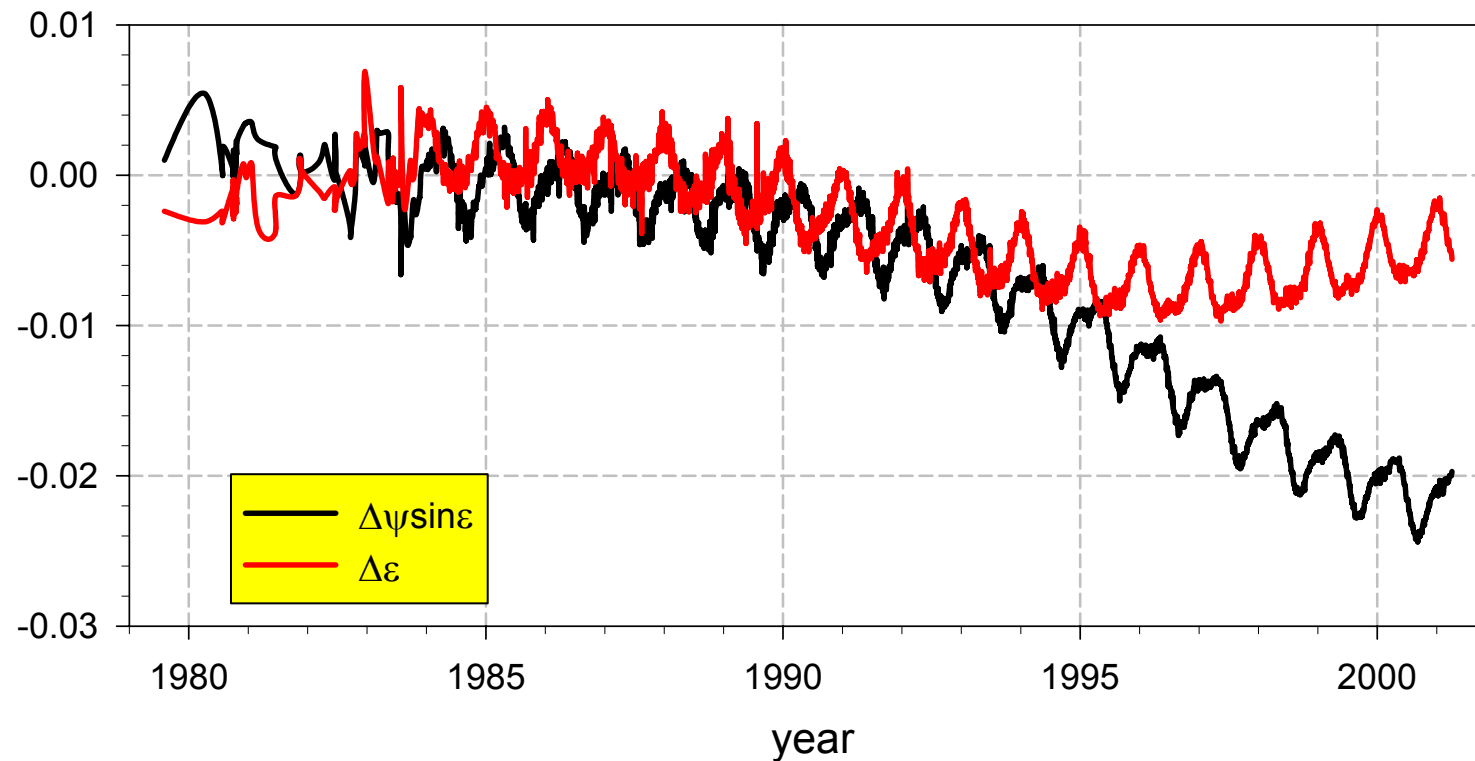


- **Several basic parameters of this model are estimated from VLBI observations.**
- **There are two versions of the nutation model:**
  - ◆ **IAU 2000A with full precision (about 0.2 mas);**
  - ◆ **IAU 2000B with a lower precision (1 mas).**
- **The model is constructed so that it describes the motion of Celestial Intermediate Pole (see below);**
- **Full model contains 1460 periodic terms (in contrast to only 106 of the old model IAU1980);**
- **Old Lieske (1977) precession required a linear correction of about 3mas/yr**



# Comments to IAU2000 resolution B1.6

VLBI observations, leading to a correction to precession and a new nutation model



## New model of precession/nutation:

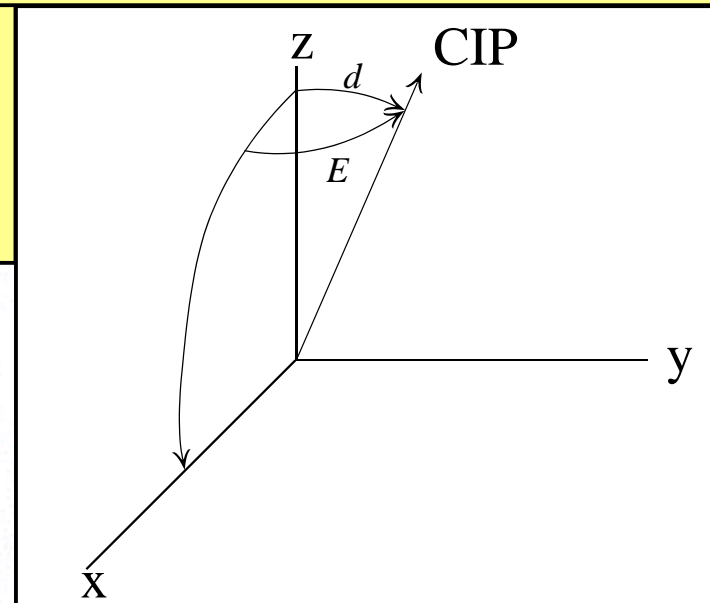
- Correction of precession (IAU 1976):
  - ◆  $\Delta\psi = -0.04177'' - 0.002997''(t-2000)$ ,
  - ◆  $\Delta\varepsilon = -0.00682'' - 0.000252''(t-2000)$ ;
- New nutation contains about 1400 periodic terms (old one only 106);
- New formulation of precession-nutation angles  $X$ ,  $Y$  (coordinates of CIP in ICRS), and accumulated rotation  $s$  of CIO along equator:

$$X = \sin d \cos E = -0.016617'' + 2004.191742''t - 0.4272190t^2 + \dots + \text{period. terms}$$

$$Y = \sin d \sin E = -0.006951'' + 0.025376''t - 22.4072510t^2 + \dots + \text{period. terms}$$

$$s = \int_{t_0}^t (\cos d - 1) \dot{E} dt = - \int_{t_0}^t \frac{X\dot{Y} - Y\dot{X}}{1 + \cos d} dt$$

$$s = 0'' \text{ (for J2000.0), } 0.07'' \text{ (for J2100.0)}$$



# Comments to IAU2006 resolution 1

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- In 2006 were adopted:
  - ◆ New precession terminology:
    - Luni-solar precession → precession of the equator;
    - Planetary precession → precession of the ecliptic;
  - ◆ New precession theory P03 (Capitaine et al. 2003), consistent with dynamical theory and IAU2000A nutation:
    - It contains the linear correction plus a quadratic term due to  $dJ_2/dt$ , and is developed to higher orders of time (5th) than the old Lieske theory (3rd);
  - ◆ New definition of the ecliptic:
    - Ecliptic pole is defined by the mean orbital angular momentum vector of the Earth-Moon barycenter in BCRS.





## Resolution IAU2000 B1.7 (CIP)

- Although only three parameters are necessary to describe mutual orientation between terrestrial and celestial systems (e.g., Euler angles), there is an obvious necessity of two others, describing the motion of a **conventionally chosen intermediary axis** with respect to both systems;
- This axis must be naturally chosen so that:
  - ◆ it is close to instantaneous axis of rotation,
  - ◆ its motion in terrestrial and celestial systems is observationally distinguishable.
- This role was played in the past by Celestial Ephemeris Pole (CEP), whose definition was based on the requirement that it does not exhibit fast (near-diurnal) motion in any of these two reference systems.



- This definition however now became obsolete and practically not feasible, due to:
  - ◆ the existence of small rapid motions (with periods of one day and shorter) of instantaneous spin axis with respect to both reference systems, caused by the oceans and the atmosphere;
  - ◆ today's precision of observation that is capable to detect these motions.
- Therefore a new Celestial Intermediate Pole (CIP) was introduced, defined so that **its periodical celestial motion (nutation) contains only the terms with periods longer than two days; all other motions are interpreted as terrestrial polar motion.**



## Comments to resolution B1.7

- CIP is a more precise definition of pole (former term - Celestial Ephemeris Pole);
- Its motion in Geocentric Celestial Reference System (GCRS) is given by a forced motion of the mean Tisserand axis of the Earth with periods longer than 2 days;
- This motion is realized by the model of precession-nutation IAU2000A plus additional small corrections, determined from the observations by IERS;
- Motion of the same pole in terrestrial reference system (ITRS) is determined from the observations by IERS, and it contains also high-frequency terms (with the exception of retrograde diurnal terms).



# Resolutions IAU2000 (B1.8) and IAU2006 (2) CEO, TEO, CIO, TIO

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- Until recently, equinox and zero meridian were used as origins, defining the angle of proper rotation of the Earth (Greenwich Sidereal Time). Instantaneous **equinox**, i.e., the intersection of Earth's equator with the ecliptic, **depends on:**
  - ◆ the theory of orbital motion of the Earth around the Sun;
  - ◆ adopted model of precession and nutation.



- From this follows that the equinox moves with respect to celestial frame along the equator (precession, equation of equinoxes). Ecliptic, i.e., the plane drawn through the orbit of the Earth (a general three-dimensional curve)
  - ◆ is determined from the observations of solar system bodies with much lower precision than VLBI;
  - ◆ is not defined uniquely, and is completely unnecessary for the transformation between terrestrial and celestial reference systems.
- Official conventional celestial system ICRS, adopted in 1997, **is not** based either on ecliptic or equinox.



- Therefore, it is reasonable to select an origin that would be **independent of the Earth's orbital motion and of the adopted model of precession-nutation**. The advantage is also to define an angle having a relatively simple relation to Universal time (UT1), whose definition should not change each time in future when the theory of Earth's orbital motion or rotation is changed.
- This is achieved by adopting Guinot's concept of 'non-rotating origin' on a moving equator, corresponding to CEP. It was called **Celestial Ephemeris Origin (CEO, now re-named to Celestial Intermediate Origin CIO)**. It is symmetrically accompanied by a similar concept in terrestrial system - **Terrestrial Ephemeris Origin (TEO, now re-named to TIO)**. The angle between CIO and TIO, **Earth Rotation Angle (or Stellar Angle)**, is tied with Universal time UT1 by a simple linear relationship.

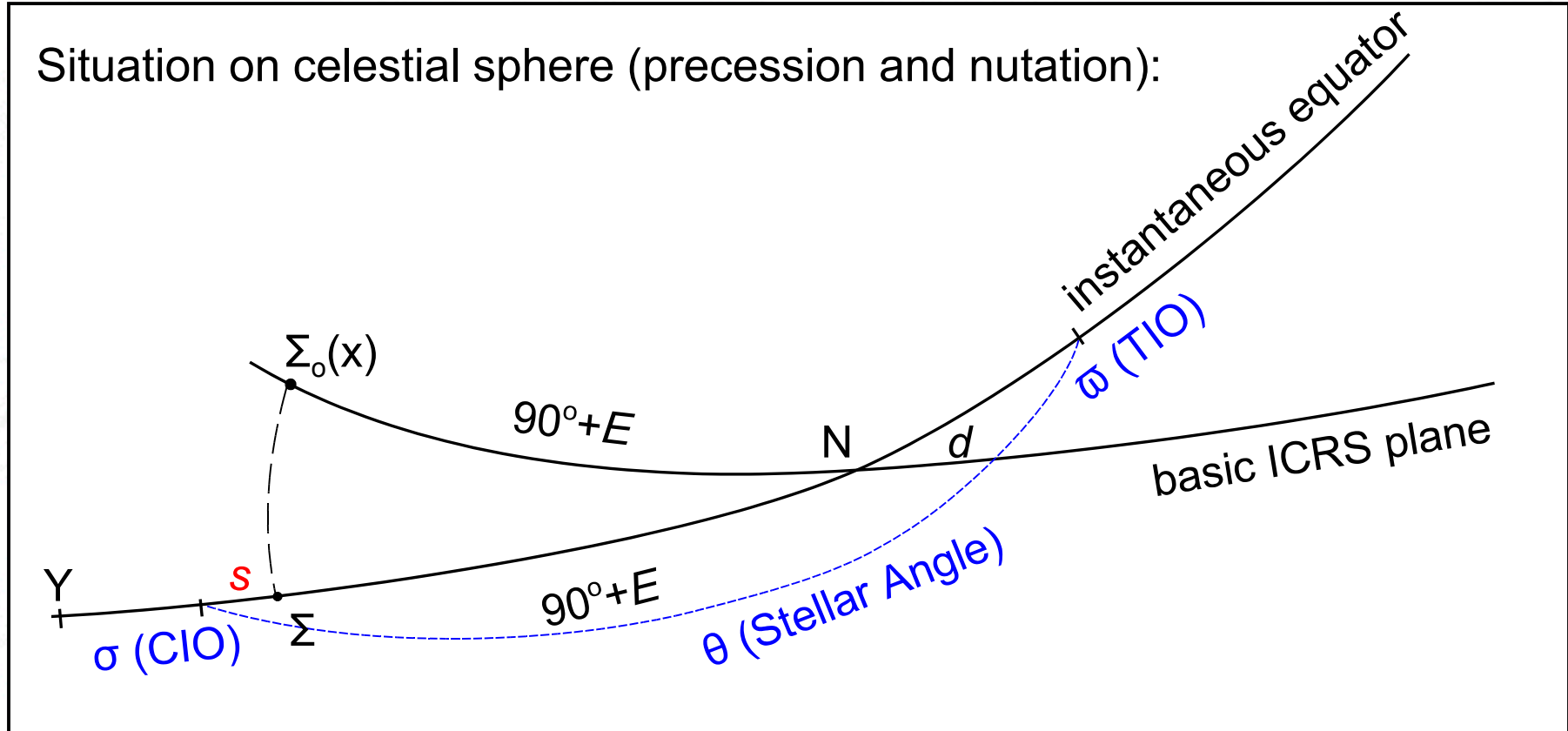


- **The transformation between the terrestrial system ITRS and the celestial geocentric system GCRS is then given by the position of CIP in GCRS, position of CIP in ITRS, and Earth Rotation Angle.**



# Comments to resolution B1.8

Situation on celestial sphere (precession and nutation):



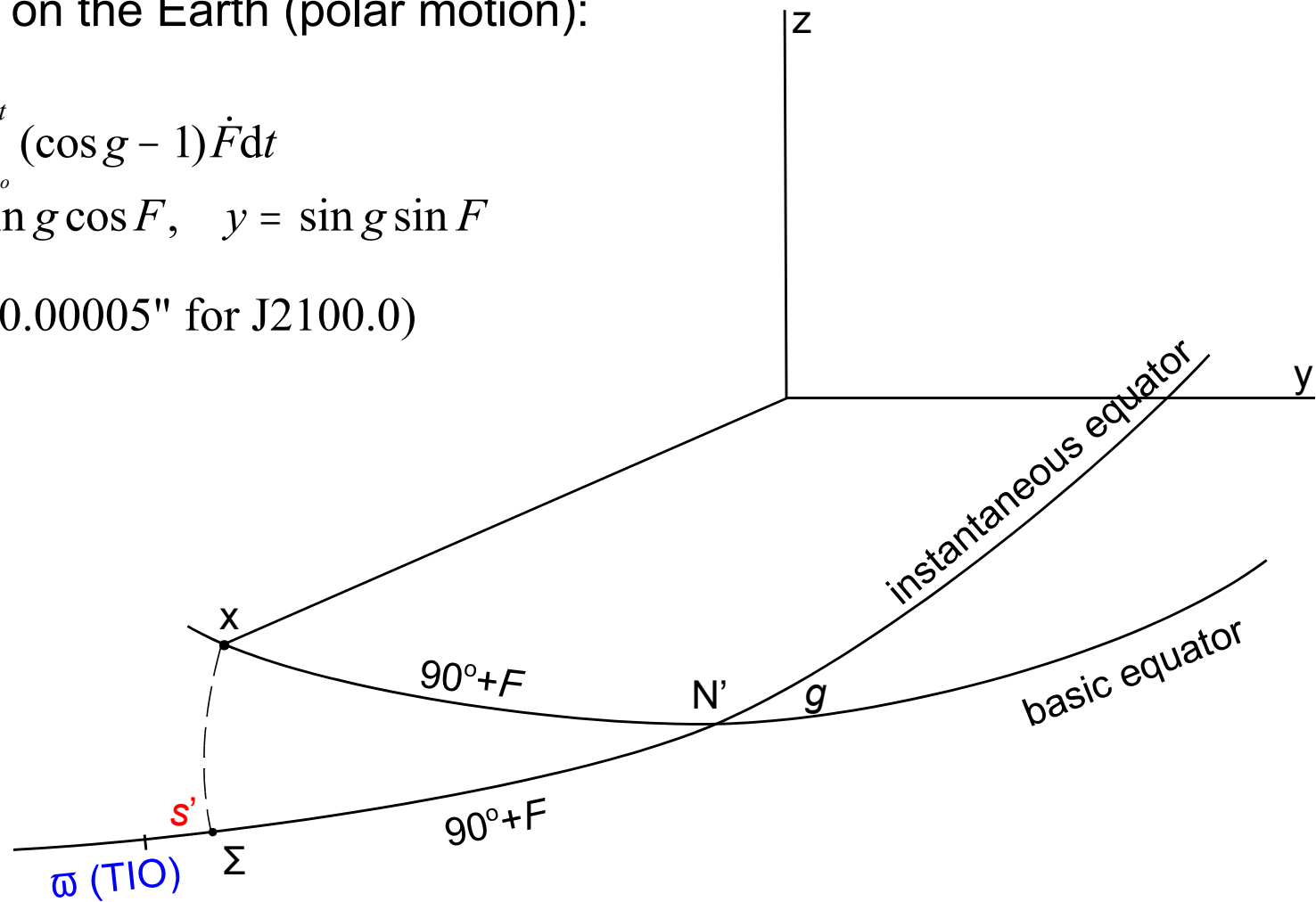


Situation on the Earth (polar motion):

$$s' = \int_{t_0}^t (\cos g - 1) \dot{F} dt$$

$$x = \sin g \cos F, \quad y = \sin g \sin F$$

( $s' < 0.00005''$  for J2100.0)



# Transformation between CRS and TRS:

Relation between Universal Time UT1 and stellar angle  $\theta$ :

$$\theta(T_u) = 2\pi(0.7790572732640 + 1.00273781191135448T_u), \quad \text{where}$$

$$T_u = JD(UT1) - 2451545.0$$

Transformation relations:

$$[CRS] = Q(t) \cdot R_3(-\theta) \cdot W(t) \cdot [TRS]$$

$$Q(t) = \begin{pmatrix} 1 - aX^2 & -aXY & X \\ -aXY & 1 - aY^2 & Y \\ -X & -Y & 1 - a(X^2 + Y^2) \end{pmatrix} \cdot R_3(s), \quad \text{where } a = \frac{1}{2} + \frac{1}{8}(X^2 + Y^2)$$

$$W(t) = R_3(-s') \cdot R_2(x) \cdot R_1(y)$$



## Resolution IAU2000 B1.9 (Terrestrial Time)

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- **Terrestrial Time (TT) was defined by the IAU already in 1991 as a time scale for all practical applications on the Earth; it replaced the Terrestrial Dynamical Time (TDT) that was defined and used earlier. TT is defined as a time scale that differs from the Geocentric Coordinate Time (TCG) only by a constant linear trend. Its unit was chosen so that it agrees with SI unit on the geoid.**



- This constant trend therefore depends on the adopted value of geopotential on the geoid, so it should be **changed each time when the IUGG adopts a new value of this constant.**
- In order to avoid this frequent change, the new definition fixes the value of the trend between TT and TCG, based on the best estimation of geopotential on the geoid, **as a defining constant.**

$$dTT/dTCG = 1 - 6.969290134 \times 10^{-10}$$



## Resolution IAU2006 3 (re-definition of TDB)

- The IAU defined, in 1979, Barycentric Dynamical Time (TDB) as a scale for barycentric ephemerides;
- The IAU introduced, in 1991, the Barycentric Coordinate Time (TCB) and recognized that TDB was a **linear transformation** of TCB;
- In 2006 the linear relationship between TDB and TCB was fixed so that the value of the trend **is a defining constant**.

$$\begin{aligned} \text{TDB} &= \text{TCB} - L_B \times (\text{JD}_{\text{TCB}} - T_0) + \text{TDB}_0, \text{ where} \\ T_0 &= 2443144.5003725 \\ L_B &= 1.550519768 \times 10^{-8}, \text{ TDB}_0 = 6.55 \times 10^{-5} \text{ s} \end{aligned}$$



## Resolution IAU2000 B2 (UTC)

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- Because the speed of rotation of the Earth is variable, Universal Time (UT1) and International Atomic Time (TAI) diverge. Therefore so called Coordinated Universal Time (UTC) was introduced, whose unit is the same as the one of the TAI (i.e., SI second), with **irregular introduction of leap seconds**. The reason is to keep UTC within certain 'reasonable' limit close to UT1:
  - ◆  $(|UT1 - UTC| < 0.9s)$ .
- UTC depends on astronomically observed values of UT1, so the decision of introducing leap seconds is in **the responsibility of IERS**.



- **Difficult predictability of leap seconds affects modern communication and navigation systems, so an IAU Working Group was established to discuss if there is a requirement for leap seconds and to consider a possible change of UTC definition.**
- **The Working Group cooperated with the appropriate groups of the International Union of Radio Science (URSI), International Telecommunications Union (ITU-R), International Bureau for Weights and Measures (BIPM), International Earth Rotation Service (IERS), and relevant navigational agencies.**



- **WG conclusions (IAU GA 2006):**
  - ◆ Insertions of leap seconds are expensive and unpredictable;
  - ◆ Telecommunications & navigation require a single, internationally recognized uniform time scale;
  - ◆ Civil time should be close to solar time:
    - a possible solution: increased tolerance to 1 hour;
  - ◆ Existing astronomical software uses UTC as a substitute for UT1:
    - There is no strong consensus within IAU either for or against a change;
    - If a change in definition occurs, 5-10 years should be allowed to make revisions in software;
    - IERS is capable to disseminate UT1 through internet;
    - IAU should be consulted before any formal action is taken.
  - ◆ **WG was dissolved.**





# CONCLUSIONS

- Equinox → Celestial Intermediate Origin (CIO);
- Zero meridian → Terrestrial Intermediate Origin (TIO);
- Greenwich sidereal time → stellar angle;
- Celestial Ephemeris Pole (CEP) → Celestial Intermediate Pole (CIP);
- Precession IAU1976 + nutation IAU1980 → precession P03 + nutation IAU2000A;
- Description and corresponding software of the new transformations can be found in:
  - ◆ IERS Conventions 2003 (IERS Technical Note No. 32, <http://tai.bipm.org/iers/conv2003/conv2003.html>);
  - ◆ SOFA (<http://www.iau-sofa.rl.ac.uk/>)

