The celestial reference system and its role in the epoch of global geodetic technologies

Jerzy B. Rogowski\textsuperscript{1}, Aleksander Brzeziński\textsuperscript{1,2}

\textsuperscript{1}Warsaw University of Technology, Faculty of Geodesy and Cartography
\textsuperscript{2}Space Research Centre, Polish Academy of Sciences, Warsaw

e-mail: j.rogowski@gik.pw.edu.pl, alek@cbk.waw.pl

Abstract. The paper discusses the role of celestial reference systems in astrometry, space and satellite geodesy. A historical review of the fundamental systems and methods for implementing international celestial reference systems (ICRS), from classical astrometry to VLBI, are presented. The paper emphasizes the role of celestial reference frames as a realization of the inertial frame. The definition of the ICRS and its realisation ITRF are also briefly discussed. The accuracy of contemporary realizations of ICRF are considered.

1 Introduction

After the launch of the first artificial satellite of the Earth in 1957, new technologies based on space geodetic observations have been introduced to geodesy. The celestial reference system defined by the fundamental star catalogues was no more adequate for current accuracy requirements. The last fundamental catalogue FK5 was replaced in 1997 by the International Celestial Reference System (ICRS); see (Ma and Feissel, 1997) for details. The ICRS is realized by coordinates of the extragalactic radio sources derived from Very Long Baseline Interferometry (VLBI) observation technique and assuming its origin in the barycenter of the solar system. This realization, designated International Celestial Reference Frame (ICRF), allowed to determine the position of an artificial satellite in space with accuracy of a few centimeters.
The extragalactic radio sources are so distant that their proper motions are practically undetectable. Therefore when using them as fiducial objects it is possible to define the ICRF axes with stable directions within 20 microarcseconds (µas). This feature along with high accuracy of the conventional precession-nutation model causes that ICRF is the best realization of the inertial system available now. 

As a realization of the inertial system, the ICRF can be used to express the equation of the satellite motion in space (e.g. Seeber, 2003)

\[ \ddot{\mathbf{r}} + \mu \frac{\mathbf{r}}{|\mathbf{r}|^3} = \mathbf{a}_p, \]  

(1)

where

- \( \mathbf{r} \) – vector defining position of the satellite with respect to the Earth’s center of mass,
- \( \ddot{\mathbf{r}} \) – second time derivative of \( \mathbf{r} \),
- \( \mu \) – Earth gravity constant (\( \mu = GM \) with \( G \) – gravity constant, \( M \) – mass of the Earth),
- \( \mathbf{a}_p \) – vector of acceleration caused by the perturbing forces.

The integration of Equation 1 with respect to time yields the instantaneous position of the satellite in the ICRS. In order to determine the position in the International Terrestrial Reference System (ITRS) it is necessary to perform the appropriate transformation. First, the origin of ICRS is moved to the geocenter obtaining the so-called Geocentric Celestial Reference System (GCRS). Then, a sequence of rotations is applied. In this step the conventional models defined by the IERS Conventions (2010) (Petit and Luzum, 2010a) and the Earth Orientation Parameters (EOP) provided by the International Earth Rotation and Reference Systems Service (IERS) are used.

The dominant part of transformation is the conventional precession-nutation model with the recently adopted version IAU 2006/2000 (IAU - International Astronomical Union). The nominal accuracy of the IAU 2006/2000 model, when using its full version “A”, is 0.3 milliarcsecond (mas) in position of the axis in space (Petit and Luzum, 2010a). This accuracy is understood as the values of residuals determined by VLBI and expressed as the so-called
celestial pole offsets. The residuals express both imperfections of the conventional model and the unmodeled physical signal. The main component of the signal is the Free Core Nutation (FCN), the resonant oscillation excited probably by the dynamically coupled system atmosphere-ocean; see e.g. (Brzeziński, 2005). The FCN signal, which is a counter-part of the free Chandler wobble in polar motion, cannot be modeled rigorously due to its random character. The IERS provides the empirical FCN model which can be used in the transformation between the GCRS and ITRS, but this model is not considered a part of the conventional precession-nutation model.

The amplitude of the FCN is variable within the range from 0.1 up to 0.5 mas. Its mean value over 1984-2010 is equal to 0.18 mas. Therefore the true accuracy of the precession-nutation model is several times higher than the declared 0.3 mas, say of the order of 0.05 mas. An obvious source of model imperfections are geophysical effects including those excited by the ocean tides. If we assume the Earth to be a rigid body without atmosphere and oceans, the accuracy of the precession-nutation model is better than 1 microarcsecond. From the practical point of view, the highest accuracy of the precession-nutation matrix (0.05 mas corresponding to 1.5 millimeter at the planet surface) is obtained when the IAU 2006/2000A model is applied along with the observed celestial pole offsets. If, however, the transformation GCRS-ITRS is applied in real time or at future epochs, the estimates of the celestial pole offsets are not available and the accuracy of the precession-nutation matrix remains at the level of 0.3 mas.

After some simplifications, the measurement of position of the celestial objects derived on the basis of position defined in the ITRF differ by the vector of deformation (Fig. 1).

- \( P' \) – instantaneous position of the point at the Earth surface,
- \( P \) – position for a given epoch expressed by the coordinates in the ITRF,
- \( \vec{R}, \vec{R}' \) geocentric vectors of \( P \) and \( P' \),
- \( \vec{dR} \) deformation vector,
- \( \vec{r} \) geocentric vector of the satellite,
Figure 1. The influence of deformation on the position of the artificial satellite

- $\vec{D}'$ vector between the true position of observer and the satellite
- $\vec{D}$ vector between the position of observer in ITRF and the satellite.

The equation

$$\vec{D} = \vec{D}' + \vec{dR}$$

(2)

defines the influence of deformation upon the observation vector.

The main factors causing deformation of the Earth are (Kryński and Rogowski, 2004):

1. Earth tides, including
   - solid Earth tides ±25 cm,
   - influence of ocean tides ±1.5 cm,
   - contribution from atmospheric tides ±1 mm.

2. Nontidal effects caused by
   - hydrology effects ±1.5 cm,
   - atmospheric loading ±1.5 cm.
3. Tectonic motions

- caused by rotation of the plate – in stable part of the EURA plate 3 cm/year,
- inter-plate motions, for EURA up to 1 cm/year on the boarders, and ±1.5 mm/year inside the plate.

2 From fundamental star systems to ICRS

Before the advent of space geodesy, the orientation of the reference system had been determined by methods of optical astrometry. The realization of the celestial reference system had been provided by the fundamental system of selected star catalogue. The most frequently used catalogues were those belonging to the series FK worked out at the Astronomical Institute in Heidelberg, Germany.

The fundamental system were not the solution which could be applied for recent satellite techniques for the following reasons:

- too low accuracy, limited by the atmospheric influence,
- strong correlation between the star proper motion and the precession constant,
- large uncertainty of the precession constant, causing rotation of the coordinate system.

The last system based on classical astrometry was that defined by the catalogue FK5 (Fricke et al., 1988) referred to the epoch J2000 and using the precession model IAU1976.

The astrometric observations had been corrected for refraction derived from the models based on meteorolgical parameters measured at the stations. When taking into account a complicated nature of the refraction phenomenon it becomes clear that such a method introduced significant errors caused by differences between the model and real state of the atmosphere.

An important attempt to eliminate the refraction errors caused by distortion of light rays crossing the whole atmosphere, particularly its lowest layers, was the ESA satellite mission Hipparcos launched in 1989 and operated between 1989 and 1993 (ESA, 1997).
Based on the mission results, new star catalogue had been developed referring to the epoch 1991.25, assuming the equator and ephemeris origin of ICRS 2000 and adopting the system of astronomical constants IAU1976. However, due to the short epoch span of Hipparcos observations (less than 4 years) the proper motions of many stars affected by multiplicity are unreliable in the Hipparcos Catalogue. It was decided to merge the catalogues FK5 and Hipparcos. The resulting catalogue FK6 (ESA, 1997; Wielen et al., 1999) adopted the equator and ephemeris origin of the ICRS 2000, star positions and parallaxes from the catalogue Hipparcos, while the proper motions from the catalogue FK5.

Finally we should mention that according to the resolution B2 of the IAU General Assembly in 1997 in Kyoto (IAU, 1998), the Hipparcos catalogue is the primary realization of the ICRS at the optical wavelengths.

Further details about the fundamental star systems and the ICRS can be found in the review papers by Kołaczek (2004).

3 The role of celestial reference systems in astrometry and space geodesy

The celestial reference system played an important role during time of optical astrometry measurements and application of traditional methods of geodetic measurements. The system was necessary for realization of the following tasks:

- determination and improvement of the parameters describing Earth rotation (precession constant, nutation, position of the instantaneous pole with respect to the planet surface i.e. polar motion, determination of the time connected to Earth rotation;
- keeping the mean terrestrial reference system invariable with respect to the figure of the Earth;
- reduction of the astronomical observations to the mean terrestrial reference system enabling correction of the orientation of geodetic system with respect to the mean rotation axis, as well as determination of the geographic latitude and longitude
Figure 2. Influence of selection of origin station for position of geodetic datum
($\Phi = \varphi, \ \Lambda = \lambda, \ \vec{N} = 0, \ A = \alpha$)

(those procedures require the knowledge of polar motion and the time related to Earth rotation);

- the earlier tasks were realized by application of the following Laplace equation yielding the orientation of geodetic networks:

$$A - \alpha = (\Lambda - \lambda) \sin \varphi$$  \hspace{1cm} (3)

where: $A$ – geodetic azimuth,
$\alpha$ – astronomic azimuth,
$\Lambda$ – geodetic longitude,
$\lambda$ –astronomic longitude,
$\varphi$ – astronomic latitude.

At the time of triangulation methods the origin of geodetic reference system was not adjusted to the center of the Earth masses, in general. Its position depended on geodetic data adopted for relating the geoid with the ellipsoid, i.e. the geodetic datum origin.

In the epoch of the space geodesy techniques (satellite laser ranging, technologies of the Global Navigation Satellite System - GNSS, VLBI) it became necessary to define a new high-precision ICRS
and its practical realization ICRF. The ICRF is defined by coordinates of selected extragalactic radio sources observed by VLBI. The following tasks could be achieved thanks to the availability of the ICRF:

- determination by the techniques of satellite geodesy of the coordinates of the point at the Earth surface with accuracy better than $10^{-9}$ of Earth radius and time derivatives of the coordinates with accuracy of 1 mm/year,
- determination of the EOP which are necessary in transformation between the celestial and terrestrial reference systems, with angular accuracy of 0.1 mas corresponding to relative accuracy of $2 \cdot 10^{-10}$.

4 Current realizations of the celestial reference system

The International Celestial Reference System was defined by Resolution B2 adopted by XXIII General Assembly of the IAU in Kyoto, 1997 (IAU, 1998). The ICRS became the standard celestial reference system in use since 1st January 1998. The same Resolution B2 of the IAU GA in Kyoto adopted the fundamental catalogue Hipparcos as a primary realization of the ICRS at optical wavelengths (IAU, 1998; Petit and Luzum, 2010). The kinematic realization of the ICRS for practical use, is the International Celestial Reference Frame with its most recent version ICRF-2 shown in Fig. 3 (Fey et al., 2009).

5 The role of the celestial reference systems in modern geodesy and navigation

ICRS is by assumption the kinematically-fixed system, therefore is not connected to any particular epoch as in case of the catalogue systems like FK5. The positions in the ICRS play the role of mean catalogue positions in classical fundamental systems referred to the mean equator and the mean vernal equinox referred to the standard epoch. However, in this case any particular reference epoch does not need to be applied. Variability of the position in the ICRS can be caused either by proper motion of the radio source (including
the effect of radial velocity) or by instabilities of its phase centre. Those properties of the ICRS cause that it is a perfect realization of the inertial system in a sense of the classical mechanics. It provides a reference for such purposes, like computation of the orbits of the artificial satellites, space navigation and compilation of the star catalogues, determination of star parallaxes and proper motions.

6 Current accuracy of realization of the inertial system

As it was mentioned earlier, ICRF-2 enables determination of the space directions with accuracy of $d\Theta = 10 \, \mu\text{as}$. As shown in Fig. 4, the corresponding accuracy of positions are:

- for the point at the surface of the Earth $dP = 0.3 \, \text{mm}$
- for the GPS satellite $dS = 1.2 \, \text{mm}$

7 Summary and conclusions

ICRF-2 is the celestial reference frame fulfilling very high accuracy and stability requirements imposed by modern space geodesy and navigation.

A certain problem waiting for solution is a low accuracy of realization of ICRS using the observations in the optical wavelengths.
Figure 4. The influence of the error in orientation of the system axes on position of the satellite and on position of the point on the Earth’s surface.
band. It is expected that new satellite mission GAIA (Turon et al., 2005; ESA, 2012; Fig. 5), scheduled for 2013, can be a significant step towards the solution of this problem.

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References

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