# PROGRESS ON THE IMPLEMENTATION OF THE NEW NOMENCLATURE IN THE ASTRONOMICAL ALMANAC

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ABSTRACT. *The Astronomical Almanac 2006*, published in January 2005, was the first edition to introduce the concepts set out in the IAU 2000 resolutions on positional astronomy. Not only was the IAU 2000A precession-nutation theory used, but the quantities and concepts relating to the Celestial Intermediate Reference System were tabulated and explained. With the preparation of the the almanac for the year 2007 (2007 edition), improvements have been made, which include the recommendations of the IAU Working Group on Nomenclature for Fundamental Astronomy.

This paper focuses on Section B of the 2007 edition of the almanac—Time-Scales and Coordinate Systems—and highlights some of the changes. A summary is also given of the checks made between SOFA and NOVAS, the software libraries that are the basis of the numbers in the almanac.

## 1. THE ASTRONOMICAL ALMANAC AND THE NEW NOMENCLATURE

*The Astronomical Almanac* (AsA) is a joint publication of the Nautical Almanac Office of the US Naval Observatory and HM Nautical Almanac Office (HMNAO) of the United Kingdom. The 2006 edition was published in January 2005 and was the first of our almanacs to implement the IAU 2000 resolutions on precession-nutation, the new Celestial Intermediate Origin (CIO), and the Earth Rotation Angle (ERA).

The AsA is a reference product that maintains international standards, so it is important that the AsA incorporate and explain new procedures that are part of those standards. At the same time, the almanac offices have a commitment to continue to serve their users by providing the data that they require. The AsA will continue for the foreseeable future to tabulate quantities and explain traditional techniques using Greenwich apparent sidereal time and right ascension measured from the equinox. For example, the tables of apparent celestial coordinates in the AsA use the traditional coordinate systems, with the equinox as the origin of right ascension. However, for those who wish to use the new techniques, based on the ERA and the CIO, Section B of the AsA—Time-Scales and Coordinate Systems—now tabulates and explains the use of these basic quantities, including a description of how to calculate an object's CIO-based right ascension. The first part of this paper describes the additions to Section B.

A problem that faced the almanac offices with the IAU 2000 resolutions, particularly the recommendation to use the CIO (Celestial Ephemeris Origin, as it was called in the text of the resolution) as the origin of right ascension, was that of nomenclature. New words and phrases were needed for the new concepts. This issue is being addressed by the IAU Working Group for Nomenclature for Fundamental Astronomy (WGNFA) (2003 GA). Although the recommendations of the working group have not yet been ratified by the IAU, many of them have been included in the 2006 almanac and the upcoming 2007 edition. This has been an iterative process, and there have been some changes in the 2007 edition, particularly in the text, as a result.

| **Equinox Based** | | **CIO Based** |
|---|---|---|
| True equator and equinox of date | | Celestial Intermediate Reference System |
| Celestial Intermediate Pole (CIP) | = | Celestial Intermediate Pole (CIP) |
| True equator of date | = | Celestial Intermediate equator |
| True equinox of date | | Celestial Intermediate origin (CIO) |
| equation of the equinoxes | | CIO locator ($s$) |
| Apparent place | | Intermediate place |
| Apparent right ascension | | Intermediate right ascension |
| Apparent declination | = | Intermediate declination |
| Greenwich apparent sidereal time (GAST) | | Earth Rotation Angle (ERA) |
| Greenwich hour angle (GHA) | = | Greenwich hour angle (GHA) |

The table above lists the various terms used in the AsA. The left-hand column gives the familiar equinox-based nomenclature while right-hand column gives the new terms that are recommended by the WGNFA. Similarly in the AsA the method for the planetary reduction to Greenwich hour angle and declination is described in parallel (see Figure 1).

| *Equinox Method* | *CIO Method* |
|---|---|
| ***5.** Apply frame bias, precession, nutation, and Greenwich apparent sidereal time to convert from the GCRS to the Terrestrial Intermediate Reference System; origin the TIO and the equator of date. | ***5.** Rotate, using $\mathcal{X}$, $\mathcal{Y}$, $s$ and $\theta$ to apply frame bias, precession-nutation and Earth rotation, from the GCRS to the Terrestrial Intermediate Reference System; origin the TIO and equator of date. |

***6.** Convert to spherical coordinates, giving the Greenwich hour angle ($H$) and declination ($\delta$) with respect Terrestrial Intermediate Reference System (TIO and equator of date).

Figure 1: Extract from the AsA *Planetary Reduction*

The tables of the almanac for the year 2007 are broadly the same as those for 2006, although there have been some changes in the headings. Figure 2 is an extract from the left-hand page tabulating **NPB**, the equinox-based matrix for transformation from the Geocentric Celestial Reference System (GCRS) to the true equator and equinox of date system.

B42 FRAME BIAS, PRECESSION AND NUTATION, 2007

GCRS TO TRUE EQUATOR AND EQUINOX OF DATE
FOR $0^h$ TERRESTRIAL TIME

| 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** | −14815 | −1578 7515 | − 685 8885 | +1578 7236 | −12470 | −41 1824 | + 685 9526 | +40 0995 | −2361 |
| **1** | −14838 | −1580 0005 | − 686 4306 | +1579 9728 | −12490 | −40 9686 | + 686 4945 | +39 8840 | −2364 |

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

Figure 2: Extract showing **NPB** matrix from AsA 2007.

For those who wish to use the CIO-based method, Fig. 3 shows an extract from the corresponding right-hand page, tabulating **C**, the matrix that transforms vectors from the GCRS to the Celestial Intermediate Reference System (CIO and equator of date). The headlines for this pair of pages are identical except that the one on the right-hand page is shaded, maintaining the style adopted to highlight material relating to the CIO. Note as well the similarity of the headings and the replacement of "ICRS" used the 2006 edition by the more correct "GCRS". These matrices are identical except for the 4 elements of the top left-hand corner, which provide the position of the origin of right ascension.

GCRS TO CELESTIAL INTERMEDIATE ORIGIN & EQUATOR OF DATE
FOR $0^h$ TERRESTRIAL TIME

| Julian Date | $C_{11}-1$ | $C_{12}$ | $C_{13}$ | $C_{21}$ | $C_{22}-1$ | $C_{23}$ | $C_{31}$ | $C_{32}$ | $C_{33}-1$ |
|---|---|---|---|---|---|---|---|---|---|
| **4100·5** | − 2353 | − 40 | − 685 9526 | −235 | − 8 | −40 0995 | + 685 9526 | +40 0995 | − 2361 |
| **4101·5** | − 2356 | − 40 | − 686 4945 | −233 | − 8 | −39 8840 | + 686 4945 | +39 8840 | − 2364 |

Values are in units of $10^{-10}$. Matrix used with ERA (B20–B23). CIP is $\mathcal{X} = \mathbf{C}_{31}$, $\mathcal{Y} = \mathbf{C}_{32}$

Figure 3: Extract showing **C** matrix from AsA 2007.

The equation of the origins, the difference between the ERA and GAST, is tabulated with the ERA. Symbols for the tabulated quantities have been added, with $E_o$, as suggested by WGNFA, representing the equation of the origins rather than the previous symbol $o$ (a confusing choice) used in the 2006 edition.

The traditional tables are all still present: the table of Universal and Sidereal Times, containing Greenwich mean and apparent sidereal time; the position and velocity of the Earth; and the nutation in longitude and obliquity and the true obliquity of the ecliptic. But also now listed with the nutations are $\mathcal{X}$ and $\mathcal{Y}$, the coordinates of the celestial intermediate pole (CIP), and the quantity $s$, now called the CIO locator.

## 2. SOFTWARE COMPARISONS

All the quantities tabulated in Section B are calculated using IAU SOFA routines (Wallace 2002), which form the core of HMNAO's software. To ensure that the quality of the AsA is maintained, comparisons have been made between the HMNAO calculations and those of the US Naval Observatory, which are based on NOVAS (Kaplan 1990) version F2.9. The first four columns of the table below are a summary of the comparisons.

The comparisons for each quantity were made for 1101 days at $0^h$ UT1 or TT as tabulated in the almanac, except for $s$. All quantities were checked with two more decimal places than are printed. The fourth column gives the number of times the last digit checked was one unit different. Note that for **C** this excludes† elements $\mathbf{C}_{21}$ and $\mathbf{C}_{12}$, where 15% of these were different with a maximum of 5 units in the $12^{th}$ place. Kaplan evaluated the **NPB** and **C** matrices at $0^h$ TDB, and calculated $s$ using an independent integration method that provided values every 2 days at $12^h$ TDB. The differences for the CIO locator $s$ ranged between $\pm 1'' \times 10^{-6}$.

Also considered was the effect on the AsA data of the P03 model of precession (Capitaine et al. 2003) that is being recommended by the IAU Working Group on Precession and the Ecliptic (Hilton et al. 2006). The last two columns of the table give the range of the differences in the terms of the printed precision for the various quantities checked. This demonstrates that the adoption of P03 hardly affects the printed data for years 2006–2008. For this reason, and the fact that it has not yet been adopted by the IAU, it was decided that the P03 model would not be used in preparing the 2007 AsA. The large differences in the true obliquity of date ($\epsilon$) indicated in the table results from the substantial change in the mean obliquity at J2000.0 adopted for P03; thus some ecliptic coordinates will change in the end figures.

These checks on P03 were calculated using a draft version of SOFA that was specially provided and a non-public version of NOVAS.

Comparisons were also made of the method for calculating geocentric apparent planetary positions described in Section B with that implemented in the latest version of NOVAS. This version of NOVAS includes relativistic gravitational light deflection caused by the major planets as well as the Sun. The comparison was made daily at $0^h$ TT from 2005 to 2015, and agreement

| HMNAO (SOFA) − NOVAS 2005-2007 | | | | IAU 2000 − P03 | | |
|---|---|---|---|---|---|---|
| | Decimal Places | Decimal Places | Number of Values 1 | | 2006 | 2006–2008 |
| Item(unit) | Printed | Checked | Different | Item | in terms of printed precision | |
| | | | | | 0.1 ms | |
| GMST (s) | 4 | 6 | 0 | GMST | $[+0.005, +0.007]$ | $[+0.004, +0.008]$ |
| GAST (s) | 4 | 6 | 1 | GAST | $[+0.005, +0.007]$ | $[+0.004, +0.008]$ |
| EE (s) | 4 | 6 | 0 | | | |
| ERA ($''$) | 4 | 6 | 0 | ERA | $[-0.007, -0.006]$ | $[-0.008, -0.005]$ |
| EO ($''$) | 4 | 6 | 20% | | | |
| $\Delta\psi$ ($''$) | 4 | 6 | 3 | | | |
| $\Delta\epsilon$ ($''$) | 4 | 6 | 0 | | 0.1 mas | |
| $\epsilon$ ($''$) | 4 | 6 | 0 | $\epsilon$ | $[+41.7, +41.8]$ | $[+41.7, +41.8]$ |
| $X$ ($''$) | 4 | 6 | 15% | $X$ | $[0.00, +0.01]$ | $[0.00, +0.01]$ |
| $Y$ ($''$) | 4 | 6 | 0 | $Y$ | $[0.04]$ | $[+0.03, +0.05]$ |
| **NPB**, **C**$^\dagger$ | 10 | 12 | 15% | $s$ | $[0.0]$ | $[0.00]$ |

was generally better than $9'' \times 10^{-6}$ in right ascension and declination. However, for the Moon, the differences on a few occasions increased to 0.0003 arcseconds, due to the numeric limitations of the double-precision Julian dates used in the light-time iteration. Also, for Uranus and Neptune the difference between the methods increases to 0.0002 arcseconds when their geocentric positions pass nearly behind Jupiter, due to the difference in light deflection calculations.

## 3. ADDITIONAL EXPLANATORY MATERIAL

It is the intention of the UK and US almanac offices to continue to review and improve the formulas and text in Section B of the AsA, and comments and suggestions from users are always welcome. A detailed explanation of the IAU resolutions on positional astronomy passed in 1997 and 2000, along with formulas for their implementation, is given in USNO Circular 179 (Kaplan 2005). The circular, which includes the equations for the P03 precession model, is intended for AsA users and others with an interest in positional astronomy. A new edition of the *Explanatory Supplement to the Astronomical Almanac* is in the early stages of preparation.

## REFERENCES


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