PyMsOfa: A Python Package for the Standards of Fundamental Astronomy (SOFA) Service (Postprint)

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Abstract

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Full Text

Preamble

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Abstract

The Standards of Fundamental Astronomy (SOFA) is a service provided by the International Astronomical Union that offers algorithms and software for astronomical calculations, released in two versions for FORTRAN 77 and ANSI C, respectively. In this work, we implement the Python package PyMsOfa for the SOFA service through three approaches: (1) a Python wrapper package based on a foreign function library for Python (ctypes), (2) a Python wrapper package with the foreign function interface for Python calling C code (cffi), and (3) a Python package directly written in pure Python codes from SOFA subroutines. The package PyMsOfa has fully implemented 247 functions of the original SOFA routines released on 2023 October 11. In addition, PyMsOfa has been extensively examined and shows exact consistency with the test examples provided by the original SOFA. This Python package is suitable not only for the astrometric detection of habitable planets from the Closeby Habitable Exoplanet Survey mission, but also for frontier themes related to black holes and dark matter that involve astrometric calculations and other fields. The source codes are available via http://pypi.org/project/PyMsOfa/ and https://github.com/CHES2023/PyMsOfa.

Key words: Astrometry and Celestial Mechanics -planets and satellites: detection -planets and satellites: terrestrial planets -system, implementation of

1. Introduction

The Standards of Fundamental Astronomy (SOFA) service was established by the International Astronomical Union (IAU) as an algorithm and program collection based on fundamental astronomical models that aim to implement IAU resolutions in an authoritative manner. The SOFA service contains transformations of coordinate systems and Earth attitude (e.g., precession and nutation, closely related to the International Earth Rotation Service) as well as astrometric parameters. The routines were written in strict compliance with IAU resolutions and have been updated as the resolutions were amended, with the latest version released on 2023 October 11.

The SOFA service is officially released in two programming languages, FORTRAN 77 and ANSI C, whose advantages of high efficiency and fast execution make them widely utilized in scientific computations. However, the Python language greatly benefits from its easy-to-learn syntax and tremendous built-in libraries for science and engineering, which motivated us to implement the full

Python package PyMsOfa for SOFA, making direct, convenient, and efficient routines available. There are several Python packages that contain SOFA features, such as Astropy, PyERFA, and pysofa (which contains only 186 of the 247 SOFA subroutines). However, this Python package represents a complete implementation of all 247 functions from a recently released SOFA version in three ways via Python: wrapped with the ctypes library, wrapped with the cffi interface, and written directly in pure Python codes based on SOFA subroutines. Thus, users familiar with the FORTRAN 77 and ANSI C versions of SOFA can easily get started with this Python package and achieve similar goals in their research.

The paper is organized as follows: in Section 2 we briefly describe several major modules that the SOFA service provides. Section 3 describes the features of the Python package and presents two examples of astrometric calculations. Finally, we provide a concise summary in Section 4.

2. Functions in the SOFA Service

The routines of the SOFA service can be divided into four categories: basic calculation module, timescale and calendar module, coordinate system transformation module, and Earth attitude module. Each category consists of dozens of routines. A brief introduction of these routines and functions is provided below, with more detailed descriptions available in the comments and SOFA documentation.

2.1. Basic Calculation Module

These routines are fundamental, mainly involving the processing of parameters, vectors, and matrices. Their purpose is to facilitate calling between SOFA routines, so they do not include all possible vector and matrix operations, as similar functionality can be implemented in many other packages. These routines can realize coordinate conversions, such as transformations between spherical and Cartesian coordinates (e.g., pymS2c and pymC2s). The vector routines process position-velocity vectors required in other programs (e.g., pymTrxpv and pymPvu). For matrices, they contain functions such as matrix rotation (e.g., pymRx). In addition, the SOFA service provides procedures for projective relations (e.g., pymTpxes) involving conversions between spherical and planar coordinates.

2.2. Timescale and Calendar Module

The timescales involved in the SOFA service are shown in Table 1. Each timescale has different applications, and there are slight time differences between them (Moyer 1981; Fairhead & Bretagnon 1990; Müller & Jappel 2012). Some timescales have linear relationships, while others must be transformed according to location (Seidelmann 1992; Soffel et al. 2003; McCarthy & Petit 2004). Figure 1 illustrates the functions involved in conversions between timescales. In addition, the discontinuity of time caused by leap seconds must be taken into account (e.g., pymDat) (Seidelmann 1992). Therefore, when performing astronomical scientific calculations, it is necessary to choose an appropriate timescale.

The Julian Date is an astronomical method for measuring time over long timespans, which is widely adopted in calendar definitions. In the SOFA service, the Julian Date is described by two parameters; for a specific calendar date with Julian Day JD = 2450123.7, this can be denoted as JD1 = 2400000.5 and JD2 = 50123.2, respectively.

2.3. Coordinate System Transformation Module

The SOFA service includes conversions between different coordinate systems, such as geodetic, geocentric, horizon, hour-angle, ICRS, ecliptic, and galactic coordinates. The package provides a complete system for astrometric parameters, ASTROM, which is composed of 30 components. These components include the time, solar system barycenter (SSB) to observer vector, direction and distance relative to the Sun, barycentric observer velocity, reciprocal of Lorentz factor, bias-precession-nutation matrix, Terrestrial Intermediate Origin (TIO) locator (McCarthy & Petit 2004), polar motion, geodetic latitude, diurnal aberration (Klioner 2003), Earth rotation angle, and refraction constants A and B (Crane 1976; Rüeger 2002). Detailed calculation procedures are provided for each component. The final ASTROM parameters represent the astrometric parameters of different stations and are independent of stars. Table 2 lists several major fundamental coordinate systems involved in the SOFA service, while Table 3 displays the functions that produce the components of ASTROM and the functions used to transform stellar parameters.

The SOFA service also handles transitions between FK4, FK5, and the Hipparcos catalog (e.g., pymFk425, pymFk524, and pymFk5hip) (Aoki et al. 1983; Yallop et al. 1989; Mignard & Froeschlé 2000). These coordinate systems cover fundamental coordinate systems in classical astrometry. In astronomical calculations, changes in coordinate systems are inseparable from changes in the position of observation targets relative to various observing stations (Green 1962). The SOFA service provides a set of authoritative algorithms for these transformations.

2.4. Earth Attitude Module

The SOFA service supplies authoritative definitions of parameters involved in Earth attitude and provides detailed algorithms. These parameters include solar system object parameters (e.g., the mean longitude of the planets and their approximate heliocentric positions and velocities, such as pymPlan94) (Simon et al. 1994; Klioner 2003), bias-precession-nutation matrix (Lieske 1979; Mathews et al. 2002; Wallace & Capitaine 2006), Earth rotation angle (Capitaine et al. 2000), celestial intermediate pole (CIP), intermediate origin (CIO) (Capitaine et al. 2003a, 2003b; Capitaine & Wallace 2006), etc. (e.g., pymPn00 and pymNum06a). There are some differences in these parameters under different models, so SOFA also provides parameters under the IAU 1976 model (Lieske et al. 1977), IAU 1980 model (Seidelmann 1982), IAU 2000 A&B model (Soffel et al. 2003), and IAU 2006 model (Seidelmann et al. 2007). The calculations of the routines are also consistent with those in the IAU resolution (Wallace & Capitaine 2006), allowing users to choose the required models and parameters for different astronomical calculations.

3. Python Features of the Package

For simplicity, this Python package of the SOFA service is described based on the ctypes library, which is a foreign function library for Python that provides C-compatible data types and allows calling functions in shared libraries. We integrated all 247 functions from the SOFA package into a C file named sofa_a.c. A dynamic shared library file (libsofa_c.so) was compiled from three source files (sofa.h, sofam.h, and sofa_a.c). By calling the shared library file through the ctypes library, we established a Python interface for each SOFA function under ANSI C, enabling the SOFA service to be employed directly in Python programs. The source code is available at https://github.com/CHES2023/PyMsOfa and http://pypi.org/project/PyMsOfa/.

This Python package differs from the ANSI C version in that the parameters involved in its functions vary beyond just the language used. In the original ANSI C version from SOFA, the input and output parameters of functions are included in the function arguments. In the Python version, the function parameters refer only to input parameters. In addition, the parameters involved in each function, along with their types and units, are briefly documented in their comments, which can be easily queried when using each function in the Python environment.

Below, we demonstrate two applications using the Python package for SOFA. For the Closeby Habitable Exoplanet Survey (CHES) mission (Ji et al. 2022), numerous functions in the SOFA service are employed to simulate observed images. Here we present two examples (see Figures 2 and 3). The first example illustrates the time expression in the SOFA service, where time is usually expressed by two parameters. These examples demonstrate how to accurately calculate the coordinates of target stars and reference stars based on Gaia Data Release 3 (DR3) at the time of observation. Using the projection theorem, the coordinates in the focal plane are calculated to determine the major observable quantity in the CHES mission: the angular distance between stars in the focal plane. These functions can further provide relevant parameters for the CHES mission (Ji et al. 2022; Tan et al. 2022). Figure 4 shows a simulated image created with the functions pymPmsafe and pymTpxes, which is in good agreement with the image produced from ESASky.

In addition to exoplanet detection, this package is also applicable to various astrometric calculations relevant to black hole and dark matter studies. Figure

5 reproduces the prediction of stellar motion orbiting a black hole using PyMsOfa. The orbital parameters in the simulations are adopted from El-Badry et al. (2023). Using this Python package, the proper motion and parallax of the star can be carefully processed to calculate accurate orbital motion under the gravitational influence of a black hole (Figure 5). This will contribute to more detailed investigations and analyses of the physical properties of black holes.

4. Summary

In this work, we describe the functionality of the Python package PyMsOfa for the SOFA service implemented in three ways: (1) a Python wrapper package based on the ctypes library, (2) a Python wrapper package with the cffi interface, and (3) a Python package directly written in pure Python codes from SOFA algorithms. These implement the SOFA service through a Python interface in various ways, but each implementation provides consistent functionality. The purpose of this work is to enable wide utilization of the authoritative algorithms in the SOFA service through a Python interface. The Python package has fulfilled the necessary requirements for all 247 functions of the SOFA service written in ANSI C, containing basic system calculations, coordinate timescale and calendar transformations, Earth attitude, and astrometric parameters. This Python package is thoroughly and correctly tested against the original examples provided by SOFA and runs stably on Linux, macOS, and Windows operating systems.

Astrometry is an ancient branch of astronomy that primarily aims to investigate the positions of celestial bodies. With rapid development, astrometry can provide clear understanding from the solar system to the entire universe based on ground-based and space-based observations. Nowadays, with improvements in astrometric accuracy, besides direct measurements of stellar positions and velocities, indirect measurements can be extensively conducted to provide vital implications for frontier themes including habitable planets, black holes, dark matter, etc. The SOFA service integrates the fundamental theory of astrometry and serves as a convenient tool for conducting astrometric calculations that can be applied to diverse research fields. This Python package was originally intended to facilitate the use of the SOFA service for various astronomical calculations. Thanks to the excellent, comprehensive features of the SOFA service, this package can also be further used for related astronomical calculations in Python.

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Note: Figure translations are in progress. See original paper for figures.