Implementing the IAU 2000 Resolutions in Almanacs

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1 Introduction

Almanacs play the important role of providing practical astronomical data in an accessible form to satisfy a wide variety of user needs. The Nautical Almanac Office of the United States Naval Observatory (USNO), and Her Majesty's Nautical Almanac Office (HMNAO) of the Rutherford Appleton Laboratory, United Kingdom, co-produce several printed almanacs to meet the requirements of specific classes of users. In addition, each office provides almanac data via computer-accessible products, such as data services on the World Wide Web and executable computer applications.

The International Astronomical Union (IAU) adopted a set of resolutions at its 2000 General Assembly (IAU 2000), several of which, if implemented, will directly affect the information published in these almanacs. This paper discusses current plans for implementing the IAU 2000 resolutions in the main almanac products produced by USNO and HMNAO. The implementation plans depend on the specific almanac; therefore, Section II provides brief descriptions of the various products that are potentially affected by the resolutions. Section III discusses some general guidelines that govern the introduction of changes into the almanacs. These guidelines must be taken into consideration when formulating an implementation plan. Finally, Section IV presents the plans for implementing the resolutions that directly affect the almanacs. These plans reflect current thinking, and may change depending on evolving technical factors, or possible programmatic changes in each almanac office.

2 The Almanacs

USNO and HMNAO co-produce several almanac products, each tailored for a particular application or class of applications. The application determines the content and format of the almanac. The primary, jointly produced almanacs are *The Astronomical Almanac*, *The Nautical Almanac*, and *The Air Almanac*. Each one is published annually.

The Astronomical Almanac (AsA) is the flagship publication that contains: precise ephemerides in several coordinate systems for all the major observable objects in the solar system; positions of selected objects outside the solar system; tables of astronomical phenomena; and other reference information. The data in the AsA are tabulated at various precisions: the most precise being the nutation components, which are tabulated to a precision of 1 milliarcsecond (mas), and the geocentric coordinates of the planets, which are given to a precision of 10 mas. The material in the AsA supports applications in a diverse set of disciplines, including astronomy, space science, geodesy, surveying, astrodynamics, military operations planning, litigation, and various types of engineering.

The Nautical Almanac (NA) contains the astronomical data required for celestial navigation at sea. The main pages contain: the Greenwich hour angle and declination of the Sun, Moon, and navigational planets; the Greenwich hour angle of Aries (the vernal equinox); positions of the navigational stars; rise and set times of the Sun and Moon for a range of latitudes; and other data. Most data on the main pages are tabulated at hourly intervals to a precision of 0.1 arcminute. Each edition also contains a sight reduction table, sight reduction formulas, and various correction tables for sight reduction. Both military and civilian marine navigators use the NA.

The Air Almanac (AA) contains the astronomical data required for aircraft navigation. The main pages contain: the Greenwich hour angle and declination of the Sun, Moon, and three navigational planets; the Greenwich hour angle of Aries; rise and set times of the Moon for a range of latitudes; and other data. The data on the main pages are tabulated at 10-minute intervals to a precision of 0.1 arcminute for the Sun and Aries, and 1 arcminute for other bodies. Each edition also contains sky diagrams for each month; sunrise, sunset, and twilight tables; and positions of the navigational stars. A different publication, *The UK Air Almanac*, was introduced by HMNAO in 1998 to meet the specific requirements of the Royal Air Force. It contains illumination information, but no navigational data.

An example of a computer-based almanac is USNO's Multi-year Interactive Computer Almanac (MICA). MICA is an executable application program that calculates, in real time, much of the information tabulated in the AsA. However, MICA goes beyond traditional printed almanacs by enabling the user to calculate data for user-specified locations at user-specified times within a relatively long time interval. The current version (1.5), released in 1998, is valid for a 16-year interval (1990-2005). The most precise data in MICA are tabulated to 1 mas. Designed primarily for professional applications, MICA is intended for the same set of users that use the AsA.

3 General Guidelines for Changing the Almanacs

At their most basic level, the almanacs must be practical. Users rely on the data in the almanacs to support a wide range of applications, such as navigation, pointing a telescope, planning an observing session, or research efforts. Thus, most users expect the content and format of the almanacs to be the same from year to year. For example, many textbooks on navigation (e.g. Bowditch 1995, Hobbs 1990) explain sight reduction by incorporating actual pages from the NA. These textbooks assume that the content and format of the NA main pages will remain the same over a very long period of time. This expectation of consistency in content and format is the main reason why changes to the almanacs occur infrequently and only after careful consideration.

There are several important questions that the almanac maker must answer in deciding whether or not to make a change to a product:

1. Will the change under consideration result in more accurate data or information in the almanacs? An answer of yes to this question is certainly a good reason for making a change, but does not alone guarantee that the change will be made.
2. Is the change under consideration based on sound, established science? Every effort is made to tie data published in the almanacs to fundamental results published in the refereed literature, and to standards established by international scientific bodies such as the IAU. Like Question 1, a "yes" answer to this question does not alone guarantee that a change will be made.
3. Will the change under consideration result in data and information that are relevant to the users of the publication? This is arguably the most important question. A good example of how the inclusion of more accurate data will result in information that is not useful or relevant to the particular user community involves the physical ephemeris of the Sun. The mean elements of the rotation of the Sun, and the daily tabulation of the Sun's rotational parameters, published in the AsA and MICA, are based on the work of Carrington (1863). More modern determinations of the fundamental quantities required for computing the Sun's physical ephemeris are available (e.g. Stark and Wöhl 1981), but the user community requires and expects that the tabulations will be based on Carrington's work. In this case, a "no" answer to Question 3 overrules a "yes" answer to

Questions 1 and 2, and the change to a more modern basis for the tabulated data is not made.

The almanac offices arrive at the answers to these three questions in several ways. Questions 1 and 2 can be answered by attending scientific meetings, reading the literature, and participating in research activities. The answer to Question 3 is more difficult to obtain. The most important factor is maintaining an ongoing communication with the various communities that use the products. Often, this involves effort on the part of the almanac offices, because users typically do not voice their needs or requirements until after a change has been made. User surveys are sometimes a valuable tool. Users of the AsA were last surveyed in 1998 via a form inserted into the book and a more extensive set of questions available on the Web. A survey of users of the AA also was recently completed. Finally, there are times when it is difficult or impossible to obtain clear answers to the three questions. In these instances, the almanac offices use their judgment, based on experience, to make a decision involving the introduction of a change. In the end, the responsibility for determining the content and format of the almanacs rests with the almanac offices.

As an example of this process, important, substantive changes to the AsA were introduced into the edition for 2003. These changes include:

- Use of star positions and proper motions from the Hipparcos (ESA 1997) and Tycho-2 (Høg *et al.* 2000) catalogs;
- Replacement of the DE200/LE200 solar system ephemerides with DE405/LE405 (Standish 1998);
- Updated rotational elements for the planets and satellites based on Seidelmann *et al.* (2000).
- A completely revised section on asteroids, including precise positional information for 15 of the largest asteroids based on modern ephemerides (Hilton 1999).
- Introduction of a complementary Web site, *The Astronomical Almanac Online*, containing data best provided in computer-accessible form.

A long lead-time is required to introduce changes into the almanacs, especially the AsA. The AsA is available to users one year before the year of the edition (e.g. the edition for 2003 was available by January 2002). Production of the book takes place during the year before the edition is available (in this example, production took place during 2001). Thus, ideally, decisions regarding changes to the AsA are reflected in the book two years after the decision has been implemented. Additional time is needed to develop, implement, and test new production software when major changes are introduced.

4 Plans for Implementing the IAU 2000 Resolutions

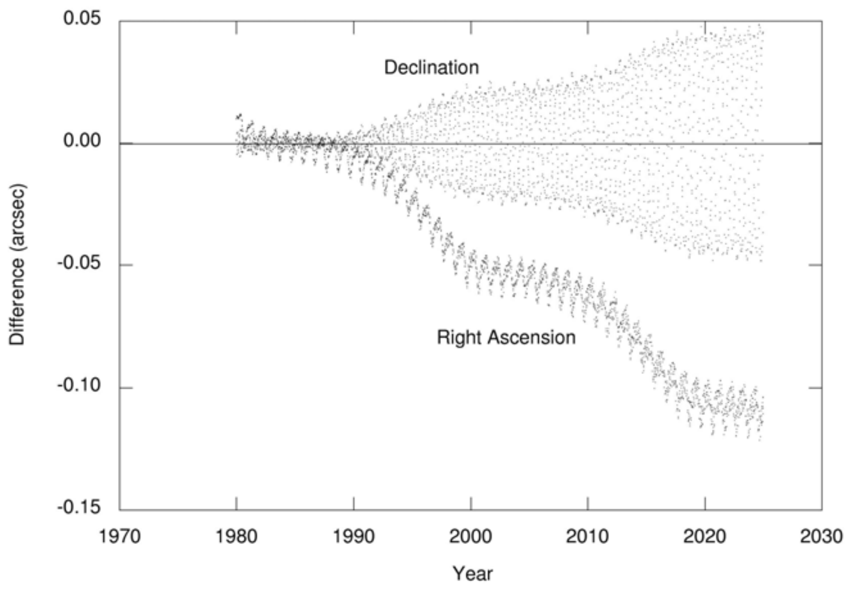
Three resolutions adopted at the 2000 IAU General Assembly in Manchester, UK, have the potential to impact directly the data provided in future editions of the almanac products. These resolutions are B1.6 (IAU 2000 Precession-Nutation Model), B1.7 (Definition of the Celestial Intermediate Pole), and B1.8 (Definition and Use of Celestial and Terrestrial Ephemeris Origins). An additional resolution, B2 (Coordinated Universal Time), could have an indirect but important effect on the navigational almanacs.

Resolution B1.6 recommends that "… the IAU 1976 Precession Model and IAU 1980 Theory of Nutation be replaced by the precession-nutation model IAU 2000A… for those who need a model at the 0.2 milliarcsecond (mas) level, or its shorter version IAU 2000B for those who need a model only at the 1 mas level, together with their associated precession and obliquity rates, and their associated celestial pole offsets at J2000.0…." The inadequacies of the IAU 1976 precession model and the IAU 1980 Theory of Nutation have been known for some time (see, for example, McCarthy and Luzum 1991), so IAU-sanctioned, improved replacements for these models are strong candidates for use in the almanacs. Software implementations of the two versions of the IAU 2000 model became available during 2001 and early 2002. Both the IAU 2000A and IAU 2000B software modules contain corrections to the IAU 1976 precession model; thus, the new precession-nutation (PN) model does not *replace* the old precession model as the resolution states. Rather, the new PN model must be used *in conjunction with* the old precession model.

Figure 1 gives an example of how the new PN model affects the computation of apparent places. This figure shows the differences between the apparent coordinates of the Moon computed using the new IAU 2000B PN model and the old IAU 1980 Theory of Nutation (Seidelmann 1982). The difference in right ascension grows from approximately 0.05 arcsecond in 2000 to 0.10 arcsecond in 2020. The maximum difference in declination over the same period ranges from approximately 0.02-0.05 arcsecond. Thus, the difference will be evident in the values tabulated in the AsA that involve apparent places.

Current plans call for the IAU 2000 PN model, probably the IAU 2000B version, to be implemented in the AsA beginning with the edition for 2005. The AsA provides data referenced to both the mean and true equinoxes of date. Because the new IAU PN model embeds the precession corrections in the nutation model, only true and apparent places will use the improved algorithm. Unless a new, independent precession model is developed and adopted, all data based on mean places of date must continue to use the IAU 1976 Precession Model, and thus will not include the precession correction. There are no immediate plans to implement the IAU 2000 PN model in the navigational almanacs (i.e. the NA and AA), since the change will have only a small, indirect effect on the tabulated values and will not improve navigational accuracy.

Figure 1: Differences in apparent right ascension ($\Delta\alpha \cos\delta$) and apparent declination (δ) of the Moon, computed using the IAU 2000B Precession-Nutation Model and the IAU 1980 Theory of Nutation. These calculations were made using the DE405/LE405 ephemerides, which are currently used in the AsA.



Neither IAU 2000A nor IAU 2000B is an optimal solution for an interactive computer application, such as the next version (2.0) of MICA. IAU 2000A carries significant computational overhead, with nearly 1400 terms and more precision than is needed. IAU 2000B has an order of magnitude fewer terms (77), and agreement with IAU 2000A to 1 mas in the interval 1995-2050 (McCarthy and Luzum 2001). However, MICA 2.0 will provide data in the interval 1850-2050, making IAU 2000B also a sub-optimal choice. From a computational viewpoint, the SF2001 PN theory (Shirai and Fukushima 2001) with 194 terms is a good compromise, although it is not IAU-sanctioned.

Resolutions B1.7 and B1.8 will be considered together. Resolution B1.7 introduces and defines the Celestial Intermediate Pole (CIP). Resolution B1.8 introduces and defines two other related concepts: the Celestial Ephemeris Origin (CEO) or "non-rotating origin," and the Earth Rotation Angle (ERA). The practical consequence of these two resolutions is to introduce a fundamental change to the geocentric celestial reference system, the terrestrial reference system, and the transformation between these systems. Concepts such as the vernal equinox as the origin of right ascension, the fundamental role of the ecliptic in defining the reference system, sidereal time, and conventional definitions of precession and nutation ($\Delta\Psi$ and $\Delta\varepsilon$) – the "classical paradigm" – are replaced by concepts such as the CEO, the CIP, the ERA (θ), and the quantities X, Y, and s – the "new paradigm" (Capitaine *et al.* 2000; Seidelmann and Kovalevsky 2002).

Implementing such a radical change in the almanacs requires a careful approach. This is especially true because the almanac user community is very broad. This community includes not only specialist astronomers, but also many non-specialist scientists and engineers. Many of these users do not read the specialized astrometry literature, and thus are unaware of the resolutions, let alone the practical consequences of the resolutions. Furthermore, it will take a considerable amount of time for many user systems to implement the resolutions. For example, implementing the new paradigm in commercial software systems requires code changes that cost money; cost alone will undoubtedly slow adoption of the new paradigm by some users of the almanacs. In short, premature and exclusive implementation of the new paradigm in the almanacs has the potential to make the almanacs irrelevant to many, if not most, users.

In light of this situation, the almanac offices have formulated a general plan for implementing Resolutions B1.7 and B1.8:

- A considerable amount of education is needed to introduce these resolutions to the broad community that uses the AsA. The IAU and the International Earth Rotation Service (IERS) must take the lead role in this important task. To assist in this effort, USNO and HMNAO have undertaken work on a USNO Circular that will describe in a practical way all IAU resolutions that have affected the almanacs since 1984. This Circular, which will also appear in stages as a supplement inside the AsA, will be ready in 2003. In addition, the two offices are participating in a project to revise the *Explanatory Supplement to The Astronomical Almanac* (Seidelmann 1992). Both of these publications will contain explanatory material on the IAU 2000 resolutions.
- Tabulations of the new-paradigm parameters X, Y, s, and θ will be published in the AsA or on its associated Web site possibly beginning as early as the edition for 2005.
- More material based on the new paradigm will be introduced into the AsA over time. However, the almanac offices anticipate that it will be necessary to continue to provide material based on the classical paradigm for a considerable period into the future. The time period for providing parallel data in the two paradigms will be determined by user needs and requirements. Careful design of the almanac material will be needed to keep the two paradigms apart.
- There are no plans to introduce the new paradigm into the navigational almanacs.

- To support fully improved data in the classical paradigm, USNO will participate in the development of a new precession theory consistent with the IAU 2000A model, as encouraged by Resolution B1.6. This activity is also consistent with the recommendations of Resolution B1.8.

Resolution B2 recommends that the IAU establish a working group to consider the redefinition of Coordinated Universal Time (UTC). This working group will discuss the requirement for leap seconds, and options for UTC, in cooperation with appropriate groups from other international organizations. Nelson *et al.* (2001) give a review of the history and issues regarding leap seconds. The current practice of celestial navigation, especially sight reduction using printed almanacs and worksheets, relies on the assumption that UT1 is kept close to UTC: a navigator "tags" his/her sights (sextant observations) with a UTC time, and reduces the sights with an almanac whose time argument is UT1. Currently, UTC is maintained to within 0.9 s of UT1; this produces a maximum error of approximately 0.4 km in position (longitude), which is significantly less than the error in the sextant observations (1-2 arcminutes, or approximately 2-4 km at the surface of the Earth). Because of this, typical sight-reduction procedures contain no provision for accounting for UT1-UTC. A significant change to the definition of UTC will likely require a change to the navigational almanacs. Despite the general adoption of the Global Positioning System (GPS) as the worldwide primary navigational system, celestial navigation is still routinely practiced as a backup means of navigation, and is still *required* by navies (e.g the US and UK navies) and merchant marine interests. A change to the definition of UTC will also affect several sections of the AsA that are based on UT1, primarily those sections that tabulate phenomena. Again, in these cases the assumption is made that UT1 and UTC are kept close to each other.

5 Summary

Almanacs provide practical astronomical data in an accessible form to satisfy the needs of a wide variety of user applications. HMNAO and USNO co-produce several printed almanacs to meet the requirements of specific classes of users, and each office provides almanac data via the World Wide Web and executable computer applications. *The Nautical Almanac* and *The Air Almanac* provide astronomical data to meet the needs of navigators, while *The Astronomical Almanac* meets the needs of a diverse set of users, including astronomers, other scientists, and engineers. Resolutions B1.6, B1.7, and B1.8, adopted at the 2000 IAU General Assembly, if implemented, will have a direct impact on the data and other information tabulated in the almanacs, especially the AsA. Changes to the almanacs are made as infrequently as possible, and with careful deliberation. The almanac makers implement a proposed change when it results in more accurate information in the almanacs, is based on sound scientific underpinnings, and results in data or information relevant to the users of the almanac. The IAU 2000 resolutions must be considered in this context before they are implemented in the almanacs. Thus, there are no immediate plans to incorporate the resolutions into the navigational almanacs, since the changes will not improve navigational accuracy, and the format changes will not be useful to the users. The current plans for the AsA call for:

- the IAU 2000 PN model to be implemented beginning with the edition for 2005;
- publication of a USNO Circular that will describe in a practical way all IAU resolutions that have affected the AsA since 1984, to be ready in 2003;
- revision of the *Explanatory Supplement to the Astronomical Almanac*, which will contain explanatory material on the IAU 2000 resolutions;
- tabulations of the new-paradigm parameters X, Y, and s, and θ to be published in the AsA or on its associated Web site possibly beginning as early as the edition for 2005;
- over time, introduction of more material based on the new paradigm;

- continued production of material based on the classical paradigm for a considerable period into the future. The time period for providing parallel data in the two paradigms will be determined by user needs and requirements;
- participation in the development of a new precession theory consistent with the IAU 2000A model, as specifically encouraged by Resolution B1.6.

These plans reflect current thinking, and may change depending on evolving technical factors, or possible programmatic changes in each almanac office. Finally, a possible redefinition of UTC, which is the subject of Resolution B2, could have an impact on the almanacs, especially the navigational almanacs. No change to UTC has been formally proposed, so it is premature to provide a plan.

6 Acknowledgments

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