SOFA AND THE ALGORITHMS FOR TRANSFORMATIONS BETWEEN TIME SCALES & BETWEEN REFERENCE SYSTEMS

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ABSTRACT. The SOFA Collection provides users with a myriad of routines. Examples will be given of the various transformations between the time scales TAI, TT, UTC, UT1, TDB, TCB and TCG, which represent the latest set of routines added to the SOFA collection. In particular this paper will also illustrate the combinations of routines that provide transformations between the Geocentric Celestial Reference System (GCRS) and the International Terrestrial Reference System (ITRS). Both the Celestial Intermediate Origin (CIO) and the equinox-based methods are shown, and those supporting International Astronomical Union (IAU) resolutions will be highlighted.

1. SOFA

SOFA, which stands for Standards of Fundamental Astronomy, is a "service" of IAU Division 1, which at present reports through Commission 19. Its task is to establish and maintain an accessible and authoritative set of algorithms and procedures that implement standard models used in fundamental astronomy. To do this, SOFA is made up of three parts: a board of experts (see Section 5), a collection of software, and a web site that makes the routines accessible to all.

The SOFA collection provides libraries of routines in Fortran and ANSI C, which form a basis—the building blocks—that enable users to write their own applications, using authoritative methods. The latest release (2010 December 1), which included 16 time-scale transformations, consists of 59 canonical routines, 72 astronomy support routines, and 55 vector/matrix utility routines; a grand total of 186 routines.

The SOFA Centre is the web site at **www.iausofa.org**. This is the public face of SOFA. From this web site, users may navigate to each routine, then view or copy the source code. Alternatively, a whole library, Fortran or ANSI C, may be downloaded. The Centre is also an archive where previous releases are available. Over the last year and a half, the site has received over 800 unique visitors each month and currently about 600 people have registered to receive news about updates.

SOFA requires continuity, and thus Division I has requested that the IAU Executive Committee consider a change in the IAU by-laws that would recognize this within the IAU structure. If this change is accepted at the 2012 General Assembly, it is proposed that SOFA would be classed as a 'service organization'.

2. SOFA – TIME SCALES

SOFA recognizes seven time scales, namely International Atomic Time (TAI), Coordinated Universal Time (UTC), Universal Time (UT1), Terrestrial Time (TT), Barycentric Dynamical Time (TDB), Geocentric Coordinated Time (TCG) and Barycentric Coordinated Time (TCB). The strategy is to provide routines that link adjacent pairs of time scales. This is the simplest scheme that gives the user most flexibility. Supplementary quantities, such as the variable parameters ΔT and UT1−UTC, must be supplied by the user.

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. Importantly, all 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. In the case of UTC, these routines deal with

leap seconds in the rare but crucial cases when it is correct to input or return more than 59 seconds. A cookbook, *Time Scale & Calendar Tools*, with examples in both Fortran and C, may be downloaded.

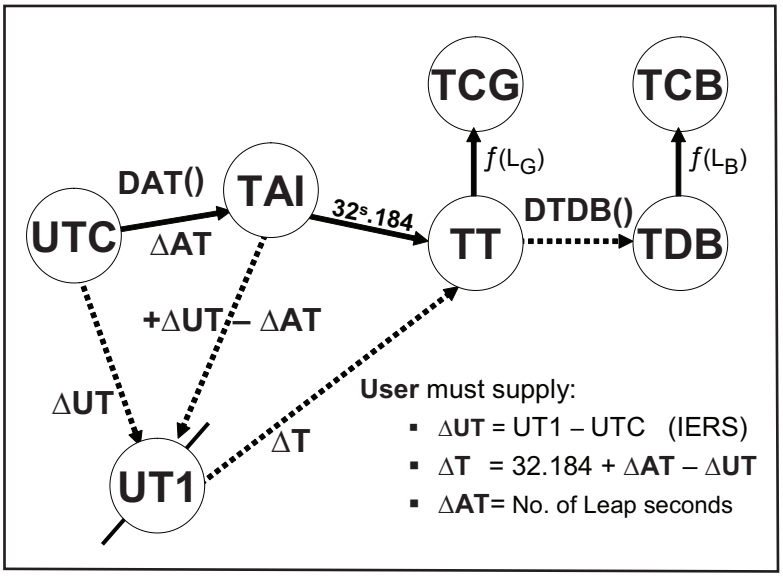

Figure 1: Time Scale Relationships. The dotted lines indicate that the user must supply the difference between the two time scales. The routines `DAT`, which returns the number of leap seconds, and `DTDB`, are part of the SOFA library. Note that the routine `DAT` must be updated whenever a leap second is inserted into UTC.

3. SOFA – TRANSFORMATIONS BETWEEN THE GCRS & THE ITRS

SOFA contains a myriad of routines in order to provide users with various options depending on the application they are writing. Thus, when looking at a whole collection, it can be quite difficult trying to choose the correct routine for the particular purpose. The following is a guide to show how, in general, the routine names are constructed in the context of the transformation between the GCRS and the ITRS, the different paradigms, and various available options. The underlying equations that represent the whole process, in both the Celestial Intermediate Origin (CIO) and equinox based paradigms, respectively, are

$$[\mathrm{ITRS}] = \mathbf{Q}[\mathrm{GCRS}] = \mathbf{W}\ \mathbf{R}_3(\mathrm{ERA})\ \mathbf{C}\ [\mathrm{GCRS}] = \mathbf{W}\ \mathbf{R}_3(\mathrm{GAST})\ \mathbf{NPB}\ [\mathrm{GCRS}]$$

and they also highlight the main reference systems. The matrix **C** or **NPB** transforms from the GCRS to the Celestial Intermediate Reference System or the true equinox and equator of date system, respectively. This is followed by a rotation about the Celestial Intermediate Pole (CIP) for Earth rotation, viz $\mathbf{R}_3$(ERA) or $\mathbf{R}_3$(GAST), i.e. a transformation to the Terrestrial Intermediate Reference System. Finally, **W** (polar motion) completes the rotation to the ITRS.

The names of the SOFA routines are short and give an indication of what the routines do. All valid routines are preceded by `iau_` in Fortran and just `iau` in ANSI C. The SOFA 'free license agreement' requires that users who change the content of any routine must remove the `iau` tag. The usual letters are `M`, `B`, `P`, `N`, `E`, `XY`, `XYS`, `S`, `ERA`, `GST`, `POM`, `C2I` and `C2T`, where the first five stand for matrix, bias, precession, nutation and equinox. The notation `XY`, `XYS` and `S` refer to the CIP and CIO locator, while `ERA` and `GST` deal with Earth rotation, and `POM` stands for polar motion. `C2I` and `PMN` provide matrices for conversion from the GCRS to the Celestial Intermediate Reference System and the true equinox and equator of date system, respectively, and `C2T` produces a matrix that transforms from the GCRS to the ITRS. Some implementations and descriptions (e.g. IERS) may provide the conversion from the ITRS. SOFA's transpose matrix routine `TR` (see Table 2) may be used to transpose a matrix, which in this case is the inverse and gives the transformation between the ITRS and the GCRS. **Note:** always check to ensure that the matrix you generate provides the transformation you require.

A two-digit year implies that there is an associated IAU resolution, but not necessarily a model designation or tag. This is well illustrated by the routine `NUT06A`, which implements the IAU 2000A

CIO-based GCRS to Intermediate	Equinox-based GCRS to Date
Bias, Precession and Nutation	
`C2I06A ( TTA, TTB, C )`	`PNM06A ( TTA, TTB, NPB )`

Table 1: Transformation from the GCRS to either the Celestial Intermediate Reference System or the true equinox and equator of date, respectively. `TTA+TTB` = TT Julian date and fraction.

CIO-based	GCRS to ITRS	Equinox-based
	Input Parameters	
`TTA+TTB` = TT Julian date and fraction; `UT1A+UT1B` = UT1 equivalent date and fraction, required for Earth rotation; x_p, y_p the coordinates of the CIP with respect to the ITRS (IERS).		
	Bias, Precession and Nutation, Earth Rotation and Polar Motion	

		`PNM06A ( TTA, TTB, NPB )`
		`GAST = GST06 ( UT1A,UT1B, TTA,TTB, NPB )`
		`POM00 ( xp, yp SP00(TTA,TTB), W )`

`C2T06A ( TTA,TTB, UT1A,UT1B, xp, yp Q )`		`C2TEQX ( NPB, GAST, W, Q )`
	ITRS to GCRS	
	`TR ( Q, Q`$^{-1}$ `)`	

Table 2: Transformation between the GCRS and ITRS, excluding the IERS corrections.

nutation after the IAU 2006 resolution dealing with precession, and includes the adjustments that are caused by changes in the obliquity and $\dot{J}_2$ (see Section 4). Lastly, if the final letter is `A` or `B`, then this usually refers to the IAU 2000A or IAU 2000B nutation series (there are no 06B routines). It should be noted that these general rules are only a guide; a few routines do not follow these guidelines.

The three tables illustrate various options. The first table, an 'almanac type' option, shows the routines that produce the matrix—CIO or equinox based—that includes bias, precession and nutation, i.e., the transformation from the CGRS to either the Intermediate Celestial Reference System or the true equinox and equator of date, respectively. Table 2, similar to Table 1, lists the routines for the GCRS to ITRS matrix and thus includes Earth rotation and polar motion. Finally Table 3, which gives the GCRS to ITRS matrix, lists the minimum combination (i.e., no matrices are re-calculated) and allows all the corrections that are supplied by the IERS to be included.

4. SOFA, GCRS TO ITRS & IAU RESOLUTIONS

SOFA routines are consistent between the CIO-based and equinox-based paradigms. Whether you select `XYS06A`, `C2T06A`, `C2I06A`, `PNM06A` or `PFW06`, the same underlying routines are used. These routines all implement the equations that are part of resolution B1 adopted at the IAU 2006 General Assembly. These include using `NUT06A`—whichever paradigm—that implements the additional adjustments that are required to be applied to `NUT00A` when using IAU 2006 precession (see 3 above). The routine `XY06` uses a different approach as it evaluates the series expressions for the X, Y of the CIP directly, and thus requires no adjustments. All these routines were coded and verified by the Board at the time of the resolutions and represent the IAU standard.

Acknowledgements. Following the Journées 2010 the Board were pleased to welcome new members Nicole Capitaine and William Folkner. The work of SOFA gets done by good will and this is an appropriate place to record and thank the Board and their host institutions: John Bangert (US Naval Observatory, USA), Steve Bell (Webmaster, HM Nautical Almanac Office (UKHO), UK), Mark Calabretta (Australia Telescope National Facility, Australia), Nicole Capitaine (Observatoire de Paris, France), William Folkner (Jet Propulsion Laboratory, USA), George Hobbs, (Australia Telescope National Facility, Australia),

CIO-based	Equinox-based
Input Parameters	
TTA+TTB = UTC + ΔAT + 32.184 = TT Julian date and fraction;	
UT1A+UT1B = UT1 equivalent date and fraction, required for Earth rotation;	
x_p, y_p the coordinates of the CIP with respect to the ITRS (IERS);	
ΔUT = UT1−UTC required for calculation of Earth rotation (IERS);	
dX and dY for the CIP (IERS)	dψ and dϵ for nutation (IERS).
GCRS to Intermediate	**GCRS to Date**
Bias, Precession and Nutation	
XYS06A (TTA, TTB, X, Y, s) or XY06 (TTA, TTB, X, Y) and s = S06 (TTA, TTB, X+dX, Y+dY)	PFW06 (TTA, TTB, γ, ϕ, ψ, ϵ_A) NUT06A (TTA, TTB, $\Delta\psi$, $\Delta\epsilon$)
C2IXYS (X+dX, Y+dY, s, C)	FW2M (γ, ϕ, $\psi+\Delta\psi+$dψ, $\epsilon_A+\Delta\epsilon+$dϵ, NPB) BPN2XY (NPB, X, Y) & s = S06 (TTA, TTB, X, Y)
Earth Rotation	
ERA = ERA00 (UT1A, UT1B+ΔUT)	GAST = ERA00 (UT1A, UT1B+ΔUT) - EORS (NPB, s)
Polar Motion	
POM00 (x_p, y_p, SP00(TTA, TTB), W)	
GCRS to ITRS	
C2TCIO (C, ERA, W, Q)	C2TEQX (NPB, GAST, W, Q)

Table 3: Transformation from the GCRS to the ITRS, allowing the user to supply all the corrections provided by the IERS, but without duplication of calculation.

Always check the documentation within each routine for the specification, method and arguments so as to ensure that it meets your requirements.

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SOFA Time Scales and Calendar Tools; Fortran edition http://www.iausofa.org/sofa_ts_f.pdf or ANSI C edition http://www.iausofa.org/sofa_ts_c.pdf.