RECENT SOFA DEVELOPMENTS

P.T. WALLACE
Space Science & Technology Department, Rutherford Appleton Laboratory,
Harwell Science and Innovation Campus, Didcot, Oxfordshire, OX11 0QX, UK
e-mail: patrick.wallace@stfc.ac.uk

ABSTRACT. SOFA is an IAU Division 1 service that provides authoritative fundamental-astronomy algorithms, including models for precession-nutation and Earth rotation. The selection of algorithms and the development of computer code is supervised by an international panel called the SOFA Review Board, and the resulting software collection is published through a dedicated website. The collection at present comprises 108 astronomy routines, 41 of which implement canonical models, plus 52 vector/matrix routines, all written in Fortran 77. Recent developments include (i) an explanatory document covering the facilities for calculating Earth orientation, (ii) a second version of the Collection, written in the C programming language, and (iii) a relaxation of the licensing conditions to facilitate use by industry. The presentation looks at aspects of the 2006 changes in the IAU precession-nutation, the increasing importance of software in the implementation of IAU models, and plans for strengthening SOFA's links with other components of IAU Division 1 and with the IERS.

1. INTRODUCTION

SOFA, which stands for *Standards of Fundamental Astronomy,* is a service operated by IAU Division 1 to provide authoritative fundamental-astronomy algorithms. It is run by an international panel, the *SOFA Reviewing Board,* and reports through Commission 19 (Rotation of the Earth). To reflect the breadth of the inputs needed for SOFA to perform its function effectively, the Board includes experts in fundamental astronomy and software, and its membership overlaps with relevant IAU working groups and the IERS Conventions effort. The present membership is John Bangert (USNO, USA), Mark Calabretta (ATNF, Australia), Anne-Marie Gontier (Observatoire de Paris, France), Catherine Hohenkerk (HMNAO, UK), Wen-Jing Jin (Shanghai Observatory, China), Brian Luzum (USNO, USA), Zinovy Malkin (Pulkovo Observatory, Russia), Jeffrey Percival (University of Wisconsin, USA) and Patrick Wallace (RAL, UK, chair). Board members who participated in the work discussed in this paper but who stepped down during 2007 were Wim Brouw (University of Groningen, Netherlands) and Dennis McCarthy (USNO, USA).

2. THE SOFA SOFTWARE COLLECTION

SOFA's output is in the form of a collection of computer codes, distributed through a website.[1] At the time of writing, the SOFA Software Collection comprises 160 Fortran subprograms. Two-thirds of these routines perform astronomical actions, the remainder providing support for vectors, rotation matrices and angular coordinates. Excluding pro forma license statements, the number of lines of code is just under 25,000, roughly half of which are comments.

A great many SOFA routines implement successive IAU precession-nutation models. Other topics include calendars, time scales, ephemerides (low precision), Earth rotation, polar motion, star space motion and certain star catalog transformations. A distinction is made between SOFA routines that implement specific models and ones that help knit these together into useful tools. 41 of the astronomy routines have the designation "canonical model", while the other 67 are classed as "support routines" (supplemented in turn by the 52 vector-matrix routines). These distinctions are important to some end

[1]The SOFA URL is currently http://www.iau-sofa.rl.ac.uk/; the website is hosted by the UK Hydrographic Office and maintained by staff of H.M. Nautical Almanac Office.

users, and are clearly specified in the preamble comments to each routine.

3. RECENT DEVELOPMENTS

The SOFA work during the year starting mid-2007 reflect decisions and recommendations made at a meeting of the Board held in Paris during April 2007. The main developments have been as follows:

- A new software release (Number 4, August 2007) was made that contains 39 additional Fortran SOFA routines to implement the IAU 2006 (P03, Capitaine et al. 2003) precession model that comes into force on 2009 January 1. In order to support the methods specified in IERS Conventions 2003, the SOFA routines include implementations of the precession-nutation based on direct series for CIP X, Y as well as implementations using spherical angles.[2]

- SOFA's software documentation consists mainly of the preamble comments that begin each routine. These are quite detailed and offer a good resource for "reference" purposes, but lack any kind of tutorial qualities. The Board decided to supplement this material with a 38-page "cookbook", called *SOFA Tools for Earth Attitude*.[3] While concentrating on Earth-attitude applications, the cookbook contains detailed examples that touch upon a wide range of SOFA capabilities.

- A version of the SOFA software in a second programming language, namely ANSI C, has been developed. See Section 4 for details.

- Fortran and C testbed programs have been developed. (The Fortran testbed was kindly contributed by Beth Stetzler of USNO.) These allow an end user to verify that he or she has successfully built the SOFA library, and that every routine can be called and passes simple tests.

- The licensing conditions for SOFA routines have been relaxed, to permit free use for all classes of user while at the same time protecting against unapproved modifications. Further details are given in Section 5.

- Consultations have been made concerning SOFA's role and its relationships with IAU Division 1 and IERS Conventions. This topic is developed in Sections 6 & 7.

4. SOFA/C

The SOFA Board's original decision to use Fortran 77 was conservative, but consistent with practices in fundamental astronomy at that time (1997). However, the development of versions of the SOFA software written in other programming languages was planned from the start.

The ultimate decision that the second version would be in ANSI C was reached after much debate, with some Board members favouring a modern object oriented (OO) language such as Java or C++. The further possibility was discussed of developing a special SOFA macro language which would capture algorithms once and for all, and allow automatic translation into multiple languages for distribution. However, after informal polls of the community, and having due regard for the available effort and expertise, it was decided to opt for plain ANSI C, and moreover to retain much the same structure (argument lists etc.) as the existing Fortran. However, internally the functions use C idiomatically, and features missing from Fortran such as a portable "include" are used to the full.

Apart from being a useful resource in its own right, the resulting C library is a good starting point for applications written in Java, C++, Python and so on, and it can be argued that the low-level approach SOFA has adopted avoids eroding the user's freedom of choice when designing the OO classes. At the time of writing, SOFA/C is complete, and release is imminent.

5. SOFTWARE LICENSING

The original license conditions for the SOFA software were drawn up with considerable care. The SOFA Board asserted ownership of the software and granted free use for non-profit research purposes, but

[2]This mixed canonical basis is a potential danger, and the end user is warned not to develop applications that use both methods and are sensitive to the microarcsecond-level differences between them.

[3]See http://www.iau-sofa.rl.ac.uk/2007_0810/sofa/sofa_pn.pdf

retained the right to charge a fee for commercial use. However, when enquiries from aerospace companies about acquiring SOFA licenses began to be received – there have been a handful of such cases to date – the obstacles to commercial exploitation became clear. The whole concept went against the grain of IAU (and IERS) activities in general, and none of the institutes of individual Board members was in a position to administer such a scheme. Consequently, the Board agreed it would be best to make the SOFA Collection "free software".

This left two problems to be solved. The first was that some of the standard free-software licenses, notably the GNU General Public License (GPL),[4] contain what has been called a "viral" element, that effectively prevents commercial use: when a company incorporates GPL items in its own products, the latter inherit the license conditions, which is usually not acceptable. The second difficulty was that whereas the world of free software approves of, and actively encourages, modification and enhancement by end users, as a way of harnessing "free" effort, this is anathema to SOFA: the circulation of "improved" versions, under the IAU banner, would be certain to lead to endless confusion. These rather unusual considerations made it necessary for SOFA once again to develop its own license conditions.

In the new SOFA license, free use is granted to all classes of user. Users may develop and distribute "derived works", but subject to these conditions (among others):

- Such derived works must say they use SOFA techniques but must not contain straight copies of what SOFA distributes;
- The source code must describe its relationship to SOFA;
- Routine names must be different from SOFA originals, and use of the *iau* prefix is prohibited;
- There must be no misrepresentation or false authorship claims, and no patent applications for SOFA algorithms;
- SOFA requirements must be reproduced intact and apply to users of the derived work.

6. USER CONFIDENCE

During the year covered by this report, the Board looked into complaints from one or two potential users that the official status of the SOFA software was unclear. SOFA has a very low profile as far as the IAU web site is concerned, and software products from such authorities as IERS Conventions appear to differ in subtle ways from what SOFA has provided. The user is thus faced with competing products, all claiming to be IAU-consistent, and all supposedly authoritative. What defines an IAU approved model?

- The wording of the Resolution?
- A Working Group report?
- A piece of software?
- A published paper?

...or some combination of the above? The related question is what the user is expected to do when shortcomings and differences surface.

A case in point is the IAU 2000A precession-nutation. The IAU Resolution (B1.6, 2000) adopted something that was at the time awaiting publication. The first authoritative realization available to the SOFA Board was the MHB_2000 Fortran code that was in circulation; SOFA adopted this code as its reference: SOFA's implementation must match to bit accuracy the numbers produced by MHB_2000. However:

- MHB_2000 treated the frame bias and the precession rate adjustments as if they were nutation components, applied in the mean system of date rather than of epoch. SOFA instead applies them directly to the appropriate classical precession angles.
- Only two components of the frame bias (ΔX and ΔY) were specified: SOFA added the missing third component, $\Delta\alpha$.

[4] http://www.gnu.org/licenses

- The MHB_2000 code used different Delaunay argument expressions for the luni-solar and planetary terms respectively; this oddity was retained by SOFA.
- The planetary argument expressions used in MHB_2000 were not quite the same as in the original references quoted; SOFA retained the MHB_2000 versions.
- The 1365 nutation terms included 38 duplicated and 3 triplicated frequencies; these were not noticed in time and appear in the SOFA code.
- The MHB_2000 code omitted certain small terms (the t term in the out-of-phase luni-solar amplitudes) that appeared in the tables subsequently published (and adopted by IERS Conventions).

There is in addition the problem (for users) that there are two different methods of implementing the IAU 2000A precession-nutation: via the classical angles, used by MHB_2000 and by SOFA, and via direct series for X, Y, used by IERS Conventions.

Most of these differences have only a small effect, undetectable by VLBI, but enough to be noticed by users comparing results from SOFA, IERS Conventions, the USNO NOVAS software and so on, all of which made different choices. And when the IAU replaced the precession part of the model with the P03 theory (2006, Resolution B.1) nothing was said explicitly about the tiny adjustments needed when combining the new precession model, with its revised obliquity and inclusion of $\dot{J}_2$, with the existing IAU 2000A nutation.

In the author's view, imperfections, ambiguities and omissions are inevitable when drawing up IAU Resolutions, and the problem for the community is how to deal with that fact of life. The questions to be answered include (i) Should the process of establishing IAU recommended models for fundamental astronomy be revised? (ii) Is the 3-year cycle too long? and (iii) Should a computer algorithm be a part of future Resolutions? The last suggestion would be a radical departure, but would eliminate uncertainty and ambiguity almost completely. Where the issue is less about algorithmic complication and more about the sheer size of a model, the alternative is for the IAU Resolution to refer to electronic tables that can be accessed through the Internet.

7. SOFA IN THE IAU HIERARCHY

The difficulties raised in the previous Section lead naturally to questions about SOFA's role and standing, and how it relates to the IAU and IERS. Does SOFA's status need to be more visibly endorsed by the IAU (and also the IERS)? For one thing, Board members need to convince their institutes that their SOFA work is important, and a more visible endorsement by the IAU would help. But more crucially the community must be able to trust the SOFA software, be confident of its long-term availability and support, and be convinced that the underlying review procedures are sound.

Another issue is SOFA's relationship to the IERS Conventions effort. The links between the two have grown over the years. Prior to the 2003 uptake of the IAU 2000A precession-nutation, SOFA-compatible software was supplied for the IERS Conventions website, and when designing new software to support the introduction of the IAU 2006 precession SOFA made decisions with IERS requirements specifically in mind (notably the implementation of the direct series for X, Y). More recently, there have been moves to harmonize IERS Conventions with SOFA programming standards. Possibilities for further strengthening the SOFA/IERS links have been raised by the IAU representative on the IERS Directing Board.

8. THE FUTURE

The completion of the SOFA algorithms for IAU 2006 precession and the imminent release of the C version have eased the pressure on SOFA to develop new software. The next technical area to consider might be the transformation between the barycentric and geocentric reference systems: parallax, light deflection and aberration. This means that the most important SOFA activities at present are to review and reform its constitution.

The immediate questions for IAU Division 1 are whether the SOFA Board should be enlarged, whether its constitution should be more formally defined, and whether it should be obliged to consult more widely than it does at present. The possibility of raising SOFA's profile on the IAU website needs to be raised. And, assuming SOFA is to continue its IAU Division 1 role, could it do so as part of a larger group of standards-related activities, located in an appropriate Commission?