APPENDIX IAU, IAG AND IUGG RESOLUTIONS

Recommendations of the International Astronomical Union (IAU), the International Association of Geodesy (IAG) and the International Union of Geodesy and Geophysics (IUGG) related to topics in this document and passed at the 1991 General Assemblies of these organizations are listed below.

IAU Resolution

Resolution A4: Recommendations from the Working Group on Reference Systems

<u>Recommendations I to IX</u>

The XXI[st] General Assembly of the International Astronomical Union.

RECOMMENDATION I

<u>considering</u>

that it is appropriate to define several systems of space-time coordinates within the framework of the General Theory of Relativity,

<u>recommends</u>

that the four space-time coordinates ($x^0 = ct$, x^1, x^2, x^3) be selected in such a way that in each coordinate system centered at the barycenter of any ensemble of masses, the squared interval ds^2 be expressed with the minimum degree of approximation in the form:

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

where c is the velocity of light, τ is proper time, and U is the sum of the gravitational potentials of the above mentioned ensemble of masses and of a tidal potential generated by bodies external to the ensemble, the latter potential vanishing at the barycenter.

Notes for Recommendation I

1. *This recommendation explicitly introduces The General Theory of Relativity as the theoretical background for the definition of the celestial space-time reference frame.*

2. *This recommendation recognizes that space-time cannot be described by a single coordinate system because a good choice of coordinate system may significantly facilitate the treatment of the problem at hand, and elucidate the meaning of the relevant physical events. Far from the space origin, the potential of the ensemble of masses to which the coordinate system pertains becomes negligible, while the potential of external bodies manifests itself only by tidal terms which vanish at the space origin.*

3. *The ds^2 as proposed gives only those terms required at the present level of observational accuracy. Higher order terms may be added as deemed necessary by users. If the IAU should find it generally necessary, more terms will be added. Such terms may be added without changing the rest of the recommendation.*

4. *The algebraic sign of the potential in the formula giving ds^2 is to be taken as positive.*

5. *At the level of approximation given in this recommendation, the tidal potential consists of all terms at least quadratic in the local space coordinates in the expansion of the Newtonian potential generated by external bodies.*

RECOMMENDATION II

<u>considering</u>

a) the need to define a barycentric coordinate system with spatial origin at the center of mass of the solar system and a geocentric coordinate system with spatial origin at the center of mass of the Earth, and the desirability of defining analogous coordinate systems for other planets and for the Moon,

b) that the coordinate systems should be related to the best realization of reference systems in space and time, and,

c) that the same physical units should be used in all coordinate systems,

<u>recommends that</u>

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

2. the time coordinates be derived from a time scale realized by atomic clocks operating on the Earth,

3. the basic physical units of space-time in all coordinate systems be the second of the International System of Units (SI) for proper time, and the SI meter for proper length,

connected to the SI second by the value of the velocity of light c = 299792458 ms^{-1}.

Notes for Recommendation II

1. *This recommendation gives the actual physical structures and quantities that will be used to establish the reference frames and time scales based upon the ideal definition of the system given by Recommendation I.*

2. *The kinematic constraint for the rate of rotation of both the geocentric and barycentric reference systems cannot be perfectly realized. It is assumed that the average rotation of a large number of extragalactic objects can be considered to represent the rotation of the universe which is assumed to be zero.*

3. *If the barycentric reference system as defined by this recommendation is used for studies of dynamics within the solar systems, the kinematic effects of the galactic geodesic precession may have to be taken into account.*

4. *In addition, the kinematic constraint for the state of rotation of the geocentric reference system as defined by this recommendation implies that when the system is used for dynamics (e. g. motions of the Moon and Earth satellites), the time dependent geodesic precession of the geocentric frame relative to the barycentric frame must be taken into account by introducing corresponding inertial terms into the equations of motion.*

5. *Astronomical constants and quantities are expressed in SI units without conversion factors depending upon the coordinate systems in which they are measured.*

RECOMMENDATION III

considering

the desirability of the standardization of the units and origins of coordinate times used in astronomy,

recommends that

1. the units of measurement of the coordinate times of all coordinate systems centered at the barycenters of ensembles of masses be chosen so that they are consistent with the proper unit of time, the SI second,

2. the reading of these coordinate times be 1977 January 1, $0^h\ 0^m\ 32^s.184$ exactly, on 1977 January 1, $0^h\ 0^m\ 0^s$ TAI exactly (JD = 2443144.5, TAI), at the geocenter,

3. coordinate times in coordinate systems having their spatial origins respectively at the center of mass of the Earth and at the solar system barycenter, and established in conformity with the above sections (1) and (2), be designated as Geocen-

tric Coordinate Time (TCG) and Barycentric Coordinate Time (TCB).

Notes for Recommendation III

1. *In the domain common to any two coordinate systems, the tensor transformation law applied to the metric tensor is valid without re-scaling the unit of time. Therefore, the various coordinate times under consideration exhibit secular differences. Recommendation 5 (1976) of IAU Commissions 4, 8 and 31, completed by Recommendation 5 (1979) of IAU Commissions 4, 19 and 31, stated the Terrestrial Dynamical Time (TDT) and Barycentric Dynamical Time (TDB) should differ only by periodic variations. Therefore, TDB and TCB differ in rate. The relationship between these scales in seconds is given by:*

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

The present estimate of the value of L_B is 1.550505×10^{-8} ($\pm$ 1 $\times 10^{-14}$) (Fukushima et al., Celestial Mechanics, 38, 215, 1986).

2. *The relation TCB - TCG involves a full 4-dimensional transformation*

$$TCB - TCG = \frac{1}{c^2}\left[\int_{t_0}^{t}\left(\frac{v_e^2}{2} + U_{ext}(x_e)\right)dt + v_e\cdot(x - x_e)\right],$$

x_e and v_e denoting the barycentric position and velocity of the Earth's center of mass and x the barycentric position of the observer. The external potential U_{ext} is the Newtonian potential of all solar system bodies apart from the Earth. The external potential must be evaluated at the geocenter. In the integral, t = TCB and t_0 is chosen to agree with the epoch of Note 3. As an approximation to TCB - TCG in seconds one might use:

$$TCB - TCG = L_C \times (JD - 2443144.5) \times 86400 + c^{-2}v_e\cdot(x-x_e) + P.$$

The present estimate of the value of L_C is 1.480813×10^{-8} ($\pm 1 \times 10^{-14}$) (Fukushima et al., Celestial Mechanics, 38, 215, 1986). It may be written as $[3GM/2c^2a] + \epsilon$ where G is the gravitational constant, M is the mass of the Sun, a is the mean heliocentric distance of the Earth, and ϵ is a very small term (of order 2×10^{-12}) arising from the average potential of the planets at the Earth.

The quantity P represents the periodic terms which can be evaluated using the analytical formula by Hirayama et al., ("Analytical Expression of TDB-TDT_0", in Proceedings of the IAG Symposia, IUGG XIXth General Assembly, Vancouver, August 10-22 1987). For observers on the surface of the Earth, the terms depending upon their terrestrial coordinates are diurnal, with a maximum amplitude of 2.1 μs.

3. *The origins of coordinate times have been arbitrarily set so that these times all coincide with the Terrestrial Time (TT) of Recommendation IV at the geocenter on 1977 January 1, $0^h\ 0^m\ 0^s$ TAI. (See note 3 of Recommendation IV.)*

4. *When realizations of TCB and TCG are needed, it is suggested that these realizations be designated by expressions such as TCB(xxx), where xxx indicates the source of the realized time scale (e. g. TAI) and the theory used for the transformation into TCB or TCG.*

RECOMMENDATION IV

considering

a) that the time scales used for dating events observed from the surface of the Earth and for terrestrial metrology should have as the unit of measurement the SI second, as realized by terrestrial time standards,

b) the definition of the International Atomic Time, TAI, approved by the 14th Conférence Générale des Poids et Mesures (1971) and completed by a declaration of the 9th session of the Comité Consultatif pour la Définition de la Seconde (1980),

recommends that

1) the time reference for apparent geocentric ephemerides be Terrestrial Time, TT,

2) TT be a time scale differing from TCG of Recommendation III by a constant rate, the unit of measurement of TT being chosen so that it agrees with the SI second on the geoid,

3) at instant 1977 January 1, $0^h\ 0^m\ 0^s$ TAI exactly, TT have the reading 1977 January 1, $0^h\ 0^m\ 32^s.184$ exactly.

Notes for Recommendation IV

1. *The basis of the measurement of time on the Earth is International Atomic Time (TAI) which is made available by the dissemination of corrections to be added to the readings of national time scales and clocks. The time scale TAI was defined by the 59th session of the Comité International des Poids et Measures (1970) and approved by the 14th Conférence Générale des Poids et Mesures (1971) as a realized time scale. As the errors in the realization of TAI are not always negligible, it has been found necessary to define an ideal form of TAI, apart from the* $32^s.184$ *offset, now designated Terrestrial Time, TT.*

2. *The time scale TAI is established and disseminated according to the principle of coordinate synchronization, in the geocentric coordinate system, as explained in CCDS, 9th Session (1980) and in Reports of the CCIR, 1990, annex to Volume VII (1990).*

3. *In order to define TT it is necessary to define the coordinate system precisely, by the metric form, to which it belongs. To be consistent with the uncertainties of the frequency of the best standard, it is at present (1991) sufficient to use the relativistic metric given in Recommendation I.*

4. *For ensuring an approximate continuity with the previous time arguments of ephemerides, Ephemeris Time, ET, a time offset is introduced so that TT - TAI =* $32^s.184$ *exactly at 1977 January 1,* 0^h *TAI. This date corresponds to the implementation of a steering process of the TAI frequency, introduced so that the TAI unit of measurement remains in close agreement with the best realizations of the SI second on the geoid. TT can be considered as*

equivalent to TDT as defined by IAU Recommendation 5 (1976) of Commissions 4, 8 and 31, and Recommendation 5 (1979) of Commissions 4, 19 and 31.

5. *The divergence between TAI and TT is a consequence of the physical defects of atomic time standards. In the interval 1977-1990, in addition to the constant offset of 32.184, the deviation probably remained within the approximate limits of ± 10μs. It is expected to increase more slowly in the future as a consequence of improvements in time standards. In many cases, especially for the publication of ephemerides, this deviation is negligible. In such cases, it can be stated that the argument of the ephemerides is TAI + 32.184.*

6. *Terrestrial Time differs from TCG of Recommendation III by a scaling factor, in seconds:*

$$TCG - TT = L_G \times (JD - 2443144.5) \times 86400.$$

The present estimate of the value of L_G is 6.969291×10^{-10} ($\pm 3 \times 10^{-16}$). The numerical value is derived from the latest estimate of gravitational potential on the geoid, W = 62636860 (± 30) m^2/s^2 (Chovitz, Bulletin Géodesique, 62, 359, 1988). The two time scales are distinguished by different names to avoid scaling errors. The relationship between L_B and L_C of Recommendation III, notes 1 and 2, and L_G is, $L_B = L_C + L_G$.

7. *The unit of measurement of TT is the SI second on the geoid. The usual multiples, such as the TT day of 86400 SI seconds on the geoid and the TT Julian century of 36525 TT days, can be used provided that the reference to TT be clearly indicated whenever ambiguity may arise. Corresponding time intervals of TAI are in agreement with the TT intervals within the uncertainties of the primary atomic standards (e.g. within $\pm 2 \times 10^{-14}$ in relative value during 1990).*

8. *Markers of the TT scale can follow any date system based upon the second, e.g. the usual calendar date of the Julian Date, provided that the reference to TT be clearly indicated whenever ambiguity may arise.*

9. *It is suggested that realizations of TT be designated by TT(xxx) where xxx is an identifier. In most cases a convenient approximation is:*

$$TT(TAI) = TAI + 32.184.$$

However, in some applications it may be advantageous to use other realizations. The BIPM, for example, has issued time scales such as TT(BIPM90).

RECOMMENDATION V

considering

that important work has already been performed using Barycentric Dynamical Time (TDB), defined by IAU Recommendation 5 (1976) of IAU Commissions 4, 8 and 31, and Recommendation 5 (1979) or IAU Commissions 4, 19 and 31.

recognizes

that where discontinuity with previous work is deemed to be undesirable, TDB may be used.

Note to Recommendation V

Some astronomical constants and quantities have different numerical values depending upon the use of TDB or TCB. When giving these values, the time scale used must be specified.

RECOMMENDATION VI

considering

the desirability of implementing a conventional celestial barycentric reference system based upon the observed positions of extragalactic objects, and,

noting

the existence of tentative reference frames constructed by various institutions and combined by the International Earth Rotation Service (IERS) into a frame used for Earth rotation series,

recommends

1. that intercomparisons of these frames be extensively made in order to assess their systematic differences and accuracy,

2. that an IAU Working Group consisting of members of Commissions 4, 8, 19, 24, 31 and 40, the IERS, and other pertinent experts, in consultation with all the institutions producing catalogues of extragalactic radio sources, establish a list of candidates for primary sources defining the new conventional reference frame, together with a list of secondary sources that may later be added to or replace some of the primary sources, and,

requests

1. that such a list be presented to the XXIInd General Assembly (1994) as a part of the definition of a new conventional reference system,

2. that the objects in this list be systematically observed by all VLBI and other appropriate astrometric programs.

Note for Recommendation VI

This recommendation essentially describes the first part of the work that must be done to prepare the realization of the reference system defined by Recommendations I and II. The choice of objects must be made in the first place by considering their observability by VLBI, but special care should be taken to include a large proportion of extragalactic radio sources with well identified optical counterparts.

RECOMMENDATION VII

considering

a) that the new conventional celestial barycentric reference frame should be as close as possible to the existing FK5 equator and equinox and dynamical equinox which are referred to J2000.0,

b) that it should be accessible to astrometry in visual as well as in radio wavelengths,

recommends

1. that the principal plane of the new conventional celestial reference system be as near as possible to the mean equator at J2000.0 and that the origin in this principal plane be as near as possible to the dynamical equinox of J2000.0,

2. that the positions of the extragalactic objects selected in accordance with Recommendation VI 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,

3. that a great effort be made to compare reference frames of all types, in particular for FK5, solar system and extragalactic reference frame,

4. that observing programs be undertaken or continued in order to relate planetary positions to radio and optical objects, and to determine the relationship between catalogues of extragalactic source positions and the best catalogues of star positions, in particular the FK5 and Hipparcos catalogues.

Notes for Recommendation VII

1. *This recommendation specifies the choice of the coordinate axes that will be adopted in the final reference frame and describes the work to be done before such a frame can be constructed. Although the considerations call for visual and radio wavelengths for the primary catalogue, other observable wavelengths are not excluded. Positions of objects observed in other wavelengths should also be referred to the same system.*

2. *The objective set by this recommendation is that there should be no discontinuity in the positions of stars when the present FK5 frame is replaced by the extragalactic reference frame. This means that the position of the extragalactic objects should be in the FK5 system for J2000.0. It is acknowledged that the best values of precession and nutation must be used in order to avoid introducing spurious proper motions into the positions of extragalactic objects. The final transfer to the preferred equinox and principal plane will be done by applying a rotation at J2000.0.*

3. *The dynamical equinox in this recommendation is defined as the intersection of the mean equator and the ecliptic. The latter is defined as the uniformly rotating plane of the orbit of the Earth-Moon barycenter averaged over the entire period for which the ephemerides are valid. Since it is ephemeris dependent, the choice of the equinoctial point will be made using the most accurate and generally available ephemerides of the solar system at the time.*

4. *The definition given to the reference system by Recommendation I and II implies the stability in time of the system of coordinates realized by the celestial reference frame. The directions of the coordinate axes should not be changed even if at some later date the realizations of the dynamical equinox or the celestial ephemeris pole are improved. Similarly, modifications to the set of extragalactic objects realizing the reference system should be made in such a way that the directions of the axes are not changed. This means that once the coordinate axes have been specified, in the way described in the first part of the recommendation, the connection between the definition of the conventional reference system and the peculiarities of the Earth's kinematics will have been severed.*

5. *As long as the relationship between the optical and the extragalactic radio frame is not sufficiently accurately determined, the FK5 catalogue shall be considered as a provisional realization of the celestial reference system in optical wavelengths.*

RECOMMENDATION VIII

<u>recognizing</u>

a) the importance to astronomy of adopting conventional values of astronomical and physical constants,

b) the values of these constants should be unchanged unless they differ significantly from their latest estimates,

c) that estimates of these constants should be improved frequently to represent the current status of knowledge,

d) the necessity of providing standard procedures using these numerical values, and,

<u>noting</u>

a) that the MERIT Standards and IERS Standards have contributed significantly to the progress of astronomy and geodesy,

b) that numerical values in these standards have served as a system of constants in analyzing observations of high quality, and

<u>considering</u>

that procedures in these standards do not cover the whole of fundamental astronomy,

<u>recommends</u>

that a permanent working group be organized by Commissions 4, 5, 8, 19, 24 and 31, in consultation with the IAG and the IERS, in order to update and improve the system of astronomical units and constants, the list of estimates of fundamental astronomical quantities and standard procedures; this group shall:

1. prepare a draft report on the system of astronomical units and constants at least six months before the XXII[nd] General Assembly (1994),

2. prepare a draft list of best estimates of astronomical quantities at least six months before each following General Assembly,

3. prepare, at least six months before each following General Assembly, a draft report on standard procedures needed in fundamental astronomy, which,

    a) should have a maximum degree of compatibility with the IERS Standard,

    b) should include the implementations of procedures in the form of tested software and/or test cases,

    c) should be available not only in written form, but also in machine-readable form,

4. prepare a draft report on possible electronic access to these units, constants, quantities and procedures at least six months before the XXII[nd] General Assembly (1994).

RECOMMENDATION IX

recognizing

that a generally accepted non-rigid Earth theory of nutation, including all known effects at the one tenth milliarcsecond level, is not yet available,

recommends

1. that those satisfied with accuracy of the nutation angles (ϵ or $\psi \sin\epsilon_0$) numerically greater than ± 0.002" (one sigma rms) may continue to use the 1980 IAU Nutation Theory (P.K. Seidelmann, Celestial Mechanics, **27**, 79, 1982),

2. that those requiring values of the nutation angles more accurate than ± 0".002 (one sigma rms) should make use of the Bulletins of the IERS which publish observations and predictions of the celestial pole offsets accurate to about ± 0".0006 (one sigma rms) for a period of up to six months in advance,

3. that the IUGG be encouraged to develop and adopt an appropriate Earth model to be used as the basis for a new IAU Theory of Nutation.

IAG Resolution

RESOLUTION N°1

The International Association of Geodesy,

Considering the IUGG Resolution on Conventional Terrestrial Reference System (CTRS), and noting

1) that the International Earth Rotation Service (IERS) is currently implementing such a system under the name of the International Terrestrial Reference System (ITRS) from VLBI, SLR, LLR and now GPS data, and

2) that the ITRS is within one meter of WGS 84,

recommends

1) that groups making highly accurate geodetic, geodynamic or oceanographic analysis should either use the ITRS directly or carefully tie their own systems to it,

2) that IERS standards should contain all necessary documentation to assist this task,

3) that for mapping, navigation or digital databases where sub-meter accuracy is not required, WGS 84 may be used in the place of ITRS,

4) that for high accuracy in continental areas, a system moving with a rigid plate may be used to eliminate unnecessary velocities provided it coincides exactly with the ITRS at a specific epoch (e. g., the ETRS 89 system selected by the EUREF subcommission).

IUGG Resolution

RESOLUTION N°2

The International Union of Geodesy and Geophysics

considering the need to define a Conventional Terrestrial Reference System (CTRS) which would be unambiguous at the millimeter level at the Earth's surface and that this level of accuracy must take account of relativity and of Earth deformation, and

noting the resolutions on Reference Systems adopted by the XXIst General Assembly of the International Astronomical Union (IAU) at Buenos Aires, 1991,

endorses the Reference System as defined by the IAU at their XXIst General Assembly at Buenos Aires, 1991 and

recommends the following definitions of the CTRS :

1) CTRS to be defined from a geocentric non-rotating system by a spatial rotation leading to a quasi-Cartesian system,

2) the geocentric non-rotating system to be identical to the Geocentric Reference System (GRS) as defined in the IAU resolutions,

3) the coordinate-time of the CTRS as well as the GRS to be the Geocentric Coordinate Time (TCG),

4) the origin of the system to be the geocenter of the Earth's masses including oceans and atmosphere, and,

5) the system to have no global residual rotation with respect to horizontal motions at the Earth's surface.