

Jan Kryński  
Institute of Geodesy and Cartography

## MAJOR CONCEPTS OF RECENT CELESTIAL AND TERRESTRIAL REFERENCE SYSTEMS

**ABSTRACT:** The XXIV IAU General Assembly in Manchester in 2000, recommended to replace on 1 January 2003, the existing celestial reference systems with the International Celestial Reference System (*ICRS*). The International Terrestrial Reference System (*ITRS*) has formally been implemented in 1991, on the basis of the Resolution 2 of the XX IUGG General Assembly in Vienna in 1991. The *ICRS* consists of the ensemble of the Barycentric Celestial Reference System (*BCRS*) and the Geocentric Celestial Reference System (*GCRS*) with coordinate times Barycentric Coordinate Time (*TCB*) and Geocentric Coordinate Time (*TCG*), respectively. New celestial reference systems are built up on the basis of the relativistic theory of astronomical reference systems. Also new definition of the Intermediate Reference System (*IRS*) that links the celestial systems with the terrestrial system has been introduced. Orientation of the celestial *IRS* and the terrestrial *IRS* using *CIP*, *CEO* and *TEO* is discussed. Motion of the *IRS* with respect to the *GCRS* is determined by the new IAU 2000 precession-nutation model, while its motion with respect to the *ITRS* is determined by the Earth rotation parameters provided by the *IERS*. Presently used time systems and their actual definitions and mutual interrelations are discussed. Comparison of two approaches of computation of apparent places, the classical one and the IAU2000 one, illustrates the use of new reference systems.

### INTRODUCTION

A consistent definition of reference systems and their realizations as well as their mutual interrelations that are adequate to positioning systems, are fundamental for both geodesy and navigation. The terrestrial reference system is a solid Earth-fixed system that rotates together with the Earth in its diurnal rotation. In a natural way, the system is referred to the spin axis of the Earth. Precise determination of that axis requires observations of extraterrestrial objects. Positions of those objects are primarily determined in the celestial reference frame that is a quasi-inertial one, i.e.

does not rotate and accelerate with respect to the celestial objects, distant from solar system. The spin axis of the Earth is, however, neither fixed to the body of the Earth, nor has a fixed orientation with respect to the universe. Gravitational attraction of the Earth by the Sun and the Moon cause the precessional motion of the spin axis of the Earth in the inertial reference system. Celestial reference frames were traditionally referred to the position of the spin axis of the Earth with respect to stars at certain epochs. Periodic variations of the positions of the Sun and the Moon with respect to the Earth perturb the precessional motion with forced nutation (frequently called simply – nutation). Motion of the spin axis of the Earth with respect to its body, the so-called polar motion, is also known as a free nutation. The mechanism of the complex motion of the rotational axis of the Earth is shown in Fig. 1.

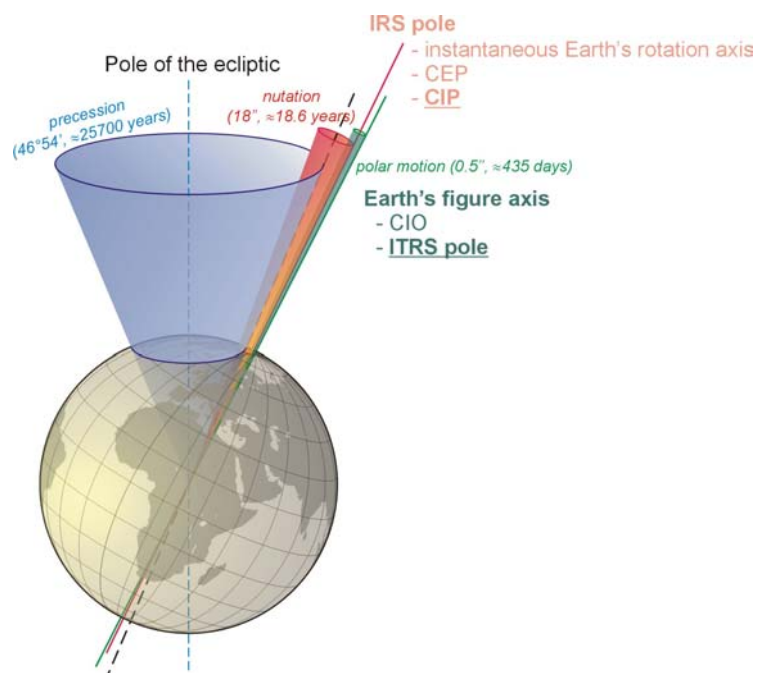


Fig. 1. Complexity of the motion of the rotational axis of the Earth

The figure axis of the Earth (green line in Fig. 1) that for many decades was identified with a mean instantaneous axis of Earth rotation over certain time interval is a primary axis of the terrestrial reference system. It also defines the terrestrial equator. The instantaneous axis of Earth rotation, corrected for forced nutation (black dashed line in Fig. 1) at certain epoch, corresponds to the primary axis of the celestial reference system.

Fundamental catalogues (FK) that contain positions, proper motions and parallaxes of the stars for epoch, e.g. 1950.0, 1975.0, 2000.0, were the realizations of the celestial reference systems. To process positional observations of extraterrestrial objects, the relation between the celestial reference system and the terrestrial reference system should be known with the accuracy consistent with the precision of positioning. The major components of the transformation of the celestial reference system into the terrestrial reference system are precession, forced nutation and the Earth orientation parameters – EOP. The EOP consist of polar motion that relates Earth's figure axis with instantaneous rotation axis (recently with the pole of the Intermediate Reference System) and the information on the actual velocity of Earth rotation that allows for linking the terrestrial reference system rotating with the Earth with the non-rotating celestial reference system. Both precession and forced nutation reflect rather regular motion. Parameters of the precession model are obtained from the analysis of all possible astrometric observations ever acquired. Theory of forced nutation is based on the model of physical and mechanical features of the planet Earth. Parameters of the model are also determined from astrometric observations. Irregular variation of EOP causes the necessity of continuous monitoring of the Earth rotation parameters<sup>1</sup>.

The advance in technology in last decades of XX century brought the development of new techniques that allow for more and more precise determination of positions of extraterrestrial objects, timing and Earth orientation parameters. Defined in the Euclidean space the existing reference systems that hardly assured a milliarcsecond accuracy level, turned out to be inadequate with respect to high precision of positioning using the VLBI, SLR, LLR and later GPS and DORIS techniques. Also transformation between the celestial reference system and the terrestrial reference system became a substantial problem when global positioning systems and space positioning techniques started to be widely used in precise navigation, geodesy and surveying. Uncertainties resulting from the definition of incompletely free-of-rotation celestial reference systems, realized by FK catalogues, started to exceed positioning errors. Imperfectness of reference systems has only partially been reduced by implementing relativistic corrections, considered as perturbations, to the model based on Newtonian mechanics [17]. In addition, theory of relativity proves that time is not absolute and it runs differently in different reference systems. The need for defining operational reference systems, both

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<sup>1</sup> Earth rotation parameters are monitored since 1899 by the IAG service (previously the International Latitude Service, then the International Polar Motion Service, the International Earth Rotation Service, and recently the International Earth Rotation and Reference Systems Service)

celestial and terrestrial ones, including space-time transformations and time systems, in terms of general relativity in an abstract 4D space at a microarcsecond accuracy level became thus urgent.

New positioning techniques provide positioning data and EOP with much higher temporal resolution than the one based on traditional astrometric observations. Such data are the basis for developing better models for Earth orientation in space, in particular nutation and Earth rotation. Radiointerferometry, laser ranging and global satellite positioning systems operate, however, in reference systems that are not mutually consistent. It causes certain difficulty in setting up combined solutions that would fully reflect the potentiality of each positioning technique. There is thus a need for developing the system that would consistently integrate VLBI, SLR, LLR, GPS (GNSS) and DORIS data. The concept of such a system – the Global Integrated Geodetic and Geodynamic Observing System (GIGGOS) [25] that in addition integrates gravity, remote sensing and levelling techniques, became a key point for the IAG IGGOS project adopted by the Resolution 3 of the XXIII IUGG General Assembly in Sapporo in 2003 [6]. The project will become operational in 2005. The basic structure of the project (Fig. 2) indicates the key role of reference systems in positioning.

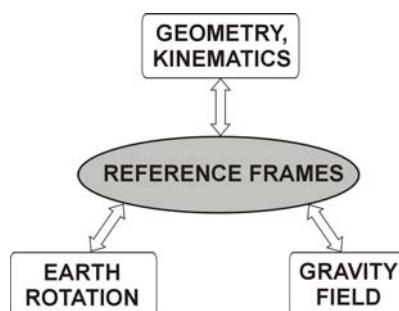


Fig. 2. The key role of reference systems in positioning

## MAJOR NEW CONCEPTS OF REFERENCE SYSTEMS

The works on new reference systems at a microarcsecond level of accuracy have been stimulated by the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG) and started in early 1980. The XXIV IAU General Assembly in Manchester in 2000, recommended to replace on 1 January 2003 the existing reference systems with the International Celestial Reference System (*ICRS*), adapted by the IAU [13].

The IAU recommendation has later been approved by the XXIII IUGG General Assembly in Sapporo in 2003 [18]. The International Terrestrial Reference System (*ITRS*) is the monitored by the IERS Conventional Terrestrial Reference System (*CTRS*), defined in the Resolution 2 of the XX IUGG General Assembly in Vienna in 1991 [5] and adapted by IUGG.

### INTERNATIONAL CELESTIAL REFERENCE SYSTEM *ICRS*

New celestial reference systems are built up on the basis of the relativistic theory of astronomical reference systems, e.g. [16], [1]. Those systems of space-time curvilinear coordinates ( $x^0 = ct, x^1, x^2, x^3$ ), centered at the barycenter of an appropriate ensemble of masses, are defined, including their metric tensors, within the framework of general theory of relativity. The geometry of space-time is determined by means of a generalized quadratic form [21]:

$$ds^2 = -c^2\tau = g_{ik}dx^i dx^k$$

where  $c$  is the speed of light in vacuum,  $t$  is coordinate time,  $\tau$  is proper time, and the coefficients  $g_{ik}$  ( $i, k = 1, 2, 3$ ) of the metric tensor are functions of spatial coordinates  $x^1, x^2, x^3$  and of time coordinate  $x^0$ .

The *ICRS* is the system of a kinematically fixed orientation with respect to 212 defining extragalactic sources [12]. The *ICRS* is aligned to the FK5 at J2000.0 within the FK5 errors [26]; its pole almost coincides with the FK5 pole at J2000.0 (differs by + several dozens of milliarcseconds) and the *ICRS* origin of right ascension almost coincides with equinox of the FK5 (differs by about +23 mas) [14]. The *ICRS* has replaced quasi-Cartesian reference systems of fundamental catalogues, defined on the basis of Newtonian mechanics. The main differences between the “old” and “new” celestial reference systems are summarized in Table 1.

The *ICRS* consists of the ensemble of the Barycentric Celestial Reference System (*BCRS*) and the Geocentric Celestial Reference System (*GCRS*) [17] with coordinate times Barycentric Coordinate Time (*TCB*) and Geocentric Coordinate Time (*TCG*), respectively. The relation between the *BCRS* and the *GCRS* is given by the post-Newtonian Lorentz transformation, specified in the Resolution B1.3 of the XXIV IAU General Assembly [13]. The axes of those systems fulfil the condition of zero mutual kinematic rotation. The *BCRS* is a quasi-inertial system created for the solar system; it is by definition kinematically fixed. The *GCRS*, devoted for the Earth, is in motion around the barycenter but has fixed directions with respect to extragalactic sources. It does not depend on varying in space direction of Earth rotation axis, what was the case of the FK5.

**Table 1.** Major differences between the “old” and “new” celestial reference systems

“old” systems	“new” systems
accuracy at the level of <b>milliarcsecond</b>	accuracy at the level of <b>microarcsecond</b>
derived from <b>Newtonian mechanics</b> (with relativistic corrections)	derived from <b>general relativity</b>
reference system: <b>FK5</b>	reference system: <b>ICRS</b>
<b>dynamical</b> system (defined using the solutions of the planetary equations of motion and positions of briget stons)	<b>kinematical</b> system(defined through positions of extragalactic objects)
<b>varying</b> with respect to inertial system (defined for the epoch)	kinematically <b>fixed</b> with respect to inertial system (negligible proper motion of extragalactic objects)
system axes referred to two moving planes: <b>equator</b> and <b>ecliptic</b> (their intersection defines <b>equinox</b> ) – at the epoch	system axes referred to <b>fixed ICRS pole</b> (almost coinciding with theFK5 pole at J2000.0) and <b>fixed ICRS origin of right ascension</b> (almost coinciding with equinox of the FK5 at J2000.0)

The *ICRS* is materialized by the International Celestial Reference Frame (*ICRF*). A realization of the *ICRF* consists of a set of precise coordinates of 212 extragalactic defining sources, derived from a large number of observations over a long data span [14]. The Barycentric Celestial Reference Frame (*BCRF*) and the Geocentric Celestial Reference Frame (*GCRF*) represent the realizations of *BCRS* and *GCRS*, respectively. The relation between the *BCRF* and *GCRF* is given by generalized Lorentz transformation. To tie optical observations to the *ICRF*, the Hipparcos Catalogue was chosen as the primary realization of the *ICRS* at optical wavelengths. Resolution B1.2 of the XXIV IAU General Assembly [13] defined the stars of the Hipparcos Catalogue that realize the Hipparcos Celestial Reference Frame (*HCRF*).

### THE IAU2000 PRECESSION-NUTATION MODEL

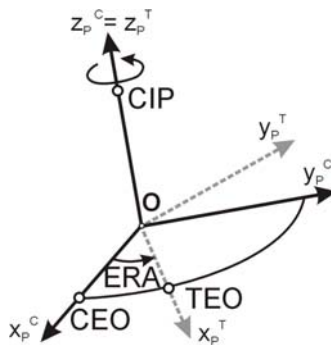
The IAU2000 precession-nutation model [4] has replaced the IAU1976 precession model and the IAU1980 nutation theory. The new precession-nutation model differs from the ones previously used, not only in terms of its accuracy but also in its content. It consists of the precession terms, the forced nutation terms of periods longer than 2 sidereal days, and also the coupling precession/nutation terms [2]. The higher frequency terms of forced nutation have been included in polar motion. The IAU2000 precession-nutation model, together with pole offsets estimated from observations, describe the motion of the primary axis of the Intermediate Reference System (*IRS*) with respect to the *GCRS*.

**INTERMEDIATE REFERENCE SYSTEM *IRS***

Primary axis of the *IRS* (Fig. 3) that was defined by the Celestial Ephemeris Pole<sup>2</sup> (*CEP*), has been replaced by the Celestial Intermediate Pole (*CIP*) that determines the equator of the *IRS*. The *CIP* at J2000.0 deviates slightly from the *GCRS* (*ICRS*) pole, in accordance with the IAU2000 precession-nutation model.

The Celestial Ephemeris Origin (*CEO*) that represents the origin of right ascension in the *IRS* equator (given by the *CIP*) has been defined in the Resolution B1.8 of the XXIV IAU General Assembly [13], with use of the theory of the “non-rotating origin” [7]. It defines the direction of the secondary axis of the celestial *IRS*. The *CEO* at J2000.0 deviates slightly from the *GCRS* (*ICRS*) origin of right ascension, in accordance with the IAU2000 precession-nutation model.

Secondary axis of the terrestrial *IRS* (Fig. 3) coincides with the Terrestrial Ephemeris Origin (*TEO*), defined also in the Resolution B1.8 of IAU. The definition of the *TEO* is also based on the theory of “non-rotating origin” of Guinot. The *TEO* represents the origin of longitude in the terrestrial *IRS*<sup>3</sup>. With rotating Earth, the terrestrial *IRS* rotates about its primary axis (*CIP*), while the celestial *IRS*, having the same primary axis, remains fixed. The angle between the directions to the *TEO* and to the *CEO* from the geocenter, called the Earth Rotation Angle (*ERA*) (Fig. 3), is the measure of actual Earth rotation. The *ERA* has replaced Greenwich Sidereal Time<sup>4</sup> (*GST*) as the parameter of transformation between the terrestrial *IRS* and the celestial *IRS*. Position of the *TEO* with respect to zero-meridian of the *ITRS* is determined with use of the IERS Earth rotation parameters.



**Fig. 3.** The Intermediate Reference System (C-celestial, T-terrestrial)

<sup>2</sup> The *CEP* has replaced the instantaneous Earth rotation in 1984 as the primary axis of the *IRS*.  
<sup>3</sup> The instantaneous Greenwich meridian played a role of the terrestrial ephemeris origin when the instantaneous Earth rotation was used as a primary axis of the *IRS*.  
<sup>4</sup> *GST* is also known as Greenwich Apparent Sidereal Time *GAST*.

The implementation of the *ERA* as a parameter of transformation between the terrestrial *IRS* and the celestial *IRS* has resulted in new definition of *UTI*. As the *ERA* increases linearly if the rotation of the Earth is uniform, *UTI* is defined as a linear function of the *ERA*. The constant coefficient of proportionality is being chosen so that a day of *UTI* is close to the duration of the mean solar day. The conventional relationship between the *ERA* and *UTI* theoretically ensures continuity in phase and rate of *UTI* with the value obtained by the previous conventional relationship between Greenwich Mean Sidereal Time (*GMST*) and *UTI* [3].

### **POLAR MOTION AND EARTH ROTATION**

To link the terrestrial *IRS* with the *ITRS*, the instantaneous position of the moving Earth pole (the *CIP*, formerly the *CEP* or instantaneous Earth rotation axis) with respect to the fixed *ITRS* pole is needed. In addition, the transformation between the terrestrial *IRS* and the celestial *IRS* requires actual velocity of Earth rotation. Since both polar motion and Earth rotation are quite irregular, they need to be continuously monitored. Recently Earth rotation parameters are determined and provided by the IERS. They are derived from the observations acquired in the framework of VLBI, IGS and laser ranging IAG services.

The coordinates  $x_p$  and  $y_p$  of the *CIP* in the *ITRS* at epoch  $t$  are defined as

$$(x_p, y_p) = (x, y)_{\text{IERS}} + (\Delta x, \Delta y)_{\text{tidal}} + (\Delta x, \Delta y)_{\text{nutatation}}$$

where  $(x, y)_{\text{IERS}}$  are pole coordinates provided by the IERS (available in the IERS bulletins),  $(\Delta x, \Delta y)_{\text{tidal}}$  are the components due to ocean tides, and  $(\Delta x, \Delta y)_{\text{nutatation}}$  are high frequency free nutation terms that are excluded from the IAU2000 precession-nutation model [14].

### **INTERNATIONAL TERRESTRIAL REFERENCE SYSTEM *ITRS***

The *ITRS* is a kinematic quasi-Cartesian system rotating with the Earth in its diurnal motion in space. In that system, coordinates of points attached to the solid surface of the Earth undergo only small variations with time, due to geophysical effects, e.g.; tectonic deformations, tidal deformations. *TCG* – the coordinate time of the *GCRS* is also the coordinate time of the *ITRS*. The origin of the *ITRS* coincides with the geocenter of Earth's masses, including oceans and atmosphere [5].



The unit of length in the *ITRS* is the metre (SI). The scale of the *ITRS* is consistent with the *TCG* time coordinate for a geocentric local frame, and is obtained by appropriate relativistic modelling. The orientation of the *ITRS* is given by the Bureau International de l'Heure (BIH) orientation at 1984.0. The time evolution of the system orientation is ensured by using a no-net-rotation condition with regards to horizontal tectonic motions over the whole Earth [14]. Direction of primary axis of the *ITRS* is defined by the *ITRS* pole while the direction of its secondary axis is defined by the *ITRS* zero-meridian.

The International Terrestrial Reference Frames (*ITRF<sub>yy</sub>*), produced by the *IERS ITRS* Product Center, are the realizations of the *ITRS*. Up to date, the frames *ITRF88*, *ITRF89*, *ITRF90*, *ITRF91*, *ITRF92*, *ITRF93*, *ITRF94*, *ITRF95*, *ITRF96*, *ITRF97*, *ITRF2000* have been provided. Until 1993, the origins and the scales of the *ITRF* were determined from selected SLR solutions. The orientation of the frames was defined by successive alignment to the BIH EOP series (except the *ITRF93* whose orientation and its rate were alligned to the *IERS* EOP series). Orientation time evolution of the frames was initially not estimated so the AM0-2 model of global velocity field [24] was recommended. The *ITRF91* orientation rate was alligned to the NNR-NUVEL-1 model, and the *ITRF92* to the NNR-NUVEL-1A model. Starting from the *ITRF94*, the frame origins were determined as a weighted mean of selected SLR and GPS solutions, while the scale – as a weighted mean of VLBI, SLR and GPS solutions, corrected by 0.7 ppb to meet the IUGG and IAU requirement to be in the *TCG* time-frame instead of Terrestrial Time *TT*, used by the analysis centres. Orientation of the frames is alligned to the *ITRF92*. Orientation time evolution is alligned to the NNR-NUVEL-1A model, over the 7 rates of the transformation parameters [14]. The *ITRF* orientation and orientation time evolution determine the *ITRF* pole (simultaneously the *ITRF* equator) and the *ITRF* zero-meridian.

Regional terrestrial reference frames alligned to the *ITRS* are its important extension. An example is the European Terrestrial Reference System 89 (*ETRS89*) that includes European permanent tracking stations only. It has been defined as coincident with the *ITRS* at epoch 1989.0, and fixed to the stable part of the Eurasian Plate. The realization of the *ETRS89* is the European Terrestrial Reference Frame 89 (*ETRF89*) that became an official spatial reference system for geodesy, navigation, surveying and mapping in most European countries.

## TIME SYSTEMS

There are many different requirements for time, e.g. for physics, navigation, astronomy, communication, geodesy and space sciences, and in addition to provide civil time. Time scale should be based on the available, reliable and sufficiently long-term operating stable standard (clock); it is expected to be uniform. Astronomical time scales that used Earth rotation or orbital motion of the Earth and planets, as “clocks” are not uniform. They are still used to monitor Earth rotation, to link terrestrial with celestial reference frames both recently and historically. They also provide time unit, compatible with civil time requirements (the Sun in upper culmination at noon), used for scaling atomic standards that exhibit substantially better short-term stability than astronomic “clocks”. Since 1958 the International Atomic Time scale (*TAI*), recently derived from over 200 atomic standards by the Bureau International des Poids et Mesures (BIPM), is the basis of time scales. Recently used time systems (atomic time systems with purple and astronomic time systems with yellow) together with their interrelations are schematically shown in Fig. 4.

Coordinated Universal Time (*UTC*) the atomic time, derived by periodically subtracting leap seconds [19] from *TAI*, as time close to solar time, is the basis of civil time.

Zonal Time (*ZT*), e.g. Central European Time, that since 1964 is the atomic time (earlier it was mean solar time), is shifted with respect to *UTC* by integer (in most cases) number of hours  $\Delta Z$ , corresponding to the time zone.

GPS Time (*GPST*) is the atomic time of the NAVSTAR GPS system that runs since 1980. It is derived from the atomic standards of the US Naval Observatory, control stations of GPS system, and of GPS satellites. *GPST* was aligned to *UTC* on 6 January 1980. Due to different standards generating time systems, *GPST* differs from *TAI* not only by a constant (19 s) but also by a time varying term  $\Delta C_0$  of the order of 10 ns. The offset of *GPST* from *UTC* is continuously broadcast in the navigation message modulating GPS signals.

Terrestrial Time (*TT*) is the atomic time that replaced in 1991 [11] Terrestrial Dynamical Time<sup>5</sup> (*TDT*) [9] as equivalent. *TT* is the proper time of the geocenter (of the *GCRS*). Its time unit, the day, has been chosen as equal to 86400 SI seconds at mean sea level. *TT* is fixed with respect to *TAI* (constant offset of 32.184 s).

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<sup>5</sup> *TDT* was used as reference for ephemerides referred to the geocenter. In 1984 the atomic time scale *TDT* has replaced Ephemeris Time (*ET*) that was a dynamic astronomical time, based on the orbital motion of the Earth around the Sun, and the orbital motion of the Moon around the Earth. *TDT* also has replaced *ET* as the basis of Quasi-uniform Universal Time (*UT2*) that is no longer in use.

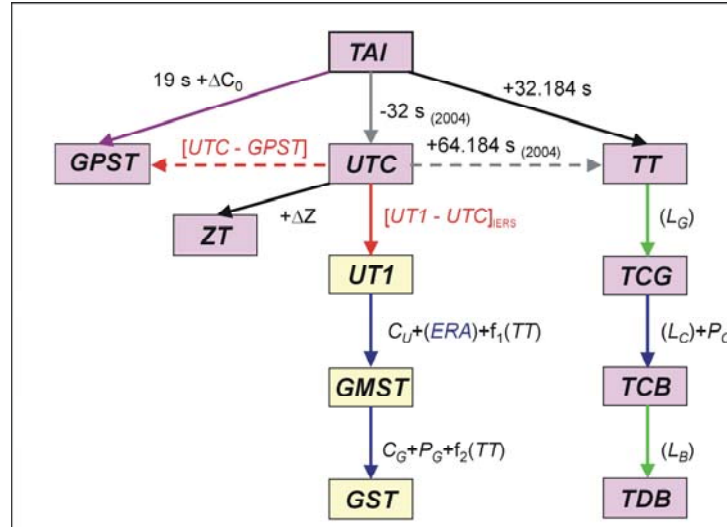


Fig. 4. Time systems

Geocentric Coordinate Time ( $TCG$ ) is the coordinate time of the  $GCRS$ ; it is a component of the relativistic metric of the  $GCRS$ .  $TT$  is defined as differing from  $TCG$  by a constant rate  $d(TT)/d(TCG) = 1 - L_G$ , i.e.

$$TCG - TT = L_G \times (JD^6 - 2\,443\,144.5) \times 86\,400$$

where  $L_G = 6.969\,290\,134 \times 10^{-10}$  became a defining astronomic constant [13].

Barycentric Coordinate Time ( $TCB$ ) is the coordinate time of the  $BCRS$ ; it is a component of the relativistic metric of the  $BCRS$ . The relation between  $TCG$  and  $TCB$  is a component of a full 4D generalized Lorentz transformation [13], [17]. According to the Recommendation III of the XXI IAU General Assembly, that relation can be approximated with an accuracy of  $10^{-14}$  with the formula [11]:

$$TCB - TCG = L_C \times (JD - 2\,443\,144.5) \times 86\,400 + P_1 + P_2$$

where the constant  $L_C$  defined from  $\langle TCG/TCB \rangle = 1 - L_C$  (the  $\langle \rangle$  operator represents averaging in the mass centre of the Earth over sufficiently long time) equals  $L_C = 1.480\,826\,867\,41 \times 10^{-8}$  ( $\pm 2 \times 10^{-17}$ ) [15],  $P_1$  is proportional to  $c^{-2}$  and is a function of the barycentric position and velocity of the Earth as well as the barycentric position of the observer, and  $P_2$  contains diurnal terms of amplitudes not exceeding  $2.1 \mu\text{as}$ .

<sup>6</sup> Julian Day in  $TT$ .

Barycentric Dynamical Time (*TDB*) is the atomic time that has replaced (*ET*) in 1984, as the time reference for ephemerides referred to the barycenter of the solar system, e.g. for ephemerides of the Moon and planets, and the argument of precession. *TDB* differs from *TT* only by periodic terms due to orbital motion of the Earth in the gravitational field of the Sun. According to the Recommendation III of the XXI IAU General Assembly, the relationship between *TDB* and *TCB* is the following [11]:

$$TCB - TDB = L_B \times (JD - 2443144.5) \times 86400$$

where the constant  $L_B$  defined from  $\langle TT/TCB \rangle = 1 - L_B$  (the  $\langle \rangle$  operator represents averaging in the mass centre of the Earth over sufficiently long time) equals  $L_B = 1.550\,519\,767\,72 \times 10^{-8} (\pm 2 \times 10^{-17})$  [15].

Mean Universal Time (*UTI*) was defined in 1940, as the mean solar time of the instantaneous Greenwich meridian. *UTI* was referred to the instantaneous axis of Earth rotation. It represented Earth rotation about its instantaneous rotation axis. Originally, *UTI* was defined as a function of *GMST*. After atomic time became the basis of time scales in 1958, *UTI* was linked to *TAI* with use of [*UTI-TAI*] corrections, generated by the BIH from astronomic observations. Since 1964, *UTI* is linked to *UTC*. The [*UTI-UTC*] corrections were provided first by the International Polar Motion Service (IPMS) and after 1988, by the IERS. New definition of *UTI*, implemented on 1 January 2003 [13], that ensures the continuity of that time scale [3], states that *UTI* is a linear function of the *ERA*:

$$ERA(T_u) = 2\pi(0.779\,057\,273\,2640 + 1.002\,737\,811\,911\,354\,48 T_u)$$

where

$$T_u = [JD(UTI) - 2\,451\,545.0]$$

*UTI* is obtained by adding [*UTI-UTC*] correction to *UTC*:

$$UTI = UTC + [UTI - UTC]$$

Greenwich Mean Sidereal Time<sup>7</sup> (*GMST*) had to be re-defined, due to implementation of new reference systems that are no longer referred to vernal equinox. *GMST* is expressed as a sum of a linear function of the *ERA* and periodic functions of *TT*:

$$GMST = 0''.014\,506 + ERA + 4612''.157\,399\,66 t + 1''.396\,677\,21 t^2 - 0''.000\,093\,44 t^3 + 0''.000\,018\,82 t^4$$

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<sup>7</sup> Before 1 January 2003, the definition of *GMST* specified in the Resolution C5 of the XVIII IAU General Assembly (IAU, 1983) was used.

where

$$t = (TT - 2000 \text{ January } 1^{\text{d}}12^{\text{h}} TT)/36\,525$$

and  $TT$  is in days.  $GMST$ , according to its new definition, is no longer the hour angle of mean vernal equinox at the Greenwich meridian [3]. The role of  $GMST$  has been reduced to keeping continuity in astronomic computations. In particular,  $ERA(J2000.0) = GMST(J2000.0)$ , and  $GST - ERA$  corresponds to the right ascension of the  $CEO$ , so it determines the position of vernal equinox in the  $CIP$  equator. New definition of  $GMST$  is compatible with the new definition of  $UTI$ .

Greenwich Sidereal Time  $GST$  is now expressed as

$$GST - GMST = \Delta\psi \cos \varepsilon_A + \sum[(C'_{s,0})_k \sin\alpha_k + (C'_{c,0})_k \cos\alpha_k] - 0''.000\,000\,87 t \sin\Omega$$

where  $\varepsilon_A$  is a precession quantity in obliquity [22] corrected by precessional variations defined by the IAU2000 precession-nutation model,  $\Delta\psi$  is the nutation angle in longitude, referred to the ecliptic of epoch, so  $\Delta\psi \cos \varepsilon_A$  represents the classical „equation of the equinoxes”. The two last terms in the above equation are the complementary terms to be added to the current „equation of the equinoxes” to provide the  $GST$  with microarcsecond accuracy [23]. Quantities  $\alpha_k$  and  $\Omega$ , and coefficients  $(C'_{s,0})_k$  and  $(C'_{c,0})_k$  are given in literature, e.g. [14], as well as in the electronic version on the web site <http://maia.usno.mil/ch5tables.html>

### COMPUTATION OF APPARENT PLACES

The link between apparent places and the catalogue positions of the stars determines the procedure of apparent places computations. That procedure has substantially been changed after implementing new reference systems (Fig. 5).

In the classical approach, the FK position of a star, the so-called mean place at epoch  $T_0$  of the catalogue, was given in the barycentric system of the catalogue, with coordinate axes oriented by the mean equator and mean equinox of epoch  $T_0$ . Rotation by precession parameters and spherical (2D) proper motion, had transformed mean place at epoch  $T_0$  into mean place at epoch  $T$ , that was given in the barycentric system with coordinate axes oriented by the mean equator and mean equinox of epoch  $T$ . Next, rotation by nutation parameters had transformed mean place at epoch  $T$  into true place at epoch  $T$ . The true place was given in the barycentric system with coordinate axes oriented by the true equator and true equinox of epoch  $T$ . Finally, the rotation due to annual paralax and annual aberration had transformed true place at epoch  $T$  into apparent place at epoch  $T$ . Apparent places were given in the geocentric system with coordinate axes oriented by the true equator and true equinox of epoch  $T$ .

The new approach – the IAU2000 approach of computing apparent places, differs substantially from the classical one. The mean place of a star is given now at epoch J2000 in the *ICRS* (*BCRS*), i.e. in the barycentric system with coordinate axes oriented by the *ICRS* pole and the *ICRS* origin of right ascension, that are aligned to the axes of the FK5 catalogue at J2000.0 with accuracy of a few dozens of milliarcseconds. Computation of apparent places consists of three major steps.

The first one concerns the correction of position due to spatial proper motion (3D) over time offset of  $T$  (expressed in *TCB*) from J2000.0. It results in determining mean place at epoch  $T$  in the *BCRS*. In the second step, the generalized Lorentz transformation transforms the *BCRS* into the *GCRS*, providing mean place at epoch  $T$  (expressed now in *TCG*) in the *GCRS*. Up to that point, orientation of coordinate axes remains unchanged; the origin of the reference system has been moved in the process of Lorentz transformation from the barycenter to the geocenter.

The final step concerns transformation of the *GCRS* into the celestial *IRS*. The transformation parameters are obtained from the IAU2000 precession-nutation model. This step transforms mean place at epoch  $T$  in the *GCRS* into apparent place at epoch  $T$  in the celestial *IRS*. Thus, according to new approach, apparent places are given in the geocentric system with coordinate axes oriented by the *CIP* and the *CEO* of epoch  $T$ .

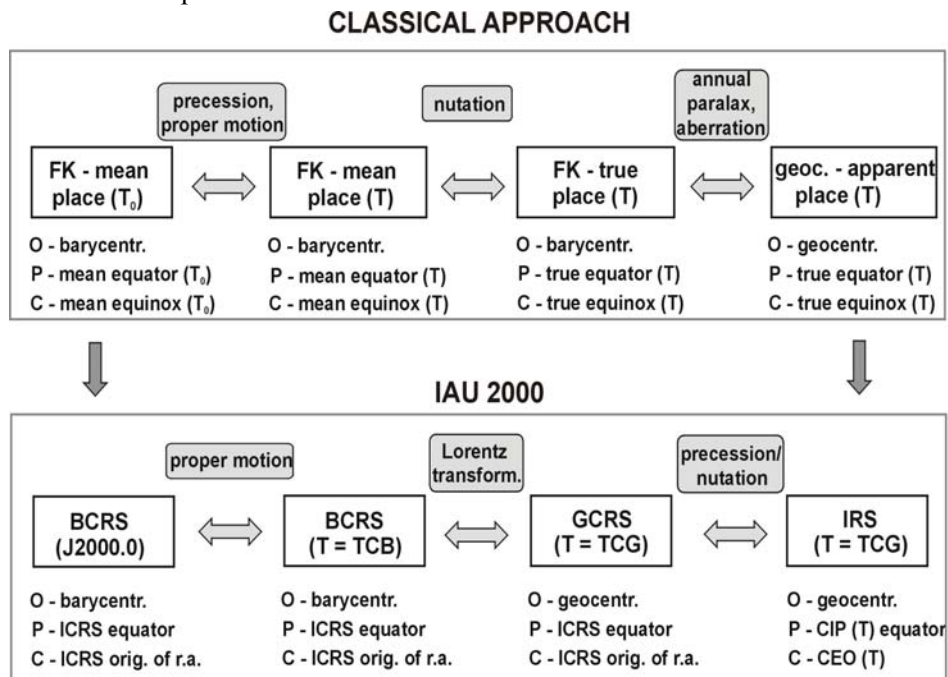


Fig. 5. Process of computation of apparent places according to the classical approach and the IAU2000 approach

Apparent places computed using the classical approach and the IAU2000 approach are referred to different reference systems. In practice, however, with accuracy not exceeding 1 mas, the equators of those systems can be considered coinciding. It results in equality of declinations in both types of apparent places. The difference in right ascensions can easily be computed as a difference of *GST* and the *ERA* at epoch *T*.

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