SOFA & ASTROMETRY

C.Y. HOHENKERK, Chair IAU SOFA Board
HM Nautical Almanac Office
UK Hydrographic Office, Taunton, TA1 2DN, United Kingdom
e-mail: Catherine.Hohenkerk@ukho.gov.uk

ABSTRACT. The International Astronomical Union's (IAU) Standards of Fundamental Astronomy (SOFA) software library has in the last year introduced a tranche of 32 new routines dealing with the subject area "astrometry". This poster provides a guide to enable users to get to grips easily with the various routines for the transformations between ICRS, ICRS astrometric, GCRS, Celestial Intermediate and observed positions of stars, together with their underlying routines for proper motion, parallax, aberration, light deflection and refraction. A summary of the current status of SOFA is also included.

1. INTRODUCTION

The tenth release (2013 December 2) of the IAU SOFA software included 32 new routines addressing Astrometry. The topic concerns the chain of transformations that link star catalog positions in the International Celestial Reference System (ICRS) with the observed direction for terrestrial and space observers. The intermediate systems include the Barycentric Celestial Reference System (BCRS), the Geocentric Celestial Reference System (GCRS), the Celestial Intermediate Reference System (CIRS), the Terrestrial Intermediate Reference System (TIRS) and the International Terrestrial Reference System (ITRS). For the typical case of a terrestrial observer the supported star positions are catalog places, astrometric ICRS $[\alpha, \delta]$, intermediate $[\alpha, \delta]$, and both topocentric (unrefracted) and observed $[\alpha, \delta]$, $[h, \delta]$ and [azimuth, altitude].

SOFA provides a simple text-based manual, containing the comments from the start of the routines, and a detailed "cookbook", *SOFA Tools for Astrometry*, which explains the software in a tutorial style. Also, there is *SOFA Tools at a Glance*, a two-page summary.

For anyone wishing to transform star positions from one system to another there are several key things about these routines and some initial decisions that have to be made. This paper gives an overview.

Note that the names of Fortran subprograms have the form `iau_NAME` while for ANSI C the function names are `iauName`. Here, for clarity, individual routines are referred to simply as `NAME`.

2. SOFA'S ASTROMETRY ROUTINES

The astrometry routines are divided into two categories and three types. This gives users the combination of ease of use as well as the ability to make their specific choices. The two categories are:

- Routines that include '13' in the name (for example `ATCI13`) require the least number of arguments and are the most convenient, as they call other SOFA routines internally to use currently adopted models, *e.g.* the `PNM06A` routine for the IAU 2006/2000A precession-nutation matrix .
- The routines without any digits in the names, which through additional arguments allow the user to provide explicit values that are independent of SOFA, such as JPL Earth coordinates.

The three types of routine, starting with the most basic, are:

1. The core astrometry routines that transform between the ICRS and the GCRS. These are `PMPX` for space motion and parallax, `AB` for aberration and the light deflection routine `LD`. There are two further light deflection routines `LDSUN` and `LDN`. Both use `LD`, where `LDSUN` assumes just the Sun is the deflection body, and this is used in SOFA's '13' routines, and `LDN` allows for N bodies. There is also an approximate routine for refraction `REFCO` and a routine `PVTOB` which takes a terrestrial observer's WGS84 longitude, latitude and height and forms the observer's position in the CIRS.
2. The `AP` routines. These routines supply the star-independent data, for example the position and velocity of the Earth. The next two letters of the name indicates the start reference system and

where the observer is located (geocentric, terrestrial, or space); for example `APCG` indicates 'celestial' (ICRS) and a geocentric observer, while `APIO` indicates the CIRS and a terrestrial observer.

3. The `AT` routines. These are the top-level routines, where the following letters indicates which systems the transformation is between. The letters are **C** for celestial, **I** for intermediate and **O** for observed *e.g.* `ATOC13` is the transformation of an **o**bserved place to an ICRS astrometric place.

   - The `AT...Q...` (quick) routines are for efficient processing of many stars for the same circumstances and require the star-independent data being already generated via an `AP` routine.
   - The `AT` routines with `N` or `Z` at the end of the name allow for multiple light-deflecting bodies and zero parallax and proper motion, respectively.

3. ACCURACY AND USER CHOICES

Estimates of the achieved accuracy are given in the cookbook. Care is taken to ensure that transformations and their inverses match to high precision. Where this is not achievable simply through rigor (by the use of vector methods for example) iteration is used. Without refraction, the inversions are self-consistent to better than 1 μas all over the celestial sphere.

The '13' routines use the IAU 2006/IAU 2000A precession-nutation models and this limits the accuracy to about 1 mas, mainly because of the (unmodeled) free core nutation and, in time, precession error. If the `EPV00` routine is used for the Earth ephemeris, as it is in the '13' routines, then errors in the aberration predictions of up to 5 μas can occur.

Over much of the sky, SOFA's predictions of light deflection by the Sun are accurate to 1 μas. Close to the Sun the errors may approach the 0.5 mas level. The routine `ATCIQN` allows for cases of other solar system bodies such as at Jupiter's limb where the deflection can be over 16 mas.

Having an understanding of the categories and types of routine together with some key aspects helps the user decide which are the required routines to deliver the positions needed. In particular,

1. between which systems the transformation operates, *e.g.* **O**bserved (ITRS) to **C**elestial (ICRS);
2. the location of the observer, *e.g.* geocentric, terrestrial, or in space;
3. the accuracy goals;
4. whether using SOFA's supplied parameters via the '13' routines or user supplied parameters;
5. whether processing many star positions for the same circumstances and therefore able to use one of the `Q` routines.

4. SOFA USAGE

Each month, SOFA's website at `http://www.iausofa.org` typically receives over 1500 unique visitors with, at present, 720 registered users. The 9th release (9a: 2012 July - 2013 November) has been downloaded 5769 times, while 10b, released in February 2014, has been downloaded 1662 times. There are currently now 220 routines, 59 of which are canonical, delivering IAU Standards.

All SOFA cookbooks are downloadable from `http://www.iausofa.org/cookbooks.html`, including *SOFA Astrometry Tools* (Fortran `sofa_ast_f.pdf and ANSI C sofa_ast_c.pdf versions`) and *SOFA Tools at a Glance* (`sofa_ast_summary.pdf`).

Acknowledgements. The SOFA project is possible due to the collaborative effort and hard work of the members of the Board: John Bangert, United States Naval Observatory (retired), Steven Bell, HM Nautical Almanac Office, UKHO, UK, Nicole Capitaine, Observatoire de Paris, France, William Folkner, Jet Propulsion Laboratory, US, Catherine Hohenkerk, HM Nautical Almanac Office (Chair), UK, Jinling Li, Shanghai Astronomical Observatory, China, Brian Luzum, United States Naval Observatory (IERS), Zinovy Malkin, Pulkovo Observatory, St Petersburg, Russia, Jeffrey Percival, University of Wisconsin, US, Scott Ransom, National Radio Astronomy Observatory, US and Patrick Wallace, RAL Space (retired), UK. Thanks are due to the Board for their oversight and in particular to Patrick Wallace, who continues to produce the source code and Steven Bell who manages the website. Thanks are also due to the institutes of Board members and to the United Kingdom Hydrographic Office for hosting the website.