SOFA—A STATUS REPORT, REVIEW AND LOOK TO THE FUTURE

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ABSTRACT. Standards of Fundamental Astronomy (SOFA) is an International Astronomical Union (IAU) service that provides accessible and authoritative algorithms and procedures that implement standard models used in fundamental astronomy. SOFA consists of a dedicated web site from which the SOFA Software Collections may be downloaded and a Board that provides and checks the material. At present this IAU Division 1 activity reports to IAU Commission 19; however the members of the international Board are selected from various Commissions. This presentation looks at SOFA's development, in particular over the last few years. For the future we consider what SOFA needs to provide and its place within the IAU.

1. SOFA — A REVIEW

SOFA is an IAU initiative started by Division 1, that has the task of establishing and maintaining an accessible and authoritative set of algorithms and procedures that implement standard models used in fundamental astronomy.

SOFA provides a collection of routines, a library, in both Fortran and ANSI C, which form a basis, the building blocks, to enable users to write their own applications, using authoritative methods. For example, there are routines that calculate precession and nutation angles, and the transformation matrix between the celestial and terrestrial reference systems that support IAU Resolutions.

To do this successfully there is a Board of experts that produces and validates the material and a web site from where the libraries may be obtained. The current Board members are John Bangert (US Naval Observatory, USA), Steve Bell (Webmaster, HM Nautical Almanac Office (UKHO), UK), Mark Calabretta (Australia Telescope National Facility, Australia), Anne-Marie Gontier[1] (Observatoire de Paris, France), George Hobbs, (Australia Telescope National Facility, Australia), Catherine Hohenkerk (Chair, HM Nautical Almanac Office, UK), Wen-Jing Jin (Shanghai Observatory, China), Brian Luzum (IERS, US Naval Observatory, USA), Zinovy Malkin (Pulkovo Observatory, Russia), Jeffrey Percival (University of Wisconsin, USA), Patrick Wallace (Rutherford Appleton Laboratory, UK). The Board represents, from IAU Division 1, Commissions on Ephemerides (4), Astrometry (8), Earth Rotation (19), Time (31) and Relativity (52). This includes members of the current working group on Numerical Standards for Fundamental Astronomy (NFSA). From Division XII we also represent Commission 5, and the Working Groups on FITS and Astronomical Data.

SOFA was initially set up by the IAU in 1994 under the Division 1 Working Group on Astronomical Standards (WGAS). Patrick Wallace was appointed as the first Chair of the SOFA Board in February 1996, a position he held for the Board's first 15 years. Work really began after the first Board meeting, in October of 1996. The first Fortran release was made in 2001 March, while the first ANSI C release was achieved in February 2009. The latest release, in January 2010, made available the seventh Fortran release and the second ANSI-C release. On March 20th of this year, Patrick Wallace stepped down and the Board elected Catherine Hohenkerk as the new Chair. The whole Board were pleased that Wallace wished to continue as a member of the Board and intended to continue providing the various routines.

The SOFA Centre is its web site (www.iausofa.org). It is the public face of SOFA. From this web site users navigate to each routine and view or copy the source code for that individual routine. Alternatively either of the current libraries, Fortran or ANSI C, may be downloaded. It also is an archive where

[1]It is with great sadness that we record the untimely death of Anne-Marie Gontier on September 24th 2010, just after the Journées in which she participated. Anne-Marie had been a member of the board almost from the beginning, which provided a strong link with the Observatoire de Paris that has been to SOFA's great benefit.

previous releases may be obtained. Over the last three years, for which statistics are available, the site receives about 800 unique visitors each month from over 100 countries.

2. SOFA'S CURRENT SOFTWARE COLLECTION

There are at present 113 astronomy routines that cover categories for:

- calendars (7),
- time scales (2),
- Earth rotation and sidereal time (15),
- ephemerides (2),
- fundamental arguments (14),
- geocentric/geodetic transformations (5),
- precession/nutation/polar motion (60),
- star space motion (2),
- star catalogue conversions (6).

Those that support IAU resolutions, such as those on precession and nutation angles, are designated as canonical routines, as are those for the fundamental arguments used for nutation. There are also the 52 utility (support) routines that perform the basic vector/matrix manipulations, conversion of degrees to radians, etc.

There are two types of documentation. There are the introductory comments to the code giving detailed information, such as what the routine does and how it is used. This includes information on the input and output arguments, the accuracy of the algorithm, as well as the references that it is based on. These preambles to each routine are pulled together into the manual. This type of information is terse and although fully specifies the routine, is not aimed at the beginner. The manual is supplied both as an ASCII (.lis) file and an Adobe Acrobat (.pdf) file. It has also been split up into smaller more useful sections; title, board members, copyright information, vector-matrix library (vml), astronomy library (lib), etc., so users need only look at what is relevant to them.

The other type of documentation are Cookbooks, each of which contains more descriptive material and includes examples, with code and intermediary results. The first cookbook, *SOFA Tools for Earth Attitude*, deals with both the equinox based and CIO based methods of transformations from the Geocentric Celestial Reference System (GCRS) to the International Terrestrial Reference System (ITRS). Included is the complete Fortran program that computes the transformation, which demonstrates five methods viz:

1. IAU 1976/1980/1982/1994 (equinox based),
2. IAU 2000A, CIO based using classical angles,
3. IAU 2000A, equinox based, using classical angles,
4. IAU 2006/2000A, CIO based using classical angles, and
5. IAU 2006/2000A, CIO based, using X, Y series.

Before the SOFA library is used it is very important to ensure that on your computer system things are working as expected. SOFA provides a tool, a validation program, for both the Fortran (`t_sofa_f.for`) and ANSI C (`t_sofa_c.c`) that is run during the compilation process (`make test`), which does this check. This is not an exhaustive test, but the validation program does call all the routines and checks the calculated results against stored values to some specified precision. The stored values have been produced independently using quadruple precision. At the end of the process a message will be displayed. Note: Users who encounter a failure of the validation program are encouraged to contact the Board

(sofa@ukho.gov.uk), noting details of the system (i.e., compiler, operating system, and hardware) upon which the failure took place.

3. LATEST RELEASE OF SOFA

In January of this year (the latest release), the SOFA web site was moved to www.iausofa.org, a web site hosted at the United Kingdom Hydrographic Office (UKHO). Since its address is independent of the host institution, in theory, if the webmaster needs to move the web site, then this will not affect users. At the same time the web site was given a new design. All the previous features are included, but the presentation has been streamlined. At present requests to the older web sites are being forwarded, however, at the next release these older sites will be removed.

A new feature allows users to register their e-mail address so that they may receive news about errors and updates. This also gives the Board some idea of how SOFA is being used.

The latest routines to be added to SOFA in the January release were for transformations between geocentric and geodetic coordinates. There are two routines, GD2GCE and GC2GDE that, given the parameters for an ellipsoid, (a, f), will convert from geodetic to geocentric coordinates and geocentric to geodetic coordinates, respectively. There is a canonical routine (EFORM) that gives the parameters, equatorial radius (a) and flattening (f), for three standard reference ellipsoids; (1) WGS84, (2) GRS80 and (3)WGS72. Lastly two routines, GD2GC and GC2GD, are provided, which are equivalent to GD2GCE and GC2GDE, but uses one of the specified standard ellipsoids.

4. LOOK TO THE FUTURE

The next tranche of routines to be added to SOFA are for transformation between time scales. At present SOFA includes two routines in this category. These routines, DAT and DTDB, do not transform between time scales, but give the differences between two particular time scales, that is between TAI and UTC, and an approximation to TT−TDB, respectively.

SOFA recognizes seven time scales, namely TAI, UTC, UT1, TT, TCG, TDB, and TCB. The strategy is to provide routines that link adjacent pairs of time scales. This gives the user the option to select those needed to construct the required chain, and importantly provide supplementary quantities such as ΔT and UT1−UTC, which either cannot be predicted or for which there are model choices. This was agreed as the simplest scheme that gives the user the most flexibility. Table 1 lists the sixteen linking routines.

Name	*Transformation*	*Date/Time Arguments*
`TAIUTC`	TAI ⇒ UTC	`TAI1, TAI2, UTC1, UTC2`
`UTCTAI`	UTC ⇒ TAI	`UTC1, UTC2, TAI1, TAI2`
`UTCUT1`	UTC ⇒ UT1	`UTC1, UTC2, DUT, UT1, UT2`
`UT1UTC`	UT1 ⇒ UTC	`UT1, UT2, DUT, UTC1, UTC2`
`TAIUT1`	TAI ⇒ UT1	`TAI1, TAI2, DTA, UT1, UT2`
`UT1TAI`	UT1 ⇒ TAI	`UT1, UT2, DTA, TAI1, TAI2`
`TTUT1`	TT ⇒ UT1	`TT1, TT2, DT, UT1, UT2`
`UT1TT`	UT1 ⇒ TT	`UT1, UT2, DT, TT1, TT2`
`TAITT`	TAI ⇒ TT	`TAI1, TAI2, TT1, TT2`
`TTTAI`	TT ⇒ TAI	`TT1, TT2, TAI1, TAI2`
`TTTCG`	TT ⇒ TCG	`TT1, TT2, TCG1, TCG2`
`TCGTT`	TCG ⇒ TT	`TCG1, TCG2, TT1, TT2`
`TTTDB`	TT ⇒ TDB	`TT1, TT2, DTR, TDB1, TDB2`
`TDBTT`	TDB ⇒ TT	`TDB1, TDB2, DTR, TT1, TT2`
`TDBTCB`	TDB ⇒ TCB	`TDB1, TDB2, TCB1, TCB2`
`TCBTDB`	TCB ⇒ TDB	`TCB1, TCB2, TDB1, TDB2`

Table 1: The SOFA time scale transformation routines. Argument pairs `TAI1, TAI2` *etc.* are the encoded times produced by the DTF2D routine and decoded using D2DTF.

The routines use SOFA's two-argument Julian date convention. Thus the two routines DTF2D and D2DTF handle the conversion between civil date and time, i.e., year, month, day, hour, minute and

seconds and the two-part Julian date (or in the case of UTC, quasi-JD) and vice versa. This includes dealing with, in the case of UTC, leap seconds and the rare but crucial cases when it is correct to print out more than 59.... seconds. Importantly, the routines take care to preserve precision by ensuring that the tiny differences are added to (or subtracted from) the smaller of the two date arguments.

To help the user there will be a cookbook called *Time Scale & Calendar Tools*, and although the Fortran and C version of the cookbook are identical, they will have different program code.

We hope to make the next release available soon after the time scale routines are independently tested by George Hobbs (Australia Telescope National Facility) who has been co-opted onto the Board on behalf of Commission 31 (Time).

For the future there are the transformations between the Barycentric Celestial Reference System (BCRS) and the Geocentric Celestial Reference System (GCRS) which include the effects of parallax, light-time, light-deflection and aberration. These effects will involve positions of the Sun and planets. A few of the SOFA Board are on the Commission 4 Working Group that has just been set up with the mission to provide universal access to the various high-precision ephemerides of solar system bodies.

The present structure of the IAU is to have groups that last for a fixed period of time. SOFA, due to the very nature of its mandate, does not conform to this. Thus Division I has requested the IAU Executive Committee to consider a change in the IAU by-laws that would permit the IAU to create service organizations and standing committees. If this proposal is accepted, then it is suggested that SOFA would be a service organization.

Acknowledgements. The work of SOFA gets done by good will and this is an appropriate place and time to put on record some acknowledgments.

The Board would like to thank the UK Hydrographic Office for hosting the SOFA web site.

Thanks are due not only to the webmaster (who is now a Board member) but also to all the Board members for all their efforts, and to their host institutions.

Finally, during the process of electing a new Chair earlier this year, it was made abundantly clear that the Board would like to record and acknowledge the leadership of Patrick Wallace over its first fifteen years during his chairmanship. The Board also acknowledges the huge contribution that he has made and is still making to SOFA and the wider astronomical community.

5. REFERENCES

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SOFA's web site is at http://www.iausofa.org