THE PAST, PRESENT AND FUTURE OF REFERENCE SYSTEMS FOR ASTRONOMY AND GEODESY

G.A. WILKINS
c/o Royal Greenwich Observatory
Madingley Road
Cambridge
England CB3 0EZ

ABSTRACT. Standard values of astronomical and geodetic constants were adopted in the late nineteenth century for use in the determination of terrestrial and celestial coordinates, and their values were changed subsequently as better values became known. The great improvements in the precision of observation during the past decade has made it necessary to develop reference systems that also include the models and procedures that are used for the analysis of observations by particular techniques. The accurate detemination of the connections between the corresponding reference frames and the adoption of unified standards are major tasks for the future.

1. Introduction

This paper is based on the informal review that I gave at the end of IAU Symposium 141 on "The inertial coordinate system on the sky". My principal aim was to draw attention to the importance of developing a coherent system of standards that encompasses the specification and use of the terrestrial reference frame as well as of the the celestial frame. I included some material from the introductory paper on the connections between reference frames that I had expected to present at the beginning of the conference. It also appeared to be necessary to discuss terminology since, in particular, the terms *reference frames* and *reference systems* had not been properly distinguished in papers given earlier in the conference. I have discussed these topics in further detail in earlier papers (Wilkins 1989a and 1989b) and many relevant papers will be found in the recent monograph on *Reference Frames* (Kovalevsky *et al.* 1989). The review papers by Mueller (1988) and Groten (1989) contain much additional information and extensive lists of references.

2. The Development of the Current Systems of Constants

2.1 Astronomical constants

The desirability of the use of standard values for certain parameters used in the computation of the principal ephemerides of the Sun, Moon and planets was recognised at a conference held in Paris in 1896. The recommended values were adopted in the ephemerides published in the *American Ephemeris* and in the (British) *Nautical Almanac* from 1901 onwards. A more comprehensive

J. H. Lieske and V. K. Abalakin (eds.), Inertial Coordinate System on the Sky, 39–46.

https://doi.org/10.1017/S0074180900086149 Published online by Cambridge University Press

"system of astronomical constants" was developed by De Sitter (1927), but this was not formally adopted. An international conference held in Paris in 1950 (Danjon 1950) decided to make no changes in the constants then in use, but it did recommend the introduction of a new system of *ephemeris time* to replace mean solar time (universal time, UT) as the argument of the ephemerides. Improved ephemerides using the new timescale were introduced in the principal almanacs in 1960; the development of the system was reviewed in the *Explanatory Supplement to the Astronomical Ephemeris* (NAO 1961).

By this time the inaccuracies of the values and the inconsistencies with the theoretical relations between some of the constants were so significant that the conference held in Paris in 1963 (Kovalevsky 1965) decided to set up a working group to prepare a new system of constants. The report of the group (Fricke *et al.* 1966) was adopted by the IAU in 1964, and the new system was introduced in the almanacs in 1968 (NAO 1967). Improvements in the techniques of observation and computation were so rapid that by 1970 it was clear that new ephemerides based on the relativistic theories would be needed by 1980. The development of a new system of constants and of new ephemerides was, however, slower than had been hoped, and they were not introduced until 1984 (NAO 1983). The new ephemerides used a new standard celestial coordinate frame, but the corresponding fundamental star catalogue FK5 is not yet published in full (Fricke *et al.* 1988). Moreover, it was clear that some of the constants adopted in 1976 (Duncombe *et al.* 1977) were not appropriate for use in 1984 and other values were used in some almanacs (*e.g.*, see NAO 1983, pp. S11–S12).

2.2 Geodetic constants

The constants that specify the size and shape of a spheroid (ellipsoid of revolution) that approximates to the actual surface of the Earth were usually chosen to give a best fit over a limited region of the surface, so that many sets of such constants have been used for mapping (for example, see the list in the *Astronomical Almanac* for 1987 onwards). The inclusion of geodetic constants in the IAU (1964) system of astronomical constants prompted the International Association of Geodesy (IAG) to introduce the IAG (1967) Geodetic Reference System, although the formal specification did not relate the axis of figure to any particular reference frame (IAG 1971). It was later stated that the axis is defined by Conventional International Origin of the coordinates of the pole of rotation. Formally the zero of terrestrial longitude was that adopted in 1884 by the international conference that was held in Washington, D.C., in 1884 for the purpose of fixing a prime meridian and a universal day, but in practice it was determined by the adopted longitudes of the observatories that contributed to the determination of universal time. The system was revised in 1980 (Moritz 1980).

The development of new techniques that were potentially able to determine the variations in the rotation of the Earth with higher precision than the technique of optical astrometry led to the setting up in 1978 of a working group that organised Project MERIT to Monitor Earth Rotation and Intercompare the Techniques of observation and analysis (Wilkins 1980). The group recognised the importance of using the same constants and reference frames for all of the six techniques in the project, and it developed a set of MERIT Standards that included many more astronomical and geodetic quantities than the currently-adopted systems (Melbourne 1983). At that time it was not possible to adopt standard reference frames, but the determination of the differences between the reference frames for the different techniques became a major objective of the project. In particular,

https://doi.org/10.1017/S0074180900086149 Published online by Cambridge University Press

the MERIT group worked closely with another group that had been set up in 1981 to develop a new COnventional TErrestrial reference System (COTES).

2.3 The current position

Following the success of the MERIT Main Campaign, the IAU and IUGG decided to accept the recommendations of the MERIT/COTES Working Group (Wilkins and Mueller 1986) and to set up a new International Earth Rotation Service (IERS). This is responsible for the establishment and maintenance of terrestrial and celestial reference frames whose relative orientation is monitored continuously. These frames have been specified in the IERS Annual Report for 1988, and new IERS standards to replace the MERIT standards have just been published (McCarthy 1989). The IERS standard celestial reference frame is based on the positions of radio sources determined by the VLBI technique, whereas the IAU standard frame is based on the FK5 catalogue of the positions of stars determined by optical techniques.

3. A Digression on Terminology and Concepts

3.1 Frames and systems

In this context it is useful to make distinctions between the following terms:

coordinate frame	coordinate system
reference frame	reference system

For this purpose it is possible to use the Newtonian concepts of space and time; the same distinctions may be made when relativistic concepts must be used. The following definitions appear to be the most appropriate, although it must be recognised that current usage does not always conform to them:

Coordinate frame: a triad of rectangular coordinate axes or other geometrical construction with respect to which a direction or the position of a point may be specified by a set of coordinates.

Coordinate system: a method of specifying the position of a point with respect to a particular coordinate frame. The most common coordinate systems are rectangular coordinates and spherical polar coordinates, but geodetic coordinates defined with respect to a spheroid are also important in geodesy.

Reference frame: a catalogue of the adopted coordinates of a set of reference objects that serves to define, or realize, a particular coordinate frame. It is usually necessary to adopt expressions that give the coordinates as functions of time; the timescale is then part of the frame. A reference frame may be intended for general use or for use with a particular technique; the former type are sometimes said to be *conventional*. In the case of dynamical reference frames the catalogues are replaced by ephemerides of the geodetic satellites, planets or other celestial objects that serve to define the frames.

Reference system: the totality of procedures, models and constants that are required for the use of one or more reference frames. An equivalent statement is that a reference system is the combination of a reference frame (represented by a catalogue of the positions of reference objects) and a set of theories and parameters that can be used to derive the positions of other objects at measured times from observations of particular types.

3.2 Ideal and standard frames

It is also useful to make a distinction between an *ideal* coordinate frame that is appropriate for explanatory purposes and for use in theoretical studies and a *standard* reference frame that is appropriate for use for practical purposes. An ideal frame is described by concepts, but it is often not possible to use these concepts directly in practical situations. In contrast, a standard frame is intended to provide an accurate and unambiguous basis for the determination of positions. The positions in the catalogue are usually chosen so that the standard frame corresponds closely to the ideal frame, but they may be chosen to satisfy some other condition.

The ideal terrestrial coordinate frame may be considered to have its origin at the centre of mass of the Earth and be fixed in the Earth. The z-axis and the x,y-plane may be described as the axis of figure and the Greenwich meridian, but since the Earth is not a rigid body such a frame would not be fixed in the Earth. For example, tectonic motions could change the direction of the axis of figure as well as the position of Greenwich with respect to the interior of the Earth. Instead the standard frame used by IERS is based on the adoption of the coordinates of a set of stations where precise geodetic measurements are made regularly; these coordinates and their rates of change are chosen so that there is no apparent net rotation of the crust of the Earth with respect to the frame and so that the z-axis and x,y-plane are continuous with those previously in use. Thus the IERS pole corresponds to the CIO, and hence to the pole of the adopted mean coordinates of the stations of the original International Latitude Service; this pole now differs significantly from the mean position of the pole of rotation and hence from the current position of the axis of figure. The IERS prime meridian is not coincident with the meridian through the transit-circle at Greenwich and it might move further away from it. The reference timescale for the IERS terestrial frame is international atomic time (TAI).

The ideal celestial coordinate frame is usually considered to have its origin at the centre of mass of the Solar System (and so is described as "barycentric") and to be "inertial" or "non-rotating"; for many purposes such a frame may be regarded as being fixed in space. The plane and direction of the centre of the Galaxy may be used to specify such a frame, but in astrometry and geodesy the z-axis is usually taken to be the mean pole of rotation of the Earth at some arbitrary epoch, while the x-axis is in the direction of the mean equinox at this epoch. It is assumed that time may be measured in a "uniform" timescale. The IERS and IAU standard reference frames correspond to such an ideal frame. To the accuracy of measurement the directions of extragalactic radio sources should be constant with respect to such a frame, but the star catalogue defining the optical frame must include proper motions, parallaxes and radial velocities with the coordinates of the stars at the epoch.

The earth-rotation parameters that are determined by IERS include the coordinates of the true pole of rotation of the Earth with respect the terrestrial frame and the difference between UT and TAI. In effect, the parameters refer to an intermediate coordinate frame whose z-axis and x-axis are the true pole and true equinox of date. (The term "true pole" is here to be understood to be the "celestial ephemeris pole".) This intermediate frame has no diurnal rotation in space, but it is subject to the nutation and precession of the axis of rotation of the Earth. Sometimes the mean pole and the mean equinox of date are used in the specification of the intermediate frame since such a frame has no short-

https://doi.org/10.1017/S0074180900086149 Published online by Cambridge University Press

period motions in space.

4. The Connections between the Terrestrial and Celestial Frames

4.1 The connections between the ideal coordinate frames

The connections, or links, between the ideal celestial and terrestrial coordinate frames may be summarised as follows:

Celestial frame (barycentric, non-rotating)

Orbital motion of the Earth around the barycentre

Precession and nutation of the axis of rotation

Intermediate frame (geocentric, aligned to axis of rotation)

Variations in the rate of rotation of the Earth

Wobble of the axis of figure around the axis of rotation

Terrestrial frame (geocentric, aligned to axis of figure)

The links between the celestial frame and the intermediate frame can be calculated from numerical models with high accuracy over long periods, although further improvements in the theory of nutation are required. On the other hand, the links between the intermediate frame and the terrestrial frame must be monitored by regular observations; the results are analysed to provide information about, for example, the interactions between the atmosphere and the crust of the Earth and about the interior of the Earth.

4.2 The connections between the standard reference frames

The connections between the standard celestial and terrestrial reference frames may be summarised from a different viewpoint as follows:

Standard celestial frame
Reference-frame parameters for each technique

Technique-dependent celestial frames Observed objects Observing instruments Technique-dependent terrestrial frames	Technique-dependent earth-rotation parameters

Reference-frame parameters for each technique

Standard terrestrial frame

https://doi.org/10.1017/S0074180900086149 Published online by Cambridge University Press

The reference timescale of the celestial frame is barycentric dynamical time (TDB), while the reference timescale of the standard terrestrial frame is TAI.

The analysis of the observations of each technique are used (a) to determine the earth-rotation parameters, (b) to derive improvements to the catalogue postions of both the observed objects and the observing instruments, and (c) to improve the models used in the analysis. The earth-rotation parameters and other results from the different techniques are combined and compared (a) to derive standard values of the earh-rotation parameters, (b) to determine the reference-frame parameters that specify the relative orientations of the standard and technique-dependent frames, and (c) to identify, if possible, any deficiencies in the reference systems for the techniques concerned.

5. Future Tasks on the Reference Systems for Astronomy and Geodesy

5.1 Operational tasks

The stucture and operational procedures of IERS have been developed in such a way as to encourage the steady improvement in the technique-dependent reference systems and in the standard reference frames. Some specific tasks that are in progress include:

(a) the densification of the IERS terestrial reference frame so as to make it more accessible for general use, although at a lower accuracy than for the primary observing sites;

(b) the densification of the IERS celestial reference frame and the improvement of the links between it and the stellar and dynamical reference frames; and

(c) the introduction of new IERS standards that will lead to reductions in the inconsistencies between the reference systems of different techniques.

5.2 Theoretical tasks

The principal outstanding theoretical task appears to be to extend and clarify the application of relativistic concepts to astrometry and geodesy. It is first of all necessary to ensure that the theoretical models and the procedures for the reduction and analysis of the observations are consistent with an adopted relativistic theory. It is also important that the new approach be described and explained in ways that will be intelligible to those who will need to use the new concepts, models and procedures.

Some improvements in the theoretical bases of the links between the reference frames are required; in particular, the theory of the nutation of the axis of rotation of the Earth needs to be refined so as to match the sub-milliarcsecond precision of current VLBI observations. Further careful consideration of the theoretical models and of the corresponding numerical procedures will be required if optical-interferometric techniques can be utilised to make angular measurements to a precision that is of the order of microarcseconds.

5.3 Organisational tasks

Project MERIT and the establishment of IERS have considerably strengthened international cooperation between the scientists and organisation whose primary interests have been in geodetic applications, such as the determination of the tectonic motions on the the Earth. It appears that the HIPPARCOS astrometric satellite mission is leading to a rejuvenation of international cooperation in astrometry. Special efforts must be made to bring together these two communities to discuss matters of common concern. Even now, many astrometrists appear to unaware of the advances that have been made in the development of a celestial reference frame based on extragalactic radio sources.

It is important that there should be full consultations about the use of the new IERS standards outside the context of the IERS. Agreement should be sought outside the IERS community so that the new standards will be suitable for general adoption by IAU and IUGG; otherwise there are risks that the standards will be ignored or modified by some groups.

Finally, efforts must be made to encourage the wider use of agreed standards. For example, even now confusion is caused and effort is wasted because many astronomers continue to use cgs units instead of SI units. The effects of using different values for astronomical and geodetic parameters are often very difficult to determine and can lead to unnecessary discrepancies between the results from different techniques of observation or analysis. Such discrepancies are minute in comparison with the differences in longitude and time that were common before the Washington conference of 1884, but I would like to think that the Leningrad conference of 1989 will lead to a similar unifying influence in astrometry and geodesy.

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