REFERENCE FRAMES

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Abstract. After a short introduction on the definition and the construction of a reference frame, the presentation concentrates on the actual construction of the new IAU conventional reference frame. The 1991 IAU resolutions on reference systems is reviewed and the present state of the implementation of these resolutions is discussed. The IERS extragalactic reference frame is described and we show that it fulfills the IAU requirements. The Hipparcos catalogue will be linked to this frame before the end of this year. The state of advancement of this job is presented.

All motions observed from the Earth as well as the motions of the Earth itself can be described only if they are referred to a system of coordinates which are supposed to be fixed or having a well known absolute time variations, that is to say with respect to something else that is fixed. But how can one decide whether there exists such a fixed system of coordinates and, moreover, that this property applies to the natural system which defines it? One can overcome this difficulty only by some assumption based on theoretical arguments which lead to consider that a certain physical structure has no rotation in the Universe. Even then, the question may arise whether the Universe is rotating as a whole. Theories predict that in any case, this rotation is very slow, far beyond the present observing capabilities.

This is the assumption that was taken by the International Astronomical Union in 1991 when it adopted a set of nine recommendations which include statements that the new celestial reference system will be based upon the

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positions of a number of distant extragalactic radio-sources such as quasars (Bergeron, 1992).

Another approach could have been made, following in this the classical precedent FK series which define the coordinate triad by imposing that the solution of equations of motions in the solar system have no centrifugal or linear acceleration. This was fine in Newtonian space, but in General Relativity theory this can have a meaning only in the tangential Euclidean space and provided that the gravitation field is small. The theory of dynamical reference systems in general relativity in presence of masses is a very complex problem, to be treated with respect to the metric tensor of space-time taking into account the motions of the masses themselves. The choice of the IAU has the advantage that it is only based upon the path of light and not on gravitating - and actually also rotating - objects.

The important point in the IAU resolution is the fact that it explicitly introduces General Relativity as the background for all theoretical and observational problems related to time and space. It actually imposed a reduced form of the metric which includes only second order terms in $1/c$

$$ds^2 = -c^2 d\tau^2 =$$

$$= -\left(1 - \frac{2U}{c^2}\right)\left(dx^0\right)^2 + \left(1 + \frac{2U}{c^2}\right)\left[\left(dx^1\right)^2 + \left(dx^2\right)^2 + \left(dx^3\right)^2\right] + \ldots$$

where $x^0 = ct, x^1, x^2$ and x^3 are the four space-time coordinates, τ is the proper time and U is the sum of the potential of the ensemble of masses of the system and of the tidal potential of external masses.

So from now on, any reference system should be devised so that comply with this description of space-time. This is the case of the celestial extragalactic system which is being designed, but must be also the case of any future dynamical system. The existing ones do not follow exactly the terms of the IAU resolutions, in particular in what concerns the barycentric and geocentric coordinate time scales: the newly defined TCB and TCG do not coincide with the previously used TDB and TDG. For instance, this applies to the dynamical system to which the series of DE200 ephemerides are referred.

The adoption of IAU resolutions incited JPL to modify its policy concerning the reference system. Starting with DE402, planetary ephemerides are rigidly constrained onto the IERS reference system (Standish, 1995). This system is based upon a number of positions of extragalactic objects such as quasars which are assumed to represent globally a fixed structure. Its tie with the preceding dynamic reference system used by JPL was determined with an accuracy of ± 3 mas for the z axis and ± 1 mas for x and y axes using VLBI and Lunar laser ranging observations (Folkner et al.,

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1994). The newest DE403 ephemerides, which have included some corrections to DE402, are of course also in this extragalactic system.

The tie did not include any time-dependent rotation. The evaluation of such a rotation would be a very interesting and important result. It would be obtained from a comparison of two reference systems built strictly within the framework of the IAU resolutions but based strictly upon each of the approaches (kinematic/extragalactic and dynamical/solar system).

However, reference systems, whatever the basics on which they are designed, are not accessible *per se* and one has to materialize them by assigning coordinates to some astronomical objects in the triad and the corresponding coordinate time selected, in other terms to implement a reference frame. How this is done has been described in many instances, and we shall not deal with this topic here. Let us only state that some new treatment of observations used in the DE ephemerides will be necessary. It is also expected that the 3000 accurate minor planet observations realized by Hipparcos should be an additional asset to such an undertaking.

Since it is the choice made by the IAU, and since it is in a good advancement stage, we shall now concentrate on the state of the art concerning what should become the next official IAU celestial reference frame and its optical extension.

The 1991 IAU resolution has set a certain number of conditions to the realization of such a reference frame.

1 - The space coordinate grids with origins at the solar system barycenter and at the centre of mass of the Earth show no global rotation with respect to a set of extragalactic objects.

2 - A list of candidates of such objects be established for 1994 General Assembly of the Union.

3 - The principal plane of the new conventional celestial reference system be as near as possible to the mean equator at J2000.0 and the origin in this principal place be as near as possible to the dynamical equinox of J2000.0.

4 - The positions of the extragalactic objects selected in accordance with point 2 and representing the reference frame be computed initially for the equator and equinox J2000.0 using the best available values of the celestial pole offset with respect to the IAU expressions for precession and nutation.

5 - The celestial reference system should be accessible to astrometry in visual as well as in radio wavelengths. It was in addition specified that as long as the relationship between the stellar optical and the extragalactic radio frames is not sufficiently accurately determined, the FK5 catalogue shall be considered as a provisional realization of the celestial reference system in optical wavelengths.

Let us see now to what extent these five conditions are or will be fulfilled in a foreseeable future. Since 1988, the International Earth Ro-

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tation Service (IERS) receives and analyses catalogues of extragalactic radio-sources obtained by several VLBI networks and compiled by different groups (GSFC/NASA, JPL, NGS/NOAA, USNO). It compares them, rotates the catalogues to a single reference system and computes a weighted mean catalogue. During the following years, the IERS sequence of catalogues rapidly converged in the sense that while the number of sources, and particularly the number of primary sources increased, the mean uncertainties of the positions has steadily and significantly decreased.

The rotation between these successive catalogues became also smaller and smaller and reached an rms of 0.002 mas between the 1994 and 1995 versions. They all were realization of a reference system called until 1994 ICRS (IERS celestial reference system at J2000.0, Arias et al., 1995). In the construction of its catalogues, IERS used the IAU conventional precession and nutation respectively defined in 1976 and 1980. Both are now known, from VLBI and lunar laser to be in error (3 mas per year for precession). Computations were performed showing that correct values of these quantities would change the position of the pole of the system by less than 20 mas. This figure is to be compared with the basic uncertainty of the FK5 pole which is estimated to be of the order of 50 mas. Similarly it was found that its offset from the mean equinox of epoch 2000.0 is 78 ± 10 mas. This is also compatible with the error of the FK5 equinox which is of the order of 100 mas as shown by comparisons with meridian and Hipparcos observations. From this, it results that ICRS complies with the conditions 3 and 4 within the uncertainties inherent in the FK5 system realization. Finally, this system is also barycentric and the IERS catalogues indeed show no global rotation of the sources included.

Considering this, the IAU working group on reference frames which met in February 1995 decided that the ICRS should be adopted as the new IAU celestial reference system under the name of ICRS (International Celestial Reference System). Actually, there were no other serious contender to ICRS and, in addition, since seven years at least, all the results concerning the Earth rotation were computed and published in this system. Because of the many implications of Earth rotation parameters in various aspects of astrometry and the Earth's dynamics, any other choice would have brought only unnecessary complications and artificial discontinuities at the time of the official adoption of the new system. Note that this decision implies that the DE400 series of JPL ephemerides are in this new international celestial reference system ICRS.

In the meantime, the work preparing the fundamental reference system progresses. As requested in the second item, a list of about 600 extragalactic sources was prepared and adopted in 1994 by the IAU. Now that the system is defined, the precise positions of these sources are being finalized and will be made available in October 1995 so that, at that time, all IAU conditions concerning the reference system and its realization in radio wavelengths will be met.

The only remaining condition concerns the extension to the stars in visual wavelengths. The best - and by far the best - catalogue of stellar positions, proper motions and parallaxes will be the Hipparcos catalogue including more than 115 000 stars with a median internal precision for each of these quantities in the range 1 to 1.5 mas or mas per year. If the reference system of this catalogue can be identified with ICRS, the last IAU reservation will be overcome. This work is in progress and should be finished by the end of 1995, date at which the Hipparcos catalogue should be completed and be entirely in the new ICRS (Lindegren and Kovalevsky, 1995). Seven methods are used to realize the link and compute the elements of two rotation matrices: the matrix R which rotates the arbitrary Hipparcos coordinate grid on ICRS and the matrix R' which is a linear function of time and which stops the rotation with respect to the extragalactic sources as a whole. These are:

1 - Comparison between positions and proper motions of radio-stars from Hipparcos catalogue and determined by VLBI. About 12 stars are used in this method and each element of R and R' is determined with an rms of 0.5 mas and 0.5 mas per year.

2 - The same method using observation by VLA and MERLIN radio interferometers.

3 - Computation of the elements of R' using the Lick, Yale and Kiev catalogues of proper motions determined with respect to galaxies from photographic observations. More than 8000 Hipparcos stars are in common with these catalogues and the uncertainty on R' seems at present to be significantly below 0.5 mas per year.

4 - Photography by a Schmidt telescope of radio sources of the primary catalogue. More than 100 plates involving approximately the same number of quasars are being analyzed for R and R'.

5 - Two or more epoch observations of specially selected areas of the sky involving Hipparcos stars and quasars. The epoch differences may reach 90 years giving conditions for R'.

6 - Hubble Space Telescope Fine Guidance Sensor observations of some Hipparcos stars with respect to quasars of known positions give information to determine R. Unfortunately, the observations started too late (April 1993) to allow precise determinations of R'.

7 - Comparing the observations of the Earth rotation with Hipparcos catalogue give information on R'. However the necessity to introduce the terrestrial reference frame as an intermediary induces possible systematic effects which are difficult to estimate.

Nine different teams in various countries are working to determine R and/or R' by one of these methods. It will be then necessary to adopt some relative weights for them before attempting a synthesis of the results.

In any case, this link will be realized (actually with the data available at present, an accuracy of 0.5 mas per year is already possible) so that at the end of 1995, the ICRS, the corresponding radio reference frame and the rotated Hipparcos catalogue will be ready, allowing the 1997 IAU general assembly to adopt them as the fundamental celestial reference system and frames.

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