IMPLEMENTATION OF THE NEW NOMENCLATURE IN THE ASTRONOMICAL ALMANAC

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ABSTRACT. Following the resolutions of the 24th International Astronomical Union in 2000 (IAU 2000) together with the implementation and availability of the various software routines, it became imperative that *The Astronomical Almanac* (AsA) included the IAU recommended techniques for applying precession-nutation. This involves introducing the Earth rotation angle (ERA), the adopted relationship between Universal Time (UT1) and the rotation of the Earth, together with the celestial intermediate origin (CIO), the corresponding origin for right ascension. The introduction of the CIO has been complicated by the fact that new nomenclature is required, which is in the process of being discussed and agreed by the IAU Working Group on Nomenclature for Fundamental Astronomy. However, an attempt has been made in the 2006 edition to incorporate the new nomenclature (which is also used here) and describe the process in a straight forward way with the intention of helping the diverse user community.

1. THE ASTRONOMICAL ALMANAC AND THE NEW NOMENCLATURE

The *Astronomical Almanac* (AsA) is a joint publication with the Nautical Almanac Office of the US Naval Observatory. However, HM Nautical Almanac Office (HMNAO) is responsible for Section B - Time-scales and Coordinate Systems, and so it became our goal to include the IAU 2000 resolutions and in particular to explain how to calculate positions using the celestial intermediate origin (CIO) and the Earth rotation angle (ERA). This report is about the changes to Section B of the AsA, and not about the almanac as a whole.

It must be stressed that the whole almanac will include the IAU 2000 precession-nutation and all the updated constants, wherever relevant. This enhancement is a continuing process, and over the last few years there have been many improvements, particularly to incorporate the IAU requirements, e.g. use of the ICRS, the JPL DE405 ephemeris, and incorporation of the Hipparcos and Tycho-2 data. Also, equally importantly, the AsA continues to provide its users with all the equinox-based data, tables, formulae and explanation that are printed each year.

The adoption of the 2000 IAU resolution B1.8 means that the IAU is asking astronomers to adopt a new method for calculating "of date" positions. This is complicated by the fact that not only is a new nomenclature required, but it has also been proposed that the name of two of the fundamental quantities (the origins) that are specifically mentioned are changed, to make things more consistent. In particular, the resolution recommends the use of the "non-rotating" origin on the equator of the celestial intermediate pole (CIP) and names these origins the Celestial Ephemeris Origin (CEO) in the Geocentric Celestial Reference System and the

Terrestrial Ephemeris Origin (TEO), in the terrestrial system. These topics are in the process

UNIVERSAL TIME AND EARTH ROTATION ANGLE, 2006

Date 0^h UT1	Julian Date 245	Earth Rotation Angle ° ′ ″	Equation of the Origins ′ ″	Date 0^h UT1	Julian Date 245	Earth Rotation Angle ° ′ ″	Equation of the Origins ′ ″
Jan. 0	**3735·5**	99 26 39·6076	− 4 34·6091	Feb. 15	**3781·5**	144 46 57·0025	− 4 41·9679
1	**3736·5**	100 25 47·8118	− 4 34·9270	16	**3782·5**	145 46 05·2067	− 4 41·9872
2	**3737·5**	101 24 56·0160	− 4 35·2004	17	**3783·5**	146 45 13·4109	− 4 42·0010
3	**3738·5**	102 24 04·2203	− 4 35·4072	18	**3784·5**	147 44 21·6152	− 4 42·0258
4	**3739·5**	103 23 12·4245	− 4 35·5460	19	**3785·5**	148 43 29·8194	− 4 42·0771

GHA = Earth rotation angle $-\alpha_i$, $\alpha_i = \alpha_e +$ equation of the origins

α_i, α_e are the right ascensions with respect to the CIO and the true equinox of date, respectively.

Figure 1: Table of Universal Time and Earth Rotation Angle

of being discussed and proposed by the IAU Working Group on Nomenclature for Fundamental Astronomy, and it is thought that they will recommend that the names be changed to the celestial intermediate origin (CIO), and terrestrial intermediate origin (TIO). Thus the new fundamental quantities of the Celestial and Terrestrial Intermediate Reference Systems are the X, Y of the CIP, the angle s that positions the CIO on the equator of the CIP, and the ERA, which relates the CIO with the TIO.

An attempt has been made in Section B of the 2006 edition of the AsA to incorporate the new quantities and describe the process in a straight forward way using the new nomenclature, with the intention of helping the diverse user community.

When undertaking such a revision, the following points were considered. The AsA is a reference product for the year, it must be useful to the people who need the information, and it must maintain standards, be up-to-date and reliable. On the other hand, it is not an educational product, nor is it at the forefront of research in fundamental astronomy. Such material is changing quickly and is not yet a standard; users require continuity. One must also consider the production process with deadlines, funding, and having access to the necessary personnel to incorporate, produce and check the new material.

One of the most difficult in this case is that the AsA is not a text book. Of course, the AsA may be used in education. In general, the style and content assumes some level of knowledge and a balance is required between explanation and information.

NUTATION, OBLIQUITY & INTERMEDIATE SYSTEM, 2006

FOR 0^h TERRESTRIAL TIME

Date 0^h TT	NUTATION in Long. $\Delta\psi$	NUTATION in Obl. $\Delta\epsilon$	True Obl. of Ecliptic ϵ $23^\circ\ 26'$	**Julian Date** 0^h TT	CELESTIAL INTERMEDIATE SYSTEM Pole $\mathcal{X}$	Pole $\mathcal{Y}$	Origin s
	″	″	″		″	″	″
Jan. 0	− 2·1954	+ 8·3424	26·9813	**3735·5**	+ 119·3163	+ 8·2546	− 0·0025
1	− 1·9865	+ 8·3810	27·0186	**3736·5**	+ 119·4543	+ 8·2931	− 0·0025
2	− 1·8262	+ 8·4452	27·0815	**3737·5**	+ 119·5731	+ 8·3570	− 0·0025
3	− 1·7383	+ 8·5198	27·1548	**3738·5**	+ 119·6630	+ 8·4316	− 0·0026
4	− 1·7246	+ 8·5872	27·2209	**3739·5**	+ 119·7234	+ 8·4989	− 0·0026

Figure 2: Table of Nutation, Obliquity and Celestial Intermediate Reference System

After due consideration, it was decided that time and manpower would not allow a complete re-write of the whole of Section B. No change would be made to the methods and algorithms, nor would the precision of any of the tables change. The new quantities and methods would be incorporated, remembering that all existing material is still required. For HMNAO, the problem of updating our software was greatly helped by using the IAU SOFA[1] Fortran library. All the basic quantities were also successfully compared with NOVAS[2], USNO's independent implemen-

tation. The assistance of the staffs of USNO's AA Department, HMNAO, and Dr. N. Capitaine are gratefully acknowledged.

Nomenclature is all pervasive but not everything is specified in the IAU resolutions. First one must consider the quantities that need tabulating and then the explanation.

ICRS FRAME BIAS, PRECESSION AND NUTATION, 2006

MATRIX ELEMENTS FOR CONVERSION FROM

ICRS TO TRUE EQUATOR AND EQUINOX OF DATE

Date 0^h TT	$\mathbf{NPB}_{11}-1$	$\mathbf{NPB}_{12}$	$\mathbf{NPB}_{13}$	$\mathbf{NPB}_{21}$	$\mathbf{NPB}_{22}-1$	$\mathbf{NPB}_{23}$	$\mathbf{NPB}_{31}$	$\mathbf{NPB}_{32}$	$\mathbf{NPB}_{33}-1$
Jan. 0	−105	−133 134	− 57 841	+133 132	− 89	−4079	+ 57 846	+4002	− 17
1	−106	−133 288	− 57 908	+133 286	− 89	−4098	+ 57 913	+4021	− 17
2	−106	−133 421	− 57 965	+133 418	− 89	−4129	+ 57 971	+4052	− 17
3	−106	−133 521	− 58 009	+133 519	− 89	−4165	+ 58 014	+4088	− 17
4	−106	−133 588	− 58 038	+133 586	− 89	−4198	+ 58 044	+4120	− 17

Values are in units of 10^{-8}. Matrix used with GAST (B12-B19). CIP is $\mathcal{X} = \mathbf{NPB}_{31}$, $\mathcal{Y} = \mathbf{NPB}_{32}$.

Figure 3: Matrix elements for conversion from ICRS to True Equinox and Equator of Date

There is a new table (see Figure 1) with ERA tabulated daily at 0^h UT1 with the Equation of the Origins, the difference between ERA and Greenwich apparent sidereal time (GAST). There is the X, Y of the CIP, and s, the angle that defines the position of the CIO on the equator of date (see Figure 2). These quantities are tabulated on the same pages as the nutations in longitude and obliquity, and the true obliquity of the ecliptic.

ICRS TO CELESTIAL INTERMEDIATE SYSTEM, 2006

MATRIX ELEMENTS FOR CONVERSION FROM

ICRS TO CELESTIAL INTERMEDIATE ORIGIN AND TRUE EQUATOR OF DATE

Julian Date	$\mathbf{C}_{11}-1$	$\mathbf{C}_{12}$	$\mathbf{C}_{13}$	$\mathbf{C}_{21}$	$\mathbf{C}_{22}-1$	$\mathbf{C}_{23}$	$\mathbf{C}_{31}$	$\mathbf{C}_{32}$	$\mathbf{C}_{33}-1$
245									
3735·5	− 1673	+ 6	− 578 4616	−237	− 8	−40 0195	+ 578 4616	+40 0195	− 1681
3736·5	− 1677	+ 6	− 579 1308	−238	− 8	−40 2059	+ 579 1308	+40 2060	− 1685
3737·5	− 1680	+ 5	− 579 7065	−240	− 8	−40 5160	+ 579 7065	+40 5161	− 1689
3738·5	− 1683	+ 5	− 580 1425	−242	− 8	−40 8775	+ 580 1425	+40 8775	− 1691
3739·5	− 1685	+ 5	− 580 4354	−244	− 8	−41 2038	+ 580 4354	+41 2038	− 1693

Values are in units of 10^{-10}. Matrix used with ERA (B20-B23).

Figure 4: Matrix elements for conversion from ICRS to the CIO and True Equator of Date

Finally there are the "precession-nutation" matrices, which are tabulated on an open pair of pages. The equinox-based bias, precession and nutation matrix is tabulated on the left-hand pages (see Figure 3) and the equivalent CIO-based matrix on the right-hand pages (see Figure 4). Shading has been used to highlight the CIO-based quantities.

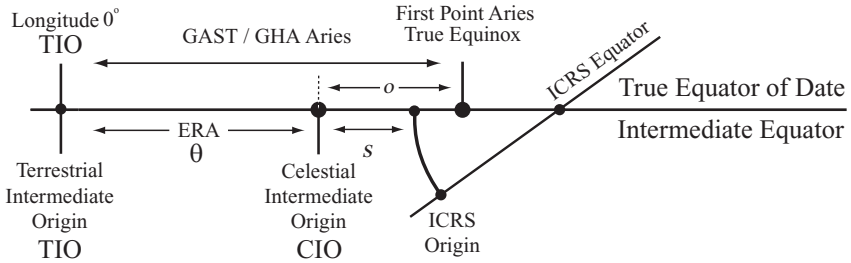

Figure 5: Schematic diagram showing the Equator, the Equinox, the CIO and the TIO

The explanation, which is the more difficult part, has been revised and extended. Apart from giving the various formulae for ERA, X, Y and s, a simple schematic diagram (see Figure 5) has

been included that shows the relationships between the old and new quantities. This shows that both methods use the same equator (and pole), and that the resulting hour angles are identical.

Equinox Method	*CIO Method*
5. Apply frame bias, precession and nutation to convert from the ICRS to the system defined by the true equator and equinox of date.	**5.** Rotate the ICRS to the intermediate system using $\mathcal{X}$,$\mathcal{Y}$ and s to apply frame bias, precession-nutation.
6. Convert to spherical coordinates, giving the geocentric apparent right ascension and declination with respect to the true equinox and equator of date.	**6.** Convert to spherical coordinates, giving the geocentric intermediate right ascension and declination with respect to the CIO and the true equator of date.
7. Calculate Greenwich apparent sidereal time and form the Greenwich hour angle for the given UT1.	**7.** Calculate the Earth Rotation Angle and form the Greenwich hour angle for the given UT1.

Figure 6: Extract from the Planetary Reduction section showing the Equinox and CIO Methods

The planetary reduction has been extended to include the calculation of Greenwich hour angle, involving GAST or ERA, as appropriate, which allows users to see that both methods produce the same result. The description of both methods is done in parallel (see Figure 6). The left-hand column gives the familiar equinox-based method, and the right-hand column gives the new CIO-based method. Shaded heading and step numbers highlight the CIO-based material.

A new example has been included that takes the ICRS star position and calculates its approximate ($1''$) altitude and azimuth at a given UT1. The purpose of the example is to show how easy it is to use the new CIO method (see Figure 7) particularly for approximate work.

Step B. Apply aberration (from $\dot{\mathbf{e}}$) and precession-nutation (using $\mathcal{X}$, $\mathcal{Y}$) to form

$$\begin{aligned} x_i &= (1 - \mathcal{X}^2/2)\, p_x - \mathcal{X}\, p_z + \dot{e_x}/c &&= -0{\cdot}373\ 494 \\ y_i &= p_y - \mathcal{Y}\, p_z + \dot{e_y}/c &&= -0{\cdot}312\ 495 \\ z_i &= \mathcal{X}\, p_x + \mathcal{Y}\, p_y + (1 - \mathcal{X}^2/2)\, p_z + \dot{e_z}/c &&= -0{\cdot}873\ 355 \end{aligned}$$

Figure 7: Extract from the altitude, azimuth example applying approximate precession-nutation

2. SUMMARY

The following table summarizes some of the terms. The left-hand column gives the familiar equinox-based nomenclature while right-hand column gives the new terms that are thought likely to be recommended by the IAU Working Group on Nomenclature for Fundamental Astronomy.

Equinox Based		**CIO Based**
True equator and equinox of date		Celestial Intermediate Reference System
Celestial Intermediate Pole (CIP), (X, Y)	=	CIP, (X, Y)
True equator of date	=	Celestial Intermediate equator
True equinox of date		Celestial Intermediate origin (CIO)
Apparent place		Intermediate place
Apparent right ascension		Intermediate right ascension
Declination	=	Declination
Greenwich apparent sidereal time (GAST)		Earth rotation angle (ERA)

3. REFERENCES

1. Wallace P., 2002, Update to SOFA report, in: *Highlights of Astronomy*, **12**, as presented at the XXIVth General Assembly of the IAU - 2000. Edited by H. Rickman. San Francisco, CA: *Astronomical Society of the Pacific*, **12**, 128. (http://www.iau-sofa.rl.ac.uk).
2. Kaplan (1990), Bull AAS **22**, pp. 930-931. For the IAU2000 version used for AsA 2006 see web site http://aa.usno.navy.mil/software/novas/new_ novas_ f/.