Software for Implementing the IAU 2000 Resolutions

Patrick Wallace

H.M. Nautical Almanac Office
Space Science and Technology Department
CLRC / Rutherford Appleton Laboratory

1 Introduction

At its XXIVth General Assembly, the International Astronomical Union adopted a number of resolutions concerning reference frames and time scales (IAU 2000). Many users will encounter the consequences of these resolutions in indirect ways, for example in the form of slightly changed tabulations in the almanacs. But many others will need new tools to help them to implement the changes in their own applications. These tools may be in the form of written prescriptions and special tabulations; however, it is vital also for actual software to be available. Such software not only avoids duplicated effort but also *defines* without ambiguity how the calculations concerned are to be carried out.

These considerations are normal whenever existing standards are changed; however certain aspects of the 2000 resolutions amount to a change in paradigm, requiring quite new strategies.

2 Available Software

The IAU *Standards Of Fundamental Astronomy* software (SOFA, Wallace 1996) comprises, at present, 79 Fortran subprograms. The collection provides a number of basic components relevant to implementing the new system:

- Routines for standard vector and matrix operations, formatting angles, dealing with spherical coordinates and so on.
- Facilities for handling calendars, epochs and time scales.
- Some limited solar-system ephemeris models, links between FK5 and ICRS, and pre-2000 Earth attitude models.
- Rigorous handling of star space-motion, taking into account both classical light-time effects and special relativity.

In addition to SOFA, a number of other libraries and packages offer a basis for implementing the 2000 standards, including SLALIB (Wallace 1994) and NOVAS (Kaplan *et al.* 1989).

As well as these general frameworks, two key algorithms have recently been published in the form of Fortran code, namely the IAU 2000A and IAU 2000B precession-nutation models (Luzum 2001, McCarthy and Luzum 2001). The rest of this report concentrates on implementing these models and on the related topic of providing tools for using Earth Rotation Angle and the Celestial Ephemeris Origin. Other aspects of the IAU 2000 system, for example in the area of time scales, will not be further discussed here.

3 New Software

The SOFA Review Board is currently considering the next tranche of new routines. These are certain to include provision for implementing elements of the IAU 2000 system, but what form this provision takes will depend on the Board's deliberations, and the proposals set out below must at this stage be regarded as just one possible way forward.

An important issue that must be addressed at the outset is the extent to which existing users of the classical (equinox-based) paradigm should be supported. These users, who comprise the overwhelming majority of the astronomical community, will expect all the benefits of the new resolutions, in terms of improved accuracy and compliance with IAU standards, but in a form that imposes little or no additional inconvenience. It will be many years before most users can make the full transition to the new paradigm, and at present few see the need to do so. Thus for the foreseeable future the suppliers of almanacs and standard software have a duty to offer tools to implement *both* the classical and new methods. With this principle in mind, the following capabilities could be added to the SOFA software:

Supporting both the **classical** and **new** paradigms:

- Implementations of the IAU 2000A and 2000B precession-nutation models.
- A routine that generates the polar-motion matrix (given x,y and, in the new paradigm, s').

Supporting the **classical** paradigm:

- A routine that implements the frame bias (GCRS to dynamical).
- A routine that generates the classical precession matrix.
- Routines that generate the nutation matrix (for both the A and B models).
- Routines that provide the final GCRS-to-true matrices (A and B).
- A GMST routine that includes the IAU 2000A/B precession adjustments.
- Routines that generate the equation of the equinoxes using the new nutation models (A and B).

Supporting the **new** paradigm:

- A routine that generates Earth Rotation Angle.
- Routines that generate the GCRS to intermediate matrix (A and B).
- Routines that generate the GCRS to TRS matrix (A and B).
- Routines to transform between astrometric, topocentric and observed places.

Note that in this scheme the goal of predicting topocentric and observed places is achieved solely by applying the *new* paradigm. The classical provisions are intended to provide "plug-compatible" replacements for users' existing components, consistent with the latest IAU models.

4 Implementing IAU 2000A/B

Comparisons have recently been carried out (Capitaine *et al.* 2002), of CIP predictions using (a) a classical precession-nutation formulation and (b) the X,Y formulation described in Capitaine *et al.* (2000), both using the IAU 2000A nutation. These tests have raised doubts about whether the published IAU 2000A algorithm fully meets the requirements of IAU 2000 Resolution B1.6.

The IAU 2000A algorithm is at heart a *nutation* model, and, although the code also provides definitive information about frame bias and precession rates, there are ambiguities over how to form the precession part of the model and how to combine the various corrections. Also, the algorithm does not address the question of offset in Right Ascension between the ICRS and mean dynamical frame at J2000. The consequences of these ambiguities and omissions are not large, but do exceed the stated accuracy objectives after a few decades. They could be resolved as follows:

- It seems most natural to use the frame bias X,Y components from IAU 2000A, together with an agreed $\Delta\alpha$, to implement the GCRS $\leftrightarrow$ dynamical rotation as a separate step.

- The CIP precession model needs to be spelt out, stipulating the specific set of Euler rotations to be used. For example we can use $R_3(\chi_A)R_1(-\omega_A)R_3(-\psi_A)R_1(\varepsilon_0)$ with the angles from Lieske *et al.* (1977) plus corrections $\Delta\psi,\Delta\varepsilon$ from IAU 2000A/B. Once the precession model is fixed, a revised GMST model can be obtained.
- The nutation angles (lunisolar + planetary) given directly by IAU 2000A (or B, depending on the user's accuracy requirements) can be used to form the nutation matrix and to calculate the equation of the equinoxes.
- The various components then play their normal roles in the classical transformation, delivering results that are fully compatible with the new paradigm.

To support the new paradigm, CIP X,Y can be obtained from the classical transformation, forming the bridge between the old and new paradigms. Alternatively, X,Y can be calculated directly (Capitaine *et al.* 2000), avoiding separate frame bias, precession and nutation stages. After evaluating s (*ibid.*), the GCRS $\leftrightarrow$ intermediate matrix can be generated. Figure 1 illustrates the two paradigms in action, both calculating Greenwich apparent hour angle and declination starting from star data in ICRS.

5 Options for Future Precession-Nutation Models

It should of course be borne in mind that the IAU resolutions themselves urge further work (on the precession component in particular: B1.6 recommendation 3): the IAU 2000A code itself is not necessarily the last word. In due course, a fully recomputed model, based on the latest results and compatible with IAU 2000A nutation, is needed.

How best to *define* the CIP is a moot point. The alternatives are separately defined transformations—bias, precession, nutation—or direct generation of X,Y. The former maintains maximum overlap between the classical and new paradigms and fits in with IAU 2000A/B; the latter is succinct and more in keeping with the post-classical spirit of the IAU 2000 resolutions, eliminates awkward questions about the overlap between precession and very-long-period nutation terms, and sidesteps all the dangers of mixing incompatible precession and nutation models or implementing them in unsuitable ways. Which should form future defining IAU standards is debatable; perhaps the relationship to VLBI observables will be a guide.

A related issue is whether it is appropriate for the IAU precession-nutation model to be truly state-of-the-art. The IAU 2000A model comprises almost 1400 terms, with coefficients as small as 100 nanoarcseconds, yet delivers an absolute accuracy of some tenths of a milliarcsecond. The limitation is the essentially unpredictable Free-Core-Nutations, which effectively set a "noise floor" for any closed-formula model. Users requiring the latest and best results are obliged to supplement their fixed nutation model with continuously updated FCN corrections; it could be argued, therefore, that a concise standard model could be adopted and corrections relative to that model, comprising both FCN and the tiny missing terms, be supplied. An obvious contender for such a "concise standard model" is IAU 2000B. However, in the present context IAU 2000B sacrifices more accuracy than need be, taking it well clear of the FCN noise floor. Perhaps a better compromise is SF2001 (Shirai and Fukushima 2001), which achieves 300 microarcseconds accuracy with only 194 terms.

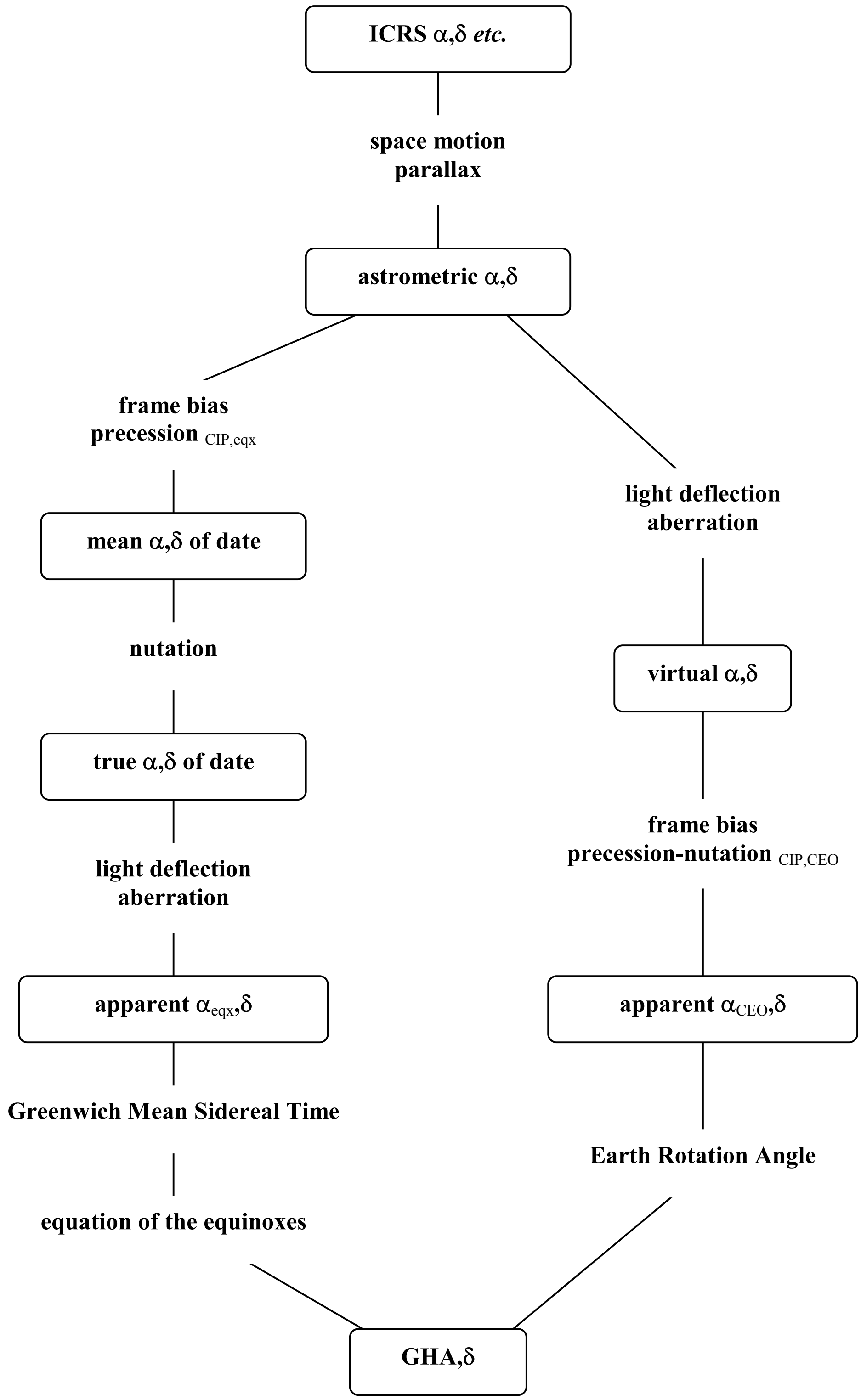

Figure 1
Two ways of predicting the Greenwich apparent hour angle and declination of a star. The left-hand branch shows one form of the classical procedure; the right-hand branch follows the IAU 2000 procedure.

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