RECENT PROGRESS IN ASTRONOMICAL NOMENCLATURE IN THE RELATIVISTIC FRAMEWORK

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ABSTRACT. Special topics of astronomical nomenclature related with relativity are discussed: the spatial orientation of the BCRS and GCRS, the problem of barycentric time scales TDB and T_{eph} and the notions of day, Julian date and Julian year.

1. THE SPATIAL ORIENTATION OF THE BCRS

The Barycentric Celestial Reference System (BCRS) was adopted by the International Astronomical Union in the year 2000 as basis for modelling high-accuracy astronomical observations, solar system spacecraft navigation, etc. Theoretically it is fixed by the form of the barycentric metric tensor (see, IAU, 2001; Rickman, 2001; Soffel, *et al.*, 2003 for more detail)

$$\begin{aligned} g_{00} &= -1 + \frac{2}{c^2} w(t,\mathbf{x}) - \frac{2}{c^4} w^2(t,\mathbf{x}) \,, \\ g_{0i} &= -\frac{4}{c^3} w^i(t,\mathbf{x}) \,, \\ g_{ij} &= \delta_{ij} \left(1 + \frac{2}{c^2} w(t,\mathbf{x}) \right) \,. \end{aligned}$$

Here the scalar function w generalizes the usual Newtonian gravitational potential and the vector function w^i describes gravito-magnetic type effects due to matter currents (moving masses). The BCRS is a particular reference system in the curved space-time of the solar system. From a mathematical point of view any kind of space-time coordinate system covering the solar system could be employed for practical applications. However, to avoid confusions and provide an unambigious way to interpret numerical values of various parameters (e.g. parameters of motion) a particular reference system should be fixed. This BCRS is a standard reference system adopted by the IAU. This does not mean, however, that other reference systems cannot be used. However, if some other reference system is used, the final results (numerical values of the parameters) should be transformed into the BCRS so that one can compare and/or combine these results with other results in a consistent way.

This BCRS is a dynamical concept in the sense that its metric tensor fixes the form of equations of motion for massive bodies as well as for light rays up to certain degrees of freedom.

The BCRS coordinates, as they are defined by the Resolution B1.3 of the IAU (2000) are fixed up to *constant change of the origin of time reckoning* and a *time-independent (constant) rotation of spatial coordinates*. In this sense the adoption of the BCRS is similar to adopting Newtonian equations of motion without Coriolis and centrifugal terms (i.e., to adopting a Newtonian inertial reference system) in the Newtonian framework. Another usual degree of freedom of an inertial reference system in the Newtonian framework is the choice the origin of spatial coordinates. For the BCRS, however, the origin is fully fixed to be the post-Newtonian barycenter of the solar system.

Now, the origin of time reckoning of the BCRS coordinate time t = TCB is also fixed by the definition of TCB, TT and TCG given by the IAU 1991 Resolutions. According to those Resolutions, on 1977 January 1, 00h 00m 00s TAI at the geocenter, the readings of TT, TCG and TCB are 1977 January 1, 00h 00m 32s.184 (JD 2443144.5003725).

However, the orientation of spatial axes was *not* fixed in the IAU (2000) resolutions. This orientation is irrelevant for physical laws, e.g., for equations of motion. Nevertheless this orientation is of major concern for astrometric problems. It is now recommended that this orientation is fixed by the ICRS. This means that in practice the spatial orientation of the BCRS is given by the ICRF, that is by the coordinates of a set of extragalactic sources obtained by VLBI observations. In the next decade the ICRF will be realized in the optical by the final Gaia catalog (ESA, 2004).

2. THE SPATIAL ORIENTATION OF THE GCRS

The Geocentric Celestial Reference System (GCRS) was adopted by the International Astronomical Union (2000) for modelling physical processes in the vicinity of the Earth and as intermediate step for relating the BCRS with the terrestrial system ITRS. The GCRS was constructed such that the gravitational fields of external bodies is represented only in forms of relativistic tidal potentials that grow at least quadratically with coordinate distance from the geocenter. The internal gravitational field from the Earth itself "coincides" with the gravitational field of a corresponding isolated Earth (in the absence of other bodies). The metric tensor of GCRS

$$\begin{aligned}
G_{00} &= -1 + \frac{2}{c^2} W(T, \mathbf{X}) - \frac{2}{c^4} W^2(T, \mathbf{X}) , \\
G_{0a} &= -\frac{4}{c^3} W^a(T, \mathbf{X}) , \\
G_{ab} &= \delta_{ab} \left(1 + \frac{2}{c^2} W(T, \mathbf{X}) \right)
\end{aligned}$$

is given by the geocentric metric potentials W and W^a. They can be split into internal-, inertial- and tidal- (external) parts. Again the GCRS is a dynamical concept and fixes the coordinates up to the degrees of freedom that we had discussed for the BCRS.

However, the IAU 2000 framework explicitly gives the complete form of the coordinate transformation between BCRS and GCRS. The implication of these coordinate transformations is that once the BCRS coordinates are fully fixed the GCRS coordinates are also fully fixed by the given coordinate transformation. If the BCRS is spatially oriented according to the ICRS the spatial coordinates of the GCRS, being kinematically non-rotating, will get an ICRS-compatible orientation.

It would be confusing and even dangerous to think that the GCRS has the *same* spatial orientation as the BCRS or ICRS. The reason is that the transformations between the BCRS and the GCRS are 4-dimensional time-dependent space-time transformations (for example, the

BCRS vector $(t, 1, 0, 0)$ is not transformed into the GCRS vector $(T, 1, 0, 0)$). The main part of the change of the GCRS spatial axes with respect to the BCRS axes comes from the Lorentz transformation. Therefore, the difference in spatial coordinates cannot simply be described by a shift in origin plus a 3-dimensional rotation. Formal differences in spatial coordinates will be of order $(v_E/c)^2 \sim 10^{-8}$ or a few mas in angle, v_E being the BCRS velocity of the Earth. These differences are automatically taken into account in high-precision relativistic models, e.g., for VLBI, astrometry etc.

3. DAY, JULIAN DATE, JULIAN YEAR AND JULIAN CENTURY

From the practical point of view it seems to be advantageous that day, Julian year and Julian century are just defined as multiples of the second: $1\,\mathrm{d} \equiv 86400\,\mathrm{s}$, 1 Julian year $\equiv 365.25\,\mathrm{d}$ and 1 Julian century $\equiv 36525\,\mathrm{d}$. With these definitions these time intervals or 'units' can be used with *any* time scale: with TCG, TT TCB and TDB or proper time of some observer.

Also the concept of Julian date can be used for any of these time scales. E.g., on 1977 January 1, $00^h00^m00^s$ TAI at the geocenter, the readings of TT, TCG and TCB are JD 2443144.5003725 (1977 January 1, $00^h00^m32^s.184$) and increase by 1 every 86400 seconds of the corresponding time scale. The equivalent $\mathrm{T_{eph}}$ reading depends upon the specific ephemeris: the same reading for TDB(DE405) is JD 2443144.5003725 $-$ 65.564518 μs. It is suggested to use the notations $\mathrm{JD_{TT}}$, $\mathrm{JD_{TCG}}$, $\mathrm{JD_{TCB}}$ and $\mathrm{JD_{TDB}}$ for the Julian dates in the corresponding time scales.

4. TDB AND $\mathrm{T_{eph}}$

Although the coordinate time TCB is a natural and physically adequate time scale for the use for solar system ephemerides for historical reasons another time scale (TDB) has been used for the same purpose. There has been a long and controversial discussion about the barycentric time scale TDB (Barycentric Dynamical Time). According to the original definition from 1976 TDB should differ from Terrestrial Time (TT) only by periodic terms. This implies, however, that TDB would not be a linear function of TCB. On the other hand the relativistic Einstein-Infeld-Hoffmann (EIH) equations of motion that form the basis of modern planetary ephemerides since about 1970 are valid only with TCB or a linear function thereof. After this was realized Standish (1998) introduced $\mathrm{T_{eph}}$ as reaction to this concern. By definition $\mathrm{T_{eph}}$ is a linear function of TCB. The rate and the offset between TCB and $\mathrm{T_{eph}}$, being dependent upon the particular ephemeris under consideration, were chosen so that $\mathrm{T_{eph}}-\mathrm{TT}$ remains as small as possible.

One can claim that TDB as defined in 1976 has never been used. Even the widely-used analytical formulas for TDB as function of TT by Hirayama et al. (1987) and by Fairhead & Bretagnon (1990) contain non-periodic terms (mixed and quadratic) while claiming that it is TDB that is realized .

The only good reason to have a scaled version of TCB is to avoid a secular drift between TT and the independent time argument of solar system ephemerides. Since TT (or TAI) is the time scale used by typical users on the Earth, the driving force for TDB is the idea to avoid in practice time scales deviating secularly. This idea, however, does not imply that the difference between that time argument and TT is purely periodic. It just means that the constants in the linear transformation between TCB and the time argument of solar system ephemerides should be chosen to minimize the differences between the latter and TT.

A natural way to relate TCB to TT and to find the optimal linear coeffients for a scaled version of TCB is a direct numerical integration of the TCB(TT) relation using some given solar system ephemeris. This way was discussed in details by Fukushima (1995) and Irwin &

Fukushima (1999). In this numerical approach it is not natural to distinguish between periodic, mixed, secular, etc. terms: TT is calculated as function of TCB.

The current situation with TDB and T_{eph} is unsatisfactory: (1) TDB as originally defined in 1976 is not compatible with widely-used equations of motion, (2) widely-used analytical realizations of TDB are not fully compatible with its original definition, (3) the linear transformation between T_{eph} and TCB is not a part of the definition of T_{eph}, but can be restored aposteriori, and, finally, (4) we have two different time scales for the same purpose. There are several ways to cure, clarify and simplify this situation. Ongoing discussions within the corresponding Working Groups of the IAU will hopefully achieve progress in this controversial question.

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