COCO

a SOFA-based star coordinate converter

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Software version 1
Document revision 1.0

2022 March 12

Contents

1 Introduction

1.1 Quick Start

Compile `coco.c`, linked to the SOFA C library[1]. All the COCO functions are explicitly included, so there is no need for `make` or any COCO library. Then launch the program and type the following commands:

```
i c
o a 2022 3 10.25
06 45 08.91728 -16 42 58.0171 -546.01m -1223.07m 379.21m -5.5
```

The `i` and `o` commands (standing for IN and OUT) specify the "from" and "to" coordinate systems, and these are reported. The third line is an ICRS catalog entry, and the resulting report...

```
 = 06 45 08.917 -16 42 58.02  J2000.00  ICRS (barycentric)  0.379   -5.5
        -0.03801      -1.2231
-> 06 46 07.324 -16 44 59.29  2010 03 10.3  apparent (geocentric)
```

shows the geocentric apparent place on 2022 Mar 10.25 (UT1) of Sirius. Typing H will display help information.

1.2 What is COCO?

The COCO application[2] converts star coordinates from one coordinate system to another. Eight systems are supported, including several types of catalog place, two sorts of apparent place, ecliptic coordinates and galactic coordinates. The options embrace several generations of precession model, and both right ascension zero points (equinox and celestial intermediate origin), but only the current IAU nutation model. The historical systems are covered not because they should be used in modern work but so that positions published in the literature can be rigorously interpreted.

COCO can perform accurate transformations between the following systems:

- mean $[\,\alpha,\delta\,]$, old FK4 convention, with E-terms
- the same but without E-terms (used in radio astronomy)
- mean $[\,\alpha,\delta\,]$, IAU 2006 (FK5 and FK6)
- $[\,\alpha,\delta\,]$, International Celestial Reference System (ICRS)

[1] See `https://www.iausofa.org`.

[2] COCO is a descendant of a program of the same name developed by the author in the 1980s under the auspices of the UK Starlink Project – see `http://www.starlink.ac.uk/docs/sun56.htx/sun56.html`. The earlier tool, written in Fortran77 and calling the SLALIB/F library rather than the IAU SOFA library, supported fewer reference systems but had more flexible input-output arrangements.

- $[\alpha, \delta]$, Celestial Intermediate Reference System (CIRS, geocentric)
- $[\alpha, \delta]$, apparent (geocentric)
- ecliptic coordinates $[\lambda, \beta]$, (mean of date)
- galactic coordinates $[l^{II}, b^{II}]$, IAU 1958 system

COCO's user-interface is spartan but sufficient. The program offers control over report resolution, and there is some basic online help. All input is free-format, and defaults are provided where meaningful. All input/output is via `stdin` and `stdout`.

2 Operating Instructions

To run COCO interactively, simply type:

```
COCO
```

The program then accepts commands and coordinates, and outputs appropriate replies. The primary commands are as follows:

```
Command                     Function

   I p    specify input coordinate system (p defined below)
   O p    specify output coordinate system (       "       )
 <coords> perform conversion  (or = to repeat last coordinates)
   E      exit
```

where the parameter `p`, specifying the coordinate system, is as follows:

```
4 [eq] [ep]   equatorial, FK4 (barycentric)
B [eq] [ep]   like FK4 but without E-terms (barycentric)
6 [eq] [ep]   equatorial, FK6 (barycentric)
C [ep]        ICRS
I [ep]        CIRS (geocentric)
A  ep         geocentric apparent
E  ep         ecliptic
G [ep]        galactic

eq = equinox, e.g. 1950 (optional B or J prefix)
ep = epoch, e.g. 1984.53 or 1983 2 26.4
```

Coordinates type 4 and B default to equinox B1950.0; coordinates type 6 default to equinox J2000.0. In all three of these coordinate systems the epoch defaults to the equinox (and in the ICRS case to J2000.0). For coordinate types I, A, E and G an explicit epoch is required.

The following commands are also available:

```
Command                      Function

  F          specify RA mode: x = H for hours, D for degrees
  S          display current settings
  ?          show format of <coords>
  H          list the commands
  R x        select report resolution:  x = H, M or L (high,medium,low)
```

All input is free-format, with spaces separating the fields (comma is also acceptable as a field separator within coordinates but would seldom be used). Both upper and lower case letters are acceptable. Blank lines can be input freely, and a comment can be appended to any line by preceding it with an asterisk or an exclamation point. No trailing garbage (apart from spaces) is tolerated. For proper motion and parallax a special notation (appending `m` or `M` to the number) indicates values in milliarcseconds.

The α format command, F, selects either hours or degrees as the units for α, affecting both the input formats which are accepted and the format of the outputs. The command "F D" selects degrees as the α unit, limits the input formats to a single number in degrees for both α and δ, and causes the output formats to be a single number in degrees for both α and δ. The command "F H" switches to the hours format, enabling a variety of sexagesimal input formats as well as plain hours and degrees, and causing the output formats to be h,m,s,d,$'$,$''$.

On startup, COCO is set to input ICRS and output FK6, with α in hours and medium report resolution.

In a typical COCO run, the first step would be to specify the input and output coordinate systems by means of the I and O commands, and then to enter the coordinates to be transformed. For example, suppose we have from a published paper a QSO position that was obtained from a plate taken in mid-1976 using reference stars from the B1950.0 SAO catalog, and we wish to express it in ICRS coordinates. The following commands could be used:

```
I 4 1950 1976.5        * input system is FK4 B1950.0; epoch is 1976.5
O C                    * output system is ICRS
12 43 25.3 +32 15 29   * measured 1950 position; no proper motion
```

Some additional operating modes are described in a later section.

Notes:

1. The results output by COCO are of more than adequate accuracy for almost all practical purposes at present and are as a rule far more precise than star coordinates published in papers. CIRS and apparent places are the least accurate forms, limited to about 0.5 milliarcsec by the unmodeled free core nutation. The more straightforward conversions are, as implementations of the accepted algorithms, several orders of magnitude better than this figure. It should be noted, however, that there were lingering debates about the precise formulation of the conversion between FK4 data and the subsequent FK5 reference system. COCO uses the algorithms published in the 1985 *Astronomical Almanac*. The differences are far too small to pose problems for non-specialists.

2. The three report resolutions provided are referred to simply as L (low), M (medium), and H (high). At resolutions "L" and "M", all the figures output are trustworthy. Resolution "H" is provided mainly to allow comparison with other predictions and to decrease rounding errors where differences are taken.

3. COCO is for use only with sources well outside the solar system. Where appropriate, stellar parallax and aberration are allowed for, but the corrections for gravitational deflection assume that the source is distant. In particular, COCO is not suitable for predicting apparent places for the Sun.

4. COCO is not intended for the full transformation of catalog entries, and reports positions only; updated proper motions, parallaxes and radial velocities are not reported. Full conversion of catalog data is best done by writing *ad hoc* programs, using the functions in the SOFA library.

5. All of COCO's coordinate systems except for CIRS and apparent place are barycentric, *i.e.* unaffected by parallax. ICRS or mean places which include displacements due to parallax, *i.e.* astrometric places, can be handled by working via intermediate or apparent place. For example, the following procedure takes an ICRS (barycentric) position and adds the (small) effect of parallax for a given date:

   (a) Set the report resolution to high.
   (b) Set the input system to ICRS.
   (c) Set the output system to geocentric apparent place for the required date.
   (d) Enter the ICRS position with proper motions and parallax (and radial velocity if available).
   (e) Note the apparent place.
   (f) Set the input system to geocentric apparent, specifying the same date as in step (c).
   (g) Set the output system to ICRS.
   (h) Type in the apparent place from step (e). The result will be close to the position entered in step (d), but with the effects of parallax added.

6. To minimize typing, COCO's commands and arguments are single characters. To suit users who prefer less terse notation there are a few opportunities to enter longer names. For the commands:

   - `E` can be `END`, `EXIT`, `Q` or `QUIT`
   - `F` can be `RA` or `FORMAT`
   - `H` can be `HELP`
   - `I` can be `INPUT` or `FROM`
   - `O` can be `OUTPUT` or `TO`
   - `R` can be `RES`
   - `S` can be `SETTINGS`

   . . . and for the coordinate systems:

   - `4` can be `FK4`

- `B` can be `BN`
- `6` can be `5` or `FK5` or `FK6`
- `C` can be `ICRS` or `ICRF`
- `I` can be `CIRS`
- `A` can be `APPT`
- `E` can be `ECL`
- `G` can be `GAL`

3 Input Formats

The input and output coordinate systems require, variously, *equinoxes* and *epochs*. The timescale is TDB, which for most uses of COCO can be regarded as the same as UTC.

Equinoxes are Besselian or Julian epochs. They can be preceded by a B or J as appropriate; in default, epochs before 1984.0 are assumed to be Besselian, while epochs 1984.0 and after are assumed to be Julian (the distinction is usually unimportant in this context). Valid examples are B1950.0, J2000, 1975.

Epochs may either be expressed as Besselian or Julian epochs, or as year,month,day in the Gregorian calendar. Valid examples are J1984.3296 and 1985 2 13.2439. Calendar dates have to have valid years and months, but a days value outside the conventional range is permissible (*e.g.* 1992 12 32)

In the mean $[\alpha, \delta]$ systems, the equinox defines the coordinate system while the epoch defines the date of observation. In the two cases where the reference frame is inertial – FK6 and galactic – the epoch is required merely to allow the proper motion to be calculated. The ICRS case is similar to the meanp places except there is no equinox (but there is an epoch).

Each input coordinate system has its own data format, as follows.

3.1 The three sorts of mean $[\alpha, \delta]$ plus ICRS

For α in hours the following formats are accepted:

```
         RA      Dec         PM       Px     RV
        h m s   d ' "  [s/y  "/y      ["   [km/s]]]
 or     h m s   d '
 or     h m     d '
 or     h       d
```

The first two, four, five, or six numeric fields, representing α and δ, are mandatory. The seventh, eighth, ninth and tenth, representing proper motion, parallax and radial velocity, are optional, with the proviso that both proper motions are required if present at all. The $[\alpha, \delta]$ fields are permitted to exceed the conventional ranges; this is to remain consistent with many existing tabulations (for example α 24 00 01.063 would be accepted and correctly interpreted). The scope for data validation is correspondingly limited.

In mixed-radix forms, all but the final field must be an integer; even a whole number expressed as a real is not permitted, so for example "6." or "6e0" would not be acceptable for the hours field of an hm or hms right ascension.

Note that the proper motions are per year rather than per century. Note also that east-west proper motion is normally seconds of time (of the angle α) rather than arcseconds (on the sky). However, COCO will accept east-west proper motion expressed in milliarcseconds on the sky if the α proper motion is followed by the character 'm'. Star data from catalogs that express proper motions in other ways (for example per century or in terms of position-angle) have to be transformed before they can be used by COCO. The special milliarcsecond notation can also be used for the declination proper motion and the parallax. See Section 1.1 for an example of this.

In the case of FK4 coordinates (with or without E-terms), omitting proper motions is interpreted as meaning that the proper motions are assumed negligible in an inertial frame. If a star has zero proper motion in the FK4 system, then zeroes must be entered explicitly; such a star will have a real proper motion of up to 0.5 arcsec per century (just as distant sources, galaxies for example, have a fictitious proper motion in the FK4 system). In addition, because the FK4 system is rotating relative to an inertial frame, if the proper motions are omitted it is important to specify the epoch at which the position was correct.

In the case of FK6 coordinates, omission of proper motions simply implies zero proper motion (FK6 is presumed not to be rotating).

The parallax and radial velocity both default to zero. (Even when the parallax is not zero, the $[\alpha, \delta]$ is barycentric – see Section 2, Note 6.)

For α in degrees (selected by the command "F D"), the following format is accepted:

```
          RA      Dec
          d        d
```

Both numbers are required. There is provision for neither sexagesimal notation nor proper motion.

3.2 Geocentric Intermediate place and Apparent place

For α in hours the following formats are accepted:

```
          RA      Dec
        h m s   d ' "
 or     h m s   d '
 or     h m     d '
```

Four, five, or six numbers are required.

For α in degrees (selected by the command "F D"), the following format is accepted:

```
          RA      Dec
          d        d
```

Both numbers are required.

3.3 Ecliptic

```
lambda  beta
   d      d
```

Both numbers are required.

3.4 Galactic

```
L2   B2
 d    d
```

Both numbers are required.

4 Supported Coordinate Systems

Section 1.2 introduced COCO's eight supported coordinate systems. Here they are, with the shortand names used by the 'I' and 'O' commands:

4 : mean $[\,\alpha, \delta\,]$, old FK4 convention, with E-terms

B : the same but without E-terms (used in radio astronomy)

6 : mean $[\,\alpha, \delta\,]$, IAU 2006 (FK5 and FK6)

C : $[\,\alpha, \delta\,]$, International Celestial Reference System (ICRS)

I : $[\,\alpha, \delta\,]$, Celestial Intermediate Reference System (CIRS, geocentric)

A : $[\,\alpha, \delta\,]$, apparent (geocentric)

E : ecliptic coordinates $[\lambda, \beta\,]$, (mean of date)

G : galactic coordinates $[l^{II}, b^{II}]$, IAU 1958 system

The first six, 4, B, 6, C, I and A, are different sorts of right ascension/declination, $[\,\alpha, \delta\,]$. The first four of those are suitable for cataloging purposes, and are barycentric; the next two are used for "current" positions, and are geocentric, and in fact differ only by the choice of RA zero point. The last two, E and G, are latitude/longitude systems, at completely differently orientations from the $[\,\alpha, \delta\,]$s.

It is important to understand that even though some of the eight systems are only subtly different from one another, a much longer list could have been assembled, containing even tinier distinctions. For example COCO does not attempt to track the successive changes in precession and nutation models since the post-FK4 era, let alone in the pre-FK4 era, and this includes successive realizations of ecliptics, equinoxes and even the ICRS. This means that only the latest I, A, E and G systems are supported, with 4 and B being the only truly "historical" options. An important goal for COCO is reliable interpretation of positions quoted in the astrophysical literature from the mid-twentieth-century onwards. It may also be a useful tool for fundamental astronomy specialists, but only as a sanity check.

4.1 Star Catalogs

Astronomers wishing to observe a particular celestial source are faced with the problem of turning a published position into the orientations of the axes of their telescope mounts. In the pre-computer era a good starting point was for star catalogs to list mean $[\alpha, \delta]$, a class of reference system where the periodic variations caused by aberration and nutation are smoothed out, leaving only the steady drifts in the orientations of the Earth's rotation axis and the ecliptic. Application of simple spherical trigonometry precession formulas, together with an initial acquisition of a bright "clock star" to set the sidereal clock empirically, were enough to achieve better than arcminute pointing. More crudely, a catalog computed for approximately the current epoch – say B1950.0[3] for a mid-century observer – would contain positions only a few arcminutes different from apparent places, and these could at a pinch be used directly. Because even small equatorial mounts are computer-controlled now, the need for star catalogs to follow precession has ceased, and all future catalogues will be J2000.0/ICRS.

4.1.1 4: FK4

FK4 was one such mean-place catalog, based on the precession models of Bessel and Newcomb, and using a standard epoch of B1950.0,

In order to facilitate the hand computation of accurate (sub-arcsecond) apparent places, FK4 contained not just the mean places of stars but also the small fraction of the annual aberration that comes from the eccentricity of the Earth's orbit. These so-called elliptic or "E-terms", always less than $0''.35$, happen to be nearly constant for any given star, and so in that era were absorbed into the catalog $[\alpha, \delta]$. The computation of accurate apparent places then involved only a simple circular-orbit approximation for the Earth's motion. Subsequent reference systems omit this ingenious but confusing trick, which as well as distorting the star positions means the FK4 system rotates at about $0''.5$ per century with respect to distant galaxies, and thereby introduces fictitious proper motions.

For details of the specific models algorithms used by COCO, see the document for the SOFA function `iauFk425`.

4.1.2 B: Bessel-Newcomb

In the second half of the twentieth century, the astrometric accuracy in certain types of radio astronomy (such as long baseline interferometry and pulsar timing) began to approach optical levels. Radio astronomers were already using the latest and most complete precession-nutation models and Earth ephemerides, and applied them rigorously without the complications of the E-terms.

The precession model COCO uses for this case is from Kinoshita, H. (1975) *Formulas for precession*, SAO Special Report No. 364, Smithsonian Institution Astrophysical Observatory, Cambridge, Massachusetts.

[3]The B stands for Besselian epoch, measured in tropical years (about 365.2422 days) from when the longitude of the ficitious mean Sun is 280°, which happens on or around January 1. Julian epochs, beginning J, are reckoned in Julian years (exactly 365.25 days) from 2000 January 1.5.

4.1.3 6: FK6

The preparations for the introduction of FK5 cataog in the 1980s included an improved precession model, the elimination of the E-terms, and the adoption of the standard epoch J2000.0. The precession model was improved still further by IAU resolutions in 2000 and again in 2006. COCO uses the IAU 2006 model for the system of the FK5 and its update FK6, based on angles computed in the SOFA function `iauP06e`.

4.1.4 C: ICRS

Although the ICRS (International Celestial Reference System) is for most practical purposes the same as FK6, the difference being an overall rotation of less than 25 milliarcseconds, it is in fact a profoundly different concept. ICRS is the spherical coordinate system based on a list of $[\,\alpha, \delta\,]$ positions of several hundred extragalactic radio sources observed with VLBI and called the International Celestial Reference Frame. It aligns (more or less) with J2000.0 mean place merely by convention. A completely differently oriented ICRS could have been adopted, but continuity with existing practice was obvious a great convenience.

The difference between ICRS and J2000.0 mean place is a set of Euler angles called the "frame bias". They are calculated by the SOFA function `iauPfw06`. It is instructive to type the following into COCO:

```
i c
o 6
r h
0 0
```

. . . producing the report:

```
 = 00 00 00.00000 +00 00 00.0000  J2000.000  ICRS (barycentric)
-> 00 00 00.00097 -00 00 00.0166  J2000.000  J2000.000  FK6
```

This shows the J2000.0 mean place of the ICRS origin, which turned out to be about $0''.022$ from the equinox.

4.2 Current Coordinates

Current coordinates, which along with a clock star allow a telescope to be pointed, are obtained from a star catalog entry by allowing for space motion, light deflection, aberration and precession-nutation. COCO goes only as far as the geocenter, whereas accurate topocentric coordinates would also have to take into account diurnal aberration (and in principle diurnal parallax) and Earth orientation parameters. The two supported coordinate systems (CIRS and apparent) are both based upon the "Celestial Intermediate Pole" and differ only in how the zero point of right ascension is defined.

For details of how SOFA transforms between ICRS coordinates and current coordinates, see the functions `iauAtci13`, `iauATic13` and `iauAtciq`. The functions support both Intermediate and

Apparent place, placing at the calling application's disposal the difference between the two RA zero points (and equivalently between apparent ST and ERA), which is called the Equation of the Origins.

n.b. precise telescope pointing would need in addition knowledge of the observatory location and ambient air conditions (not to mention instrumental parameters), all of which lie outside the capabilities that COCO addresses.

4.2.1 I: Intermediate Place

The Celestial Intermediate Reference System (COCO code I) uses as its right ascension zero point the Celestial Intermediate Origin. This is a kinematically defined point that unlike the classical origin, the equinox, from moment to moment does not move along the equator. The pay-off for this choice of origin is that hour angles can be computed using the"Earth Rotation Angle", a linear function of Universal Time UT1.

4.2.2 A: Apparent Place

The geocentric apparent place (COCO code A) uses as its right ascension zero point the (classical) equinox, the ascending node of the ecliptic on the equator. Though this geometrical point is much more intuitively obvious than the kinematically defined CIO, it does mean that to compute hour angles involves apparent Sidereal Time, a complicated function of both UT1 and TDB (the successor to "Ephemeris Time").

4.3 Non-equatorial

Both ecliptic coordinates and galactic coordinates are simply rotations of the star's barycentric direction with respect to the ICRS.

4.3.1 E: Ecliptic

COCO's ecliptic coordinates, $[\,\lambda, \phi\,]$, are based on the IAU 2006 precession model. The associated rotation matrix is generated by the SOFA function `iauEcm06`.

The ecliptic is a rather ill-defined concept; the Earth's orbit is not a plane, and its changing orientation means definitions based on geometry and kinematics disagree at the $0\rlap{.}''1$ level. Consequently although ecliptic coordinates remain useful for descriptive purposes they have fallen out of use in high-precision work.

4.3.2 G: Galactic

The formal IAU 1958 definition of Galactic coordinates $[\, \mathrm{L}^{\mathrm{II}}, \mathrm{B}^{\mathrm{II}} \,]$ is based on a pole and meridian defined in the obsolete FK4 reference system. Expressing it in modern terms involves a degree of interpretation; deciding what to do about the E-terms of aberration (see Section 4.1.2, earlier) is an example of this. However, the physical uncertanties in the IAU 1958 definition, which are of order $0\overset{\circ}{.}1$, make the choice of redefinition of canonical interest only. The SOFA functions called by SOFA adopt the formulation defined in the Hipparcos Catalogue – see `iauIcrs2g` for details.

Like ecliptic coordinates, Galactic coordinates are good for descriptive uses but not for high precision astrometry.

5 Files

The following lists all the COCO files and the purpose of each one:

`addbi.c`	C source for the `Addbi` function
`addet.c`	C source for the `Addet` function
`coco.c`	C source for the COCO application
`coco.pdf`	documentation PDF
`coco.tex`	documentation LaTeX source
`cocoml.c`	C source for the `main()` function
`dbjin.c`	C source for the `Dbjin` function
`decco.c`	C source for the `Decco` function
`decpar.c`	C source for the `Decpar` function
`dfltin.c`	C source for the `Dfltin` function
`dp.c`	C source for the `Dp` function
`dqp.c`	C source for the `Dqp` function
`dr2tn.c`	C source for the `Dr2tn` function
`epco.c`	C source for the `Epco` function
`epj2d.c`	C source for the `Epj2d` function
`etrms.c`	C source for the `Etrms` function
`euler.c`	C source for the `Euler` function
`getcmd.c`	C source for the `Getcmd` function
`getsys.c`	C source for the `Getsys` function
`help.c`	C source for the `Help` function
`iform.c`	C source for the `Iform` function
`int2in.c`	C source for the `Int2in` function
`intin.c`	C source for the `Intin` function
`kbj.c`	C source for the `Kbj` function
`pm.c`	C source for the `Pm` function
`prec4.c`	C source for the `Prec4` function
`prec6.c`	C source for the `Prec6` function
`preces.c`	C source for the `Preces` function
`r2dr.c`	C source for the `R2dr` function
`repco.c`	C source for the `Repco` function
`repra.c`	C source for the `Repra` function
`repres.c`	C source for the `Repres` function
`repsys.c`	C source for the `Repsys` function
`subbi.c`	C source for the `Subbi` function
`subet.c`	C source for the `Subet` function
`tok.c`	C source for the `Tok` function
`tranco.c`	C source for the `Tranco` function