Comparision of “Old” and “New” Concepts: Reference Systems

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Abstract: As a consequence of the IAU 2000 resolutions, the old celestial dynamical reference system, materialized by the FK5, is replaced by the ICRS, which consists of the BCRS and the GCRS, both kinematically defined by the position of the same extragalactic radiosources. The relation between them involves the geodesic precession and nutation, and the Lense-Thirring precession. Then, the reduction procedures for the intermediate reference system to the GCRS and the BCRS are sketched. The effect of the galactic rotation is not taken into account.

1 The old and the new Reference Systems

From 1991 to 2000, the IAU has introduced, and progressively established in a well defined manner, a new reference system, the International Celestial Reference System (ICRS) and its associated frame, the International Celestial Reference Frame (ICRF). Ideally, a reference system is a set of space coordinates, which is fixed in some defined way, and a time scale. The theoretical background that allowed to construct such a *fixed* or *inertial* (following the old terminology) has evolved with time. Under the pressure of the improvement of the accuracy of observations, more sophisticated definitions of what space and time are in our environment became necessary.

The old system

The old system was essentially derived from Newtonian Mechanics. General Relativity was only superficially present under the form of so called *relativistic corrections*, which were treated as perturbations to Newtonian equations. Different time-scales were introduced (geocentric and barycentric), but the space coordinates were essentially Euclidean, even if corrections for geodesic precession and light deflection were introduced.

Actually, the main drawback of the old system was that the reference axes were based upon the position of two moving planes (equator and ecliptic) at some epoch. The consequence was that it was necessary to have a theoretically based motion of these planes. But sometimes, it was necessary to replace the equinox provided by the theory by an extrapolation of positions obtained by observations. This situation was particularly inconvenient for the definition of the equinox J2000.0, which had to be placed despite an erroneous constant of precession and an insufficient nutation/precession theory. The result is that there were three different equinoxes (the FK5 equinox and two different dynamical).

The reference system was theoretically dynamical, defined using the solutions of the planetary equations of motion with the condition that there is no Coriolis acceleration that would be caused by a rotation of the coordinate axes. The fiducial points defining the reference frame (the FK5) were stars, whose positions were not accurately linked to planets, in particular at high latitudes. So the FK5 was also constrained by a value of the Oort’s constants, which describe the differential rotation of the Galaxy in the vicinity of the Sun. This gave rise to the inconsistencies between the FK5 equinox, and those based upon dynamical theories.

The new system

The new system is kinematic, because it is defined through the positions of extragalactic objects, whose proper motions are assumed to be negligible in comparison with the accuracy of observations. The space-time is described by a metric tensor in the framework of the theory of General Relativity, which is a geometric theory, and does not imply dynamics in the definition of the reference system. The ICRS consists of the ensemble of the Barycentric Celestial Reference System (BCRS) and the Geocentric Celestial Reference System (GCRS), whose definitions, as well as their relationship in terms of a generalized Lorentz transformation, are given in the IAU Resolution B1.3 (2000). They have the particularity of being both kinematically defined by a set of extragalactic objects and realized by the ITRF in radio wavelengths. The axes are chosen in such a way that the discontinuity with the old ones is as small as observations permit.

2 The Barycentric Celestial Reference System

Let us first consider the BCRS. The axes are fixed in time. I suggest that the coordinates of an object in these axes are referred as right ascension and declination without any additional qualification. Since they are barycentric, stellar objects are not subject to parallax, and the only variations in the coordinates are due to their proper motions and the perspective acceleration effect. Therefore, one must still indicate the date t of the position: $\alpha(t)$ and $\delta(t)$. This date does not correspond to what used to be called *epoch*. Because the BCRS is, by construction, kinematically fixed, there is no epoch in the old sense (e. g. J2000.0 or B1950). which corresponded to the position of reference axes. Actually, the ICRS positions behave like the old mean places referred to the mean equator and equinox at a standard epoch, but here, there is no epoch involved.

The International Celestial Reference Frame

The frame realizing the ICRS is the ITRF, defined by the positions of extragalactic radiosources, assumed to be fixed. The optical realization is the Hipparcos Catalogue from which the problem stars have been removed. It is the Hipparcos Celestial Reference Frame (HCRF). The positions are in the ICRS, but the reference date t is 1991.25. So, to obtain the position of a star A at a date T observed with respect to n stars S_i, $i = 1$ to n, one must first transform the positions of S_i by the displacement due to their proper motions from t to T:

$$\begin{aligned}\alpha_i(T) &= \alpha_i(t) + \mu_\alpha(T - t),\\ \delta_i(T) &= \delta_i(t) + \mu_\delta(T - t).\end{aligned}$$

Similar precautions must be taken when the position of A is referred to stars of other catalogues such as TYCHO2 or AC2000, which are in ICRS, but whose reference date is different, and not necessarily J2000.0.

3 The Geocentric Celestial Reference System

Since observations are generally made from the Earth, they refer to the GCRS, which is consequently in motion around the barycenter. But since it has fixed directions with respect to extragalactic sources, there is a Coriolis-like effect from the relativistic theory of the transformation if we refer it to the BCRS. This transformation, given in the IAU 2000 recommendation B1.3 must be applied. In practice, it is the geodesic precession and nutation, and in some cases, also the Lense-Thirring precession. Both are, in essence, very different effects from the classical precession and nutation due to gravitational forces.

1. *Geodesic precession.* It is a rotation around an axis perpendicular to the ecliptic. Its magnitude is given by:

$$\psi_G = \frac{3}{2}\frac{Gm_\odot n}{c^2 r},$$

   where n is the mean motion of the Earth's orbit and r is the distance of the Earth-Moon system to the origin of the BCRS. Its value, a circular-orbit average, is

$$\psi_G = 19.194 \text{ mas per year.}$$

   There are also periodic terms in this transformation, called geodesic nutation, along the ecliptic, whose largest term is $\Delta\psi_G = -0.153 \sin l$, where l is the mean anomaly of the Sun.

2. *Lense-Thirring precession.* If the accuracy of observations is very high, it may be necessary to take into account the c^{-3} terms of the transformation. It is the Lense-Thirring precession corresponding to the gravitomagnetic field. Until now, it is neglected.

In describing the motions of artificial satellites or the Moon, one must use the GCRS. This *natural* reference system moves with the Earth around the Sun, so that the equations of motion of these bodies must take into account the Coriolis-like accelerations in the framework of General Relativity. Therefore, when writing the equations of motion of these objects, one must stay in the GCRS and not include the geodetic precession-nutation terms in the reduction algorithms. If one uses the IAU precession-nutation series in which geodesic precession is included, it will be necessary to subtract these terms, before using the observations for dynamical studies, but then include the additional accelerations in the equations.

4 The Instantaneous Axes of Reference

Earth based observations are normally referred to an instantaneous system of reference axes. In the old system, it was defined by the direction of the Celestial Ephemeris Pole (CEP) perpendicular to the true (instantaneous) equator and the true ecliptic as the origin on the equator. The new system is called Intermediate Reference System (IRS) with a slightly different pole (the Celestial Intermediate Pole, CIP) and, on the corresponding true equator, the Celestial Ephemeris Origin (CEO). In the general case, one wishes to transform the intermediate (or true) coordinates α_i and δ_i in the IRS into the BCRS coordinates α and δ. To do this, one must apply the IAU-2000 precession-nutation series and the geodesic precession-nutation. Both are actually included there. This is a simplification for the user, but may be misleading from the point of view of the physical interpretation. One must, of course, also apply the aberration correction and, if the stellar parallax is known, the parallactic correction as well. For the bodies of the solar system, the situation is more complicated and one should compute the planetary parallax and the light time in the BCRS.

5 Further Remarks

1. The motion of the barycenter of the solar system is not linear in its orbit about the center of the Galaxy. There is therefore a Coriolis-like acceleration, which gives rise to a *galactic* geodesic precession. It is not included in the definition of the ICRS. This means that on should either distinguish between a *natural* barycentric system from the BCRS, or to apply, in the dynamical representations of the motion of planets in the BCRS, the corresponding acceleration.

2. The ICRF provides a fixed coordinate system for computing solar system ephemerides. It is generally convenient to use a coordinate system based on an approximation to the principal plane of the solar system, like a fixed ecliptic, as used in the past. To be consistent with ICRS and its origin, a fixed ecliptic should be defined as a fixed plane through the origin of the ICRS with a fixed inclination ε_0 equal to the mean obliquity at J 2000.0.

3. Although the IERS will introduce the new system in 2003, the old system will continue to be used. It is not a satisfactory situation. All the new star catalogues are now published in the ICRS, which is not exactly the FK5 J2000.0 system. Astrometrists should be encouraged to shift entirely to the new system, including the IRS, to avoid misleading comparisons between results, and use systematically a completely consistent environment.