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Standards of Fundamental Astronomy

SOFA Miscellaneous Topics

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Contents

1 Introduction

SOFA stands for *Standards of Fundamental Astronomy.* The SOFA software is a collection of Fortran 77 and ANSI C subprograms that implement official IAU algorithms for fundamental-astronomy computations. At the present time the SOFA software comprises 192 astronomy functions supported by 55 utility functions that deal with angles, vectors and matrices and called the SOFA vector-matrix library (VML).

The core documentation for the SOFA collection consists of classified and alphabetic lists of subroutine calls plus detailed preamble comments in the source code of individual functions. Tutorial descriptions of the purpose of the SOFA functions and how to use them appear in a set of so-called "cookbooks", each focusing on a different topic, namely precession-nutation, time scales, astrometry and the vector/matrix tools. These broad subject areas account for the bulk of the SOFA functions; the present document fills in the gaps by covering various narrower and self-contained topics.

The different topics and the associated functions are introduced below. In most cases a lengthy discussion is unnecessary, and once the existence of a particular function has been flagged the detailed specification (in Section 2) is all that the user will need.

1.1 Ecliptic coordinates

SOFA provides three functions to support ecliptic coordinates $[\lambda, \beta]$, namely `iauEqec06`, `iauEceq06` and `iauEcm06`. All three are based on the IAU 2006 precession.

Classically the transformation from equatorial coordinates $[\alpha, \delta]$ is simply a rotation $\mathbf{R}_1(\epsilon_0)$, with different choices of equinox, obliquity and type of $[\alpha, \delta]$ available. However, since the IAU's 2000 resolutions the role of the ecliptic in high precision applications has declined, while J2000.0 mean $[\alpha, \delta]$ as a standard reference system has given way to the ICRS. Consequently SOFA offers only mean equinox and ecliptic of date for $[\lambda, \beta]$ and ICRS for $[\alpha, \delta]$. Although these are inhomogenous systems (for example the ICRS and mean J2000.0 origins are separated by about $0\overset{''}{.}02$), they are the most useful choices for modern applications.

To transform $[\lambda, \beta]$ to $[\alpha, \delta]$:

```
iauEceq06 ( date1, date2, dl, db, &dr, &dd );
```

The arguments `date1` and `date2` (given) are TT in the usual SOFA two-part format; `dl` and `db` (given) are $[\lambda, \beta]$ in radians; `dr` and `dd` (returned) are the ICRS $[\alpha, \delta]$ in radians.

The inverse transformation, from $[\alpha, \delta]$ to $[\lambda, \beta]$, is:

```
iauEqec06 ( date1, date2, dr, dd, &dl, &db );
```

Where a large number of positions are to be transformed, it is more efficient to generate the required r-matrix once:

```
iauEcm06 ( date1, date2, rm );
```

. . . and then use it repeatedly. The source code for `iauEqec6` and `iauEceq06` shows exactly how to do this.

1.2 Galactic coordinates

SOFA provides two functions to support galactic coordinates $[\, l^{II}, b^{II} \,]$, namely `iauIcrs2g` and `iauG2icrs`. The IAU 1958 system of Galactic coordinates is problematical in several respects (see the detailed comments for the two functions) and SOFA has not attempted to deliver that system canonically. Instead, a formulation based upon the one published with the Hipparcos catalog has been used.

To transform ICRS $[\, \alpha, \delta \,]$ to galactic coordinates $[\, l^{II}, b^{II} \,]$:

```
iauIcrs2g ( dr, dd, &dl, &db );
```

The arguments `dr` and `dd` (given) are the ICRS $[\, \alpha, \delta \,]$ in radians; `dl` and `db` (returned) are galactic longitude and latitude $[\, l^{II}, b^{II} \,]$ in radians.

The inverse transformation, from $[\, l^{II}, b^{II} \,]$ to $[\, \alpha, \delta \,]$, is:

```
iauG2icrs ( dl, db, &dr, &dd );
```

1.3 Hipparcos/FK5

Neglecting zonal errors, the Hipparcos star catalog differs systematically from the earlier FK5 catalog in both orientation and spin, of order 32 mas and 1 mas/y respectively. SOFA provides five functions for transforming positions and space motions between the two systems:

- `iauH2fk5` transforms an Hipparcos catalog entry ($\alpha, \delta, \mu_\alpha, \mu_\delta$, parallax and radial velocity) into an FK5 catalog entry.
- `iauHfk5z` does the same but for stars whose Hipparcos proper motion, parallax and radial velocity are all unknown.
- `iauFk52h` transforms an FK5 catalog entry into an Hipparcos catalog entry.
- `iauFk5hz` does the same but for stars whose Hipparcos proper motion, parallax and radial velocity are all unknown.
- `iauFk5hip` expresses the rotation and spin in the form needed by the other functions.

The calls are:

```
iauH2fk5 ( rh, dh, drh, ddh, pxh, rvh, r5, d5, dr5, dd5, px5, rv5 );

iauHfk5z ( rh, dh, date1, date2, &r5, &d5, &dr5, &dd5 );

iauFk52h ( r5, d5, dr5, dd5, px5, rv5, &rh, &dh, &drh, &ddh, &pxh, &rvh );

iauFk5hz ( r5, d5, date1, date2, &rh, &dh );

iauFk5hip ( r5h, s5h );
```

Arguments `rh`, `dh`, `drh`, `ddh`, `pxh`, `rvh` are the Hipparcos $\alpha, \delta, \mu_\alpha, \mu_\delta$, parallax and radial velocity, while `r5`, `d5`, `dr5`, `dd5`, `px5`, `rv5` are the same for FK5; `date1` and `date2` are TDB as a two part JD. The units are radians, radians/year, arcseconds and km/s as appropriate, and μ_α is $\Delta\alpha/\Delta t$ rather than $\Delta\alpha \cos\delta/\Delta t$. Argument `r5h` is an r-matrix giving FK5 orientation with respect to Hipparcos while `s5h` is an r-vector giving the rate of change in radians/year.

1.4 FK4/FK5

In the decades prior to the introduction of the FK5 catalog in the 1980s, astrometric results were published with respect to its predecessor, FK4. Quite apart from the change of equinox from B1950.0 to J2000.0 and the consequent 50 years of precession, the two systems differ in rather complicated ways. The precession model itself was changed, the practice of incorporating in FK4 positions part of the correction for annual aberration (the so-called E-terms) ceased, and the proper motion system was revised to take account of Galactic rotation[1]

Although there is now no reason to perpetuate the use of FK4 conventions, there remains a need to interpret published astrometry from the earlier era, and SOFA provides four functions to help with this:

- `iauFk425` transforms an FK4 catalog entry ($\alpha, \delta, \mu_\alpha, \mu_\delta$, parallax and radial velocity) into an FK5 catalog entry.
- `iauFk45z` does the same but for stars whose FK5 proper motion, parallax and radial velocity are all unknown.
- `iauFk524` transforms an FK5 catalog entry into an FK4 catalog entry.
- `iauFk54z` does the same but for stars whose FK5 proper motion, parallax and radial velocity are all unknown.

The calls are:

[1]FK4-based astrometry of a distant object such as a QSO would exhibit fictitious proper motion of up to $0''.5$ per century.

```
iauFk425 ( r1950, d1950, dr1950, dd1950, p1950, v1950,
           &r2000, &d2000, &dr2000, &dd2000, &p2000, &v2000 );

iauFk45z ( r1950, d1950, bepoch, &r2000, &d2000 );

iauFk524 ( r2000, d2000, dr2000, dd2000, p2000, v2000,
           &r1950, &d1950, &dr1950, &dd1950, &p1950, &v1950 );

iauFk54z ( r2000, d2000, bepoch, &r1950, &d1950, &dr1950, &dd1950 );
```

The arguments `r1950`, `d1950`, `dr1950`, `dd1950`, `p1950`, `rv1950` are the B1950.0 FK4 $\alpha, \delta, \mu_\alpha, \mu_\delta$, parallax and radial velocity, while `r2000`, `d2000`, `dr2000`, `dd2000`, `p2000`, `rv2000` are the same for J2000.0 FK5. The units are radians, radians/year, arcseconds and km/s as appropriate, and μ_α is $\Delta\alpha/\Delta t$ rather than $\Delta\alpha\cos\delta/\Delta t$.

1.5 Geodesy

Many positional-astronomy problems require knowledge of the terrestrial observer's position, velocity and orientation. Whereas some low accuracy applications can approximate the Earth's figure as a sphere, an oblate spheroid is of course much (2-3 orders of magnitude) better. The most demanding applications need to go even further, taking into account tidal effects (both sea and earth) and local topography. SOFA support for the spherical approximation consists of no more than the general-purpose vector-matrix tools, but there are five functions that address the geometry of the oblate spheroid approximation; there is no SOFA support for the stages beyond that, nor for any gravimetric aspects.

One function, `iauEform`, returns the equatorial radius and flattening factor of one of three standard reference ellipsoids, namely WGS84, GRS80 and WGS72. The remaining four functions, `iauGc2gd`, `iauG2gde`, `iauGd2gc`, and `iauGd2gce`, provide conversions between two sorts of latitude, namely *geocentric*, based on the line from the geocenter to the observer, and *geodetic*, based on the normal to the reference ellipsoid at the observer's position; the two differ by up to $0.^\circ 2$ (at 45° latitude). The caller can either choose one of the standard reference ellipsoids (typically WGS84) or instead specify the ellipsoid parameters explicitly. The calls are:

```
j = iauEform ( n, a, f, j );

j = iauGc2gd ( n, xyz, &elong, &phi, &height );
j = iauGc2gde ( a, f, xyz, &elong, &phi, &height );

j = iauGd2gc ( n, elong, phi, height, xyz );
j = iauGd2gce ( a, f, elong, phi, height, xyz );
```

The argument `n` identifies which reference ellipsoid to use, with 1, 2 and 3 representing WGS84, GRS80 and WGS72 respectively; for the cases where the user elects to specify a reference ellipsoid, `a` is the equatorial radius (meters) and `f` is the flattening factor $(a-b)/a$, where a and b are the equatorial and polar radii; `xyz` is the observer's geocentric vector (meters); `elong` is the longitude (east positive); `phi` is the geodetic latitude; and `height` is the height above the reference ellipsoid (meters); `j` is the returned status, with zero indicating success.

1.6 Solar-system ephemerides

SOFA's support for solar-system ephemerides is very limited. None of the available high-accuracy ephemerides (numerically integrated or analytical) has IAU canonical status and so would confront SOFA with a difficult choice; another reason is that the need to read the associated files would be an obstacle to developing platform independent code. The SOFA facilities are restricted to what can be done affordably in self-contained Fortran or C code, and only three tools, none with any IAU canonical status, are provided:

- `iauEpv00` predicts heliocentric and barycentric Earth position and velocity using an abridged form of the VSOP2000 planetary theory that was specially developed for SOFA by P. Bretagnon. It was designed to deliver microarcsecond accuracies when computing parallax and aberration, and achieves about 10 km and 5 mm/s (worst case). This is good enough for a wide variety of applications, and the function is used extensively by other SOFA functions.
- `iauMoon98` predicts the geocentric position and velocity of the Moon using J. Meeus's ELP/MPP02 based algorithm. It achieves worst-case accuracies of about 20 km and 200 mm/s, giving predictions for the terrestrial observer within about 20 arcseconds. This is good enough for calculating visibility, rise/set times and sky brightness, but not for occultations and eclipses.
- `iauPlan94` computes very approximate heliocentric positions and velocities of the eight planets (or in Earth's case the Earth-Moon barycenter). Accuracy varies from planet to planet: seen by a terrestrial observer, Mercury and Venus predictions are within a few arcseconds, 0.5 arcminutes for Mars, 1.5 arcminutes for Jupiter through Uranus and 0.2 arcminutes for Neptune. This is adequate for simple "planetarium" applications but not for predicting occultations *etc.*.

The calls are:

```
j = iauEpv00 ( date1, date2, pvh, pvb );
```

where `date1` and `date2` are the TDB as a two-part JD, `pvh` and `pvb` are the Earth's heliocentric and barycentric pv-vectors (BCRS, au, au/day), and `j` is the status (0 = OK);

```
iauMoon98 ( date1, date2, pv );
```

where `date1` and `date2` are the TT as a two-part JD, and `pv` is the Moon pv-vector (GCRS, au, au/day); and

```
j = iauPlan94 ( date1, date2, np, pv );
```

where `date1` and `date2` are the TDB as a two-part JD, `np` selects the planet (1-9 = Mercury, Venus, EMB, Mars and so on), and `j` is the status (0 = OK).

2 Function specifications

This section comprises individual descriptions of the functions covered by the present document, in aphabetical order.

Arguments are nearly always of type `double`. In a few cases (always with names beginning I-N) they are `int`. Status values returned as a function value are always `int`.

In accordance with SOFA conventions, Julian Dates are supplied as two arguments which added together are the JD (in a specified time scale). This is done to offer a range of tradeoffs between convenience and resolution. Common choices include:

- zero plus JD
- 2400000.5 plus MJD
- Julian Day Number plus fraction of a day.

Angles are always radians. (*n.b.* Parallaxes, which are distance measures rather than angles, are in arcseconds.)

iauEceq06 *ecliptic coordinates to RA,Dec, IAU 2006* iauEceq06

CALL :

```
iauEceq06 ( date1, date2, dl, db, &dr, &dd )
```

ACTION :

Transformation from ecliptic coordinates (mean equinox and ecliptic of date) to ICRS RA,Dec, using the IAU 2006 precession model.

GIVEN :

date1	`double`	TT as a 2-part. . .
date2	`double`	. . . Julian Date (Note 1)
dl,db	`double`	ecliptic longitude and latitude (radians)

RETURNED :

dr,dd	`double*`	ICRS right ascension and declination (radians)

NOTES :

1. The TT date `date1+date2` is a Julian Date, apportioned in any convenient way between the two arguments. For example, JD(TT) = 2450123.7 could be expressed in any of these ways, among others:

`date1`	`date2`	
2450123.7	0.0	(JD method)
2451545.0	−1421.3	(J2000 method)
2400000.5	50123.2	(MJD method)
2450123.5	0.2	(date & time method)

   The JD method is the most natural and convenient to use in cases where the loss of several decimal digits of resolution is acceptable. The J2000 method is best matched to the way the argument is handled internally and will deliver the optimum resolution. The MJD method and the date & time methods are both good compromises between resolution and convenience.

2. No assumptions are made about whether the coordinates represent starlight and embody astrometric effects such as parallax or aberration.

3. The transformation is approximately that from ecliptic longitude and latitude (mean equinox and ecliptic of date) to mean J2000.0 right ascension and declination, with only frame bias (always less than 25 mas) to disturb this classical picture.

iauEcm06 — *ICRS to ecliptic matrix, IAU 2006* — iauEcm06

CALL :

```
iauEcm06 ( date1, date2, rm )
```

ACTION :

ICRS equatorial to ecliptic rotation matrix, IAU 2006.

GIVEN :

date1	`double`	TT as a 2-part...
date2	`double`	...Julian Date (Note 1)

RETURNED :

rm	`double[3][3]`	ICRS to ecliptic rotation matrix

NOTES :

1. The TT date `date1+date2` is a Julian Date, apportioned in any convenient way between the two arguments. For example, JD(TT) = 2450123.7 could be expressed in any of these ways, among others:

`date1`	`date2`	
2450123.7	0.0	(JD method)
2451545.0	−1421.3	(J2000 method)
2400000.5	50123.2	(MJD method)
2450123.5	0.2	(date & time method)

The JD method is the most natural and convenient to use in cases where the loss of several decimal digits of resolution is acceptable. The J2000 method is best matched to the way the argument is handled internally and will deliver the optimum resolution. The MJD method and the date & time methods are both good compromises between resolution and convenience.

2. The matrix `rm` operates in the sense:

$$\mathbf{v}_{ecl} \quad = \quad \mathbf{R} \cdot \mathbf{v}_{ICRS}$$

where $\mathbf{R}$ is the matrix `rm` returned by the present function, $\mathbf{v}_{ICRS}$ is a vector with respect to ICRS right ascension and declination axes and $\mathbf{v}_{ecl}$ is the same vector with respect to the (inertial) ecliptic and equinox of date.

3. $\mathbf{v}_{ICRS}$ is a free vector, merely a direction, typically of unit magnitude, and not bound to any particular spatial origin, such as the Earth, Sun or SSB. No assumptions are made about whether it represents starlight and embodies astrometric effects such as parallax or aberration. The transformation is approximately that between mean J2000.0 right ascension and declination and ecliptic longitude and latitude, with only frame bias (always less than 25 mas) to disturb this classical picture.

iauEform *Earth reference ellipsoids* iauEform

CALL :

```
status = iauEform ( n, &a, &f )
```

ACTION :

Return the parameters of the specified Earth reference ellipsoid.

GIVEN :

n	`i`	ellipsoid identifier (Note 1)

RETURNED :

a	`double*`	equatorial radius (meters, Note 2)
f	`double*`	flattening (Note 2)

RETURNED (function value) :

	`int`	status: 0 = OK −1 = illegal identifier (Note 3)

NOTES :

1. The identifier `n` is a number that specifies the choice of reference ellipsoid. The following are supported:

n	*ellipsoid*
1	WGS84
2	GRS80
3	WGS72

   The number `n` has no significance outside the SOFA software.

2. The ellipsoid parameters are returned in the form of equatorial radius in meters (`a`) and flattening (`f`). The latter is a number around 0.00335, *i.e.* around 1/298.

3. For the case where an unsupported `n` value is supplied, zero `a` and `f` are returned, as well as error status.

REFERENCES :

1. Moritz, H., *Bull. Geodesique* 66-2, 187 (1992).
2. *Department of Defense World Geodetic System 1984*, National Imagery and Mapping Agency Technical Report 8350.2, Third Edition, p3-2.
3. Seidelmann, P.K. (Ed.) (1992), *Explanatory Supplement to the Astronomical Almanac*, University Science Books, p220.

iauEpv00 — *Earth position and velocity* — iauEpv00

CALL :

```
status = iauEpv00 ( date1, date2, pvh, pvb )
```

ACTION :

Earth position and velocity, heliocentric and barycentric, with respect to the Barycentric Celestial Reference System.

GIVEN :

date1	`double`	TDB as a 2-part...
date2	`double`	...Julian Date (Note 1)

RETURNED :

pvh	`double[2][3]`	heliocentric Earth position/velocity (au, au/day)
pvb	`double[2][3]`	barycentric Earth position/velocity (au, au/day)

RETURNED (function value) :

`int`	status: 0 = OK +1 = warning: date outside 1900-2100 CE

NOTES :

1. The TDB date `date1+date2` is a Julian Date, apportioned in any convenient way between the two arguments. For example, JD(TDB) = 2450123.7 could be expressed in any of these ways, among others:

`date1`	`date2`	
2450123.7	0.0	(JD method)
2451545.0	−1421.3	(J2000 method)
2400000.5	50123.2	(MJD method)
2450123.5	0.2	(date & time method)

The JD method is the most natural and convenient to use in cases where the loss of several decimal digits of resolution is acceptable. The J2000 method is best matched to the way the argument is handled internally and will deliver the optimum resolution. The MJD method and the date & time methods are both good compromises between resolution and convenience. However, the accuracy of the result is more likely to be limited by the algorithm itself than the way the date has been expressed.

2. On return, the arrays `pvh` and `pvb` contain the following:

`pvh[0][0]`	x	
`pvh[0][1]`	y	heliocentric position, au
`pvh[0][2]`	z	
`pvh[1][0]`	$\dot{x}$	
`pvh[1][1]`	$\dot{y}$	heliocentric velocity, au/d
`pvh[1][2]`	$\dot{z}$	
`pvb[0][0]`	x	
`pvb[0][1]`	y	barycentric position, au
`pvb[0][2]`	z	
`pvb[1][0]`	$\dot{x}$	
`pvb[1][1]`	$\dot{y}$	barycentric velocity, au/d
`pvb[1][2]`	$\dot{z}$	

   The vectors are oriented with respect to the BCRS. The time unit is one day in TDB.

3. The function is a **simplified solution** from the planetary theory (X. Moisson, P. Bretagnon, 2001, Celes. Mechanics & Dyn. Astron., **80**, 3/4, 205-213). It is a simplified form of the theory as implemented in Fortran code originally provided by P. Bretagnon (private communication, 2000).

4. Comparisons over the time span 1900-2100 with this simplified solution and the JPL DE405 ephemeris give the following results:

	RMS	*max*	
Heliocentric:			
position error	3.7	11.2	km
velocity error	1.4	5.0	mm/s
Barycentric:			
position error	4.6	13.4	km
velocity error	1.4	4.9	mm/s

   Comparisons with the JPL DE406 ephemeris show that by 1800 and 2200 the position errors are approximately double their 1900-2100 size. By 1500 and 2500 the deterioration is a factor of 10 and by 1000 and 3000 a factor of 60. The velocity accuracy falls off at about half that rate.

iauEqec06 — *ICRS to ecliptic coordinates* — iauEqec06

CALL :

```
iauEqec06 ( date1, date2, dr, dd, &dl, &db )
```

ACTION :

Transformation from ICRS equatorial coordinates to ecliptic coordinates (mean equinox and ecliptic of date) using IAU 2006 precession model.

GIVEN :

date1	`double`	TT as a 2-part...
date2	`double`	...Julian Date (Note 1)
dr,dd	`double*`	ICRS right ascension and declination (radians)

RETURNED :

dl,db	`double*`	ecliptic longitude and latitude (radians)

NOTES :

1. The TDB date `date1+date2` is a Julian Date, apportioned in any convenient way between the two arguments. For example, JD(TDB) = 2450123.7 could be expressed in any of these ways, among others:

`date1`	`date2`	
2450123.7	0.0	(JD method)
2451545.0	−1421.3	(J2000 method)
2400000.5	50123.2	(MJD method)
2450123.5	0.2	(date & time method)

   The JD method is the most natural and convenient to use in cases where the loss of several decimal digits of resolution is acceptable. The J2000 method is best matched to the way the argument is handled internally and will deliver the optimum resolution. The MJD method and the date & time methods are both good compromises between resolution and convenience.

2. No assumptions are made about whether the coordinates represent starlight and embody astrometric effects such as parallax or aberration.

3. The transformation is approximately that from mean J2000.0 right ascension and declination to ecliptic longitude and latitude (mean equinox and ecliptic of date), with only frame bias (always less than 25 mas) to disturb this classical picture.

iauFk425 *B1950.0 FK4 to J2000.0 FK5* iauFk425

CALL :

```
iauFk425 ( r1950, d1950, dr1950, dd1950, p1950, v1950,
           &r2000, &d2000, &dr2000, &dd2000, &p2000, &v2000 )
```

ACTION :

Convert a star's catalog data from the old FK4 (Bessel-Newcomb) system to the later IAU 1976 FK5 (Fricke) system.

GIVEN (all B1950.0, FK4) :

r1950	`double`	B1950.0 RA (radians)
d1950	`double`	B1950.0 Dec (radians)
dr1950	`double`	B1950.0 RA proper motion (radians/trop.yr)
dd1950	`double`	B1950.0 Dec proper motion (radians/trop.yr)
p1950	`double`	parallax (arcsec)
v1950	`double`	radial velocity (km/s, +ve = moving away)

RETURNED (all J2000.0, FK5) :

r2000	`double*`	J2000.0 RA (radians)
d2000	`double*`	J2000.0 Dec (radians)
dr2000	`double*`	J2000.0 RA proper motion (radians/Jul.yr)
dd2000	`double*`	J2000.0 Dec proper motion (radians/Jul.yr)
p2000	`double*`	parallax (arcsec)
v2000	`double*`	radial velocity (km/s, +ve = moving away)

NOTES :

1. The proper motions in right ascension are $\Delta\alpha/\Delta t$ rather than $\Delta\alpha\cos\delta/\Delta t$, and are per year rather than per century.
2. The conversion is somewhat complicated, for several reasons:
   - Change of standard epoch from B1950.0 to J2000.0.
   - An intermediate transition date of 1984 January 1.0 TT.
   - A change of precession model.
   - Change of time unit for proper motion (tropical to Julian).
   - FK4 positions include the E-terms of aberration, to simplify the hand computation of annual aberration. FK5 positions assume a rigorous aberration computation based on the Earth's barycentric velocity.
   - The E-terms also affect proper motions, and in particular cause objects at large distances to exhibit fictitious proper motions.

The algorithm is based on Smith *et al.* (1989) and Yallop *et al.* (1989), which presented a matrix method due to Standish (1982) as developed by Aoki *et al.* (1983), using Kinoshita's development of Andoyer's post-Newcomb precession. The numerical constants from Seidelmann (1992) are used canonically.

3. Conversion from B1950.0 FK4 to J2000.0 FK5 only is provided for. Conversions for different epochs and equinoxes would require additional treatment for precession, proper motion and E-terms.

4. In the FK4 catalog the proper motions of stars within 10° of the poles do not embody differential E-terms effects and should, strictly speaking, be handled in a different manner from stars outside these regions. However, given the general lack of homogeneity of the star data available for routine astrometry, the difficulties of handling positions that may have been determined from astrometric fields spanning the polar and non-polar regions, the likelihood that the differential E-terms effect was not taken into account when allowing for proper motion in past astrometry, and the undesirability of a discontinuity in the algorithm, the decision has been made in this SOFA algorithm to include the effects of differential E-terms on the proper motions for all stars, whether polar or not. At epoch J2000.0, and measuring "on the sky" rather than in terms of $\Delta\alpha$, the errors resulting from this simplification are less than 1 milliarcsecond in position and 1 milliarcsecond per century in proper motion.

REFERENCES :

1. Aoki, S. *et al.*, 1983, *Conversion matrix of epoch B1950.0 FK4-based positions of stars to epoch J2000.0 positions in accordance with the new IAU resolutions.* Astron.Astrophys. **128**, 263-267.

2. Seidelmann, P.K. (Ed.), 1992, *Explanatory Supplement to the Astronomical Almanac*, ISBN 0-935702-68-7.

3. Smith, C.A. *et al.*, 1989, *The transformation of astrometric catalog systems to the equinox J2000.0.* Astron.J. **97**, 265.

4. Standish, E.M., 1982, *Conversion of positions and proper motions from B1950.0 to the IAU system at J2000.0.* Astron.Astrophys., **115**, 1, 20-22.

5. Yallop, B.D. *et al.*, 1989, *Transformation of mean star places from FK4 B1950.0 to FK5 J2000.0 using matrices in 6-space.* Astron.J. **97**, 274.

iauFk45Z *B1950.0 FK4 to J2000.0 FK5, no PM* iauFk45Z

CALL :

```
iauFk45z ( r1950, d1950, bepoch, &r2000, &d2000 )
```

ACTION :

Convert a star's catalog data from the old FK4 (Bessel-Newcomb) system to the later IAU 1976 FK5 (Fricke) system, in such a way that the FK5 proper motion is zero. Because such a star has, in general, a non-zero proper motion in the FK4 system, the function requires the epoch at which the position in the FK4 system was determined.

GIVEN :

r1950	`double`	B1950.0 RA (radians)
d1950	`double`	B1950.0 Dec (radians)
bepoch	`double`	Besselian epoch (*e.g.* 1979.3)

RETURNED :

r2000	`double*`	J2000.0 RA (radians)
d2000	`double*`	J2000.0 Dec (radians)

NOTES :

1. The epoch `bepoch` is strictly speaking Besselian, but if a Julian epoch is supplied the result will be affected only to a negligible extent.

2. The method is from Appendix 2 of Aoki *et al.* (1983), but using the constants of Seidelmann (1992). See the function `iauFk425` for a general introduction to the FK4 to FK5 conversion.

3. Conversion from B1950.0 FK4 to J2000.0 FK5 only is provided for. Conversions for different epochs and equinoxes would require additional treatment for precession, proper motion and E-terms.

4. In the FK4 catalog the proper motions of stars within 10° of the poles do not embody differential E-terms effects and should, strictly speaking, be handled in a different manner from stars outside these regions. However, given the general lack of homogeneity of the star data available for routine astrometry, the difficulties of handling positions that may have been determined from astrometric fields spanning the polar and non-polar regions, the likelihood that the differential E-terms effect was not taken into account when allowing for proper motion in past astrometry, and the undesirability of a discontinuity in the algorithm, the decision has been made in this SOFA algorithm to include the effects of differential E-terms on the proper motions for all stars, whether polar or not. At epoch J2000.0, and measuring "on the sky" rather than in terms of $\Delta\alpha$, the errors resulting from this simplification are less than 1 milliarcsecond in position and 1 milliarcsecond per century in proper motion.

REFERENCES :

1. Aoki, S. *et al.*, 1983, *Conversion matrix of epoch B1950.0 FK4-based positions of stars to epoch J2000.0 positions in accordance with the new IAU resolutions.* Astron.Astrophys. **128**, 263-267.
2. Seidelmann, P.K. (Ed.), 1992, *Explanatory Supplement to the Astronomical Almanac*, ISBN 0-935702-68-7.

iauFk524 — *J2000.0 FK5 to B1950.0 FK4* — iauFk524

CALL :

```
iauFk524 ( r2000, d2000, dr2000, dd2000, p2000, v2000,
           &r1950, &d1950, &dr1950, &dd1950, &p2000, &v1950 )
```

ACTION :

Convert J2000.0 FK5 star catalog data to B1950.0 FK4.

GIVEN (all J2000.0, FK5) :

r2000	`double*`	J2000.0 RA (radians)
d2000	`double*`	J2000.0 Dec (radians)
dr2000	`double*`	J2000.0 RA proper motion (radians/Jul.yr)
dd2000	`double*`	J2000.0 Dec proper motion (radians/Jul.yr)
p2000	`double*`	parallax (arcsec)
v2000	`double*`	radial velocity (km/s, +ve = moving away)

RETURNED (all B1950.0, FK4) :

r1950	`double*`	B1950.0 RA (radians)
d1950	`double*`	B1950.0 Dec (radians)
dr1950	`double*`	B1950.0 RA proper motion (radians/trop.yr)
dd1950	`double*`	B1950.0 Dec proper motion (radians/trop.yr)
p1950	`double*`	parallax (arcsec)
v1950	`double*`	radial velocity (km/s, +ve = moving away)

NOTES :

1. The proper motions in right ascension are $\Delta\alpha/\Delta t$ rather than $\Delta\alpha\cos\delta/\Delta t$, and are per year rather than per century.

2. The conversion is somewhat complicated, for several reasons:

   - Change of standard epoch from J2000.0 to B1950.0.
   - An intermediate transition date of 1984 January 1.0 TT.
   - A change of precession model.
   - Change of time unit for proper motion (Julian to tropical).
   - FK4 positions include the E-terms of aberration, to simplify the hand computation of annual aberration. FK5 positions assume a rigorous aberration computation based on the Earth's barycentric velocity.
   - The E-terms also affect proper motions, and in particular cause objects at large distances to exhibit fictitious proper motions.

   The algorithm is based on Smith *et al.* (1989) and Yallop *et al.* (1989), which presented a matrix method due to Standish (1982) as developed by Aoki *et al.* (1983), using Kinoshita's development of Andoyer's post-Newcomb precession. The numerical constants from Seidelmann (1992) are used canonically.

3. In the FK4 catalog the proper motions of stars within 10° of the poles do not embody differential E-terms effects and should, strictly speaking, be handled in a different manner from stars outside these regions. However, given the general lack of homogeneity of the star data available for routine astrometry, the difficulties of handling positions that may have been determined from astrometric fields spanning the polar and non-polar regions, the likelihood that the differential E-terms effect was not taken into account when allowing for proper motion in past astrometry, and the undesirability of a discontinuity in the algorithm, the decision has been made in this SOFA algorithm to include the effects of differential E-terms on the proper motions for all stars, whether polar or not. At epoch J2000.0, and measuring "on the sky" rather than in terms of $\Delta\alpha$, the errors resulting from this simplification are less than 1 milliarcsecond in position and 1 milliarcsecond per century in proper motion.

REFERENCES :

1. Aoki, S. *et al.*, 1983, *Conversion matrix of epoch B1950.0 FK4-based positions of stars to epoch J2000.0 positions in accordance with the new IAU resolutions.* Astron.Astrophys. **128**, 263-267.
2. Seidelmann, P.K. (Ed.), 1992, *Explanatory Supplement to the Astronomical Almanac*, ISBN 0-935702-68-7.
3. Smith, C.A. *et al.*, 1989, *The transformation of astrometric catalog systems to the equinox J2000.0.* Astron.J. **97**, 265.
4. Standish, E.M., 1982, *Conversion of positions and proper motions from B1950.0 to the IAU system at J2000.0.* Astron.Astrophys., **115**, 1, 20-22.
5. Yallop, B.D. *et al.*, 1989, *Transformation of mean star places from FK4 B1950.0 to FK5 J2000.0 using matrices in 6-space.* Astron.J. **97**, 274.

iauH2fk5 *Hipparcos to FK5* iauH2fk5

CALL :

```
iauH2fk5 ( rh, dh, drh, ddh, pxh, rvh, &r5, &d5, &dr5, &dd5, &px5, &rv5 )
```

ACTION :

Transform Hipparcos star data into the FK5 (J2000.0) system.

GIVEN (all Hipparcos, epoch J2000.0) :

rh	`double`	RA (radians)
dh	`double`	Dec (radians)
drh	`double`	proper motion in RA (radians/Jyear)
ddh	`double`	proper motion in Dec (radians/Jyear)
pxh	`double`	parallax (arcsec)
rvh	`double`	radial velocity (km/s, +ve = moving away)

RETURNED (all FK5, equinox J2000.0, epoch J2000.0) :

r5	`double*`	RA (radians)
d5	`double*`	Dec (radians)
dr5	`double*`	proper motion in RA (radians/Jyear)
dd5	`double*`	proper motion in Dec (radians/Jyear)
px5	`double*`	parallax (arcsec)
rv5	`double*`	radial velocity (km/s, +ve = moving away)

NOTES :

1. This function transforms Hipparcos star positions and proper motions into FK5 J2000.0.
2. The proper motions in right ascension are $\Delta\alpha/\Delta t$ rather than $\Delta\alpha\cos\delta/\Delta t$, and are per year rather than per century.
3. The FK5 to Hipparcos transformation is modeled as a pure rotation and spin; zonal errors in the FK5 catalog are not taken into account.
4. See also `iauFk52h`, `iauFk5hz`, `iauHfk5z`.

REFERENCE :

F.Mignard & M.Froeschle, Astron.Astrophys., **354**, 732-739 (2000).

iauFk54z *J2000.0 FK5 to B1950.0 FK4, zero PM & px* iauFk54z

CALL :

```
iauFk45z ( r2000, d2000, bepoch, &r1950, &d1950, &dr1950, &dd1950 )
```

ACTION :

Convert a star's catalog data from the IAU 1976 FK5 (Fricke) system to the former FK4 (Bessel-Newcomb) system, for cases such as distant radio sources where it is presumed there is zero parallax and no proper motion. Because of the E-terms of aberration, such objects have (in general) non-zero proper motion in FK4, and the present function returns those fictitious proper motions.

GIVEN :

r2000	`double`	J2000.0 RA (radians)
d2000	`double`	J2000.0 Dec (radians)
bepoch	`double`	Besselian epoch (*e.g.* 1979.3)

RETURNED :

r1950	`double*`	B1950.0 RA (radians)
d1950	`double*`	B1950.0 Dec (radians)
dr1950	`double*`	B1950.0 RA proper motion (radians/trop.yr)
dd1950	`double*`	B1950.0 Dec proper motion (radians/trop.yr)

NOTES :

1. In contrast to the `iauFk524` function, here the FK5 proper motions, the parallax and the radial velocity are presumed zero.
2. Conversion from J2000.0 FK5 to B1950.0 FK4 only is provided for. Conversions involving other equinoxes would require additional treatment for precession.
3. The position returned by this function is in the B1950.0 FK4 reference system but at Besselian epoch `bepoch`. For comparison with catalogs the `bepoch` argument will frequently be 1950.0. (In this context the distinction between Besselian and Julian epoch is insignificant.)
4. The right ascension of the returned (fictitious) proper motion is $\Delta\alpha/\Delta t$ rather than $\Delta\alpha \cos\delta/\Delta t$.

iauFk5hip — *FK5 to Hipparcos rotation & spin* — iauFk5hip

CALL :

```
iauFk5hip ( r5h, s5h )
```

ACTION :

Form the FK5 to Hipparcos rotation matrix and spin vector.

RETURNED :

r5h	`double[3][3]`	r-matrix: FK5 rotation wrt Hipparcos (Note 2)
s5h	`double[3]`	r-vector: FK5 spin wrt Hipparcos (Note 3)

NOTES :

1. This function models the FK5 to Hipparcos transformation as a pure rotation and spin; zonal errors in the FK5 catalog are not taken into account.
2. The r-matrix `r5h` operates in the sense:

   $$\mathbf{v}_H = \mathbf{R} \cdot \mathbf{v}_F$$

   where $\mathbf{R}$ is the r-matrix `r5h` returned by the present function, $\mathbf{v}_F$ is a vector in the FK5 frame and $\mathbf{v}_H$ is the equivalent Hipparcos vector.
3. The r-vector `s5h` represents the time derivative of the FK5 to Hipparcos rotation. The units are radians per year (Julian, TDB).

REFERENCE :

F.Mignard & M.Froeschle, Astron.Astrophys., **354**, 732-739 (2000).

iauFk5hz — *FK5 to Hipparcos, zero PM* — iauFk5hz

CALL :

```
iauFk5hz ( r5, d5, date1, date2, &rh, &dh )
```

ACTION :

Transform an FK5 (J2000.0) star position into the system of the Hipparcos catalog, assuming zero Hipparcos proper motion.

GIVEN :

r5	`double`	FK5 RA (radians), equinox J2000.0, at date
d5	`double`	FK5 Dec (radians), equinox J2000.0, at date
date1	`double`	TDB as a 2-part...
date2	`double`	...Julian Date (Notes 1,2)

RETURNED :

rh	`double*`	Hipparcos RA (radians)
dh	`double*`	Hipparcos Dec (radians)

NOTES :

1. This function converts a star position from the FK5 system to the Hipparcos system, in such a way that the Hipparcos proper motion is zero. Because such a star has, in general, a non-zero proper motion in the FK5 system, the function requires the date at which the position in the FK5 system was determined.

2. The TDB date `date1+date2` is a Julian Date, apportioned in any convenient way between the two arguments. For example, JD(TDB) = 2450123.7 could be expressed in any of these ways, among others:

`date1`	`date2`	
2450123.7	0.0	(JD method)
2451545.0	−1421.3	(J2000 method)
2400000.5	50123.2	(MJD method)
2450123.5	0.2	(date & time method)

The JD method is the most natural and convenient to use in cases where the loss of several decimal digits of resolution is acceptable. The J2000 method is best matched to the way the argument is handled internally and will deliver the optimum resolution. The MJD method and the date & time methods are both good compromises between resolution and convenience.

3. The FK5 to Hipparcos transformation is modeled as a pure rotation and spin; zonal errors in the FK5 catalog are not taken into account.

4. The position returned by this function is in the Hipparcos reference system but at date `date1+date2`.

5. See also `iauFk52h`, `iauH2fk5`, `iauHfk5z`.

REFERENCE :

F.Mignard & M.Froeschle, Astron.Astrophys., **354**, 732-739 (2000).

iauG2icrs — *Galactic coordinates to ICRS* — iauG2icrs

CALL :

```
iauG2icrs ( dl, db, &dr, &dd )
```

ACTION :

Transformation from Galactic coordinates to ICRS.

GIVEN :

dl	`double`	Galactic longitude (radians)
db	`double`	Galactic latitude (radians)

RETURNED :

dr	`double*`	ICRS right ascension (radians)
dd	`double*`	ICRS declination (radians)

NOTES :

1. The IAU 1958 system of Galactic coordinates was defined with respect to the now obsolete reference system FK4 B1950.0. When interpreting the system in a modern context, several factors have to be taken into account:

   - The inclusion in FK4 positions of the E-terms of aberration.
   - The distortion of the FK4 proper motion system by differential Galactic rotation.
   - The use of the B1950.0 equinox rather than the now-standard J2000.0.
   - The frame bias between ICRS and the J2000.0 mean place system.

   The Hipparcos Catalogue (Perryman & ESA 1997) provides a rotation matrix that transforms directly between ICRS and Galactic coordinates with the above factors taken into account. The matrix is derived from three angles, namely the ICRS coordinates of the Galactic pole and the longitude of the ascending node of the galactic equator on the ICRS equator. They are given in degrees to five decimal places and for canonical purposes are regarded as exact. In the Hipparcos Catalogue the matrix elements are given to 10 decimal places (about 20 μas). In the present SOFA function the matrix elements have been recomputed from the canonical three angles and are given to 30 decimal places.

2. The inverse transformation is performed by the function `iauIcrs2g`.

REFERENCE :

Perryman M.A.C. & ESA, 1997, ESA SP-1200, *The Hipparcos and Tycho catalogues. Astrometric and photometric star catalogues derived from the ESA Hipparcos Space Astrometry Mission.* ESA Publications Division, Noordwijk, Netherlands.

iauGc2gd — *geocentric to geodetic, standard ellipsoid* — iauGc2gd

CALL :

```
status = iauGc2gd ( n, xyz, &elong, &phi, &height )
```

ACTION :

Transform geocentric coordinates to geodetic using the selected reference ellipsoid.

GIVEN :

n	`int`	ellipsoid identifier (Note 1)
xyz	`double[3]`	geocentric vector (Note 2)

RETURNED :

elong	`double*`	longitude (radians, east +ve, Note 3)
phi	`double*`	latitude (geodetic, radians, Note 3)
height	`double*`	height above ellipsoid (geodetic, Notes 2,3)

RETURNED (function value) :

`int`	status: 0 = OK −1 = illegal identifier (Note 3) −2 = internal error (Note 3)

NOTES :

1. The identifier `n` is a number that specifies the choice of reference ellipsoid. The following are supported:

N	*ellipsoid*
1	WGS84
2	GRS80
3	WGS72

   The number `n` has no significance outside the SOFA software.

2. The geocentric vector (`xyz`, given) and height (`height`, returned) are in meters.

3. An error status of −1 means that the identifier `n` is illegal. An error status of −2 is theoretically impossible. In all error cases, all three results are set to `-1e9`.

4. The inverse transformation is performed in the function `iauGd2gc`.

iauGc2gde *geocentric to geodetic, specified ellipsoid* iauGc2gde

CALL :

```
status = iauGc2gde ( a, f, xyz, &elong, &phi, &height )
```

ACTION :

Transform geocentric coordinates to geodetic using a reference ellipsoid of specified form.

GIVEN :

a	`double`	equatorial radius (Notes 2,4)
f	`double`	flattening (Note 3)
xyz	`double[3]`	geocentric vector (Note 4)

RETURNED :

elong	`double*`	longitude (radians, east +ve)
phi	`double*`	latitude (geodetic, radians)
height	`double*`	height above ellipsoid (geodetic, Note 4)

RETURNED (function value) :

`int`	status: 0 = OK −1 = illegal `f` −2 = illegal `a`

NOTES :

1. This function is closely based on the `GCONV2H` subroutine by Toshio Fukushima (see reference).
2. The equatorial radius, `a`, can be in any units, but meters is the conventional choice.
3. The flattening, `f`, is (for the Earth) a value around 0.00335, *i.e.* around 1/298.
4. The equatorial radius, `a`, and the geocentric vector, `xyz`, must be given in the same units, and determine the units of the returned height, `height`.
5. If an error occurs (`status < 0`), `elong`, `phi` and `height` are unchanged.
6. The inverse transformation is performed in the function `iauGd2gce`.
7. The transformation for a standard ellipsoid (such as WGS84) can more conveniently be performed by calling `iauGc2gd`, which uses a numerical code (1 for WGS84) to identify the required `a` and `f` values.

REFERENCE :

Fukushima, T., *Transformation from Cartesian to geodetic coordinates accelerated by Halley's method*, J.Geodesy (2006) **79**, 689-693.

iauGd2gc *geodetic to geocentric, standard ellipsoid* iauGd2gc

CALL :

```
status = iauGd2gc ( n, elong, phi, height, xyz )
```

ACTION :

Transform geodetic coordinates to geocentric using the selected reference ellipsoid.

GIVEN :

n	`int`	ellipsoid identifier (Note 1)
elong	`double`	longitude (radians, east +ve, Note 3)
phi	`double`	latitude (geodetic, radians, Note 3)
height	`double`	height above ellipsoid (geodetic, Notes 2,3)

RETURNED :

xyz	`double[3]`	geocentric vector (Note 2)

RETURNED (function value) :

`int`	status: 0 = OK
	-1 = illegal identifier (Note 3)
	-2 = illegal case (Note 3)

NOTES :

1. The identifier `n` is a number that specifies the choice of reference ellipsoid. The following are supported:

N	*ellipsoid*
1	WGS84
2	GRS80
3	WGS72

   The number `n` has no significance outside the SOFA software.

2. The height (`height`, given) and the geocentric vector (`xyz`, returned) are in meters.

3. No validation is performed on the arguments `elong`, `phi` and `height`. An error status of -1 means that the identifier `n` is illegal. An error status of -2 protects against cases that would lead to arithmetic exceptions. In all error cases, `xyz` is set to zeros.

4. The inverse transformation is performed in the function `iauGc2gd`.

iauGd2gce *geodetic to geocentric, specified ellipsoid* iauGd2gce

CALL :

```
status = iauGd2gce ( a, f, elong, phi, height, xyz )
```

ACTION :

Transform geodetic coordinates to geocentric using a reference ellipsoid of specified form.

GIVEN :

a	`double`	equatorial radius (Notes 1,3,4)
f	`double`	flattening (Notes 2,4)
elong	`double`	longitude (radians, east +ve, Note 4)
phi	`double`	latitude (geodetic, radians, Note 4)
height	`double`	height above ellipsoid (geodetic, Notes 3,4)

RETURNED :

xyz	`double[3]`	geocentric vector (Note 3)

RETURNED (function value) :

	`int`	status: $0 =$ OK $-1 =$ illegal case (Note 4)

NOTES :

1. The equatorial radius, `a`, can be in any units, but meters is the conventional choice.
2. The flattening, `f`, is (for the Earth) a value around 0.00335, *i.e.* around 1/298.
3. The equatorial radius, `a`, and the geocentric vector, `xyz`, must be given in the same units, and determine the units of the returned height, `height`.
4. No validation is performed on individual arguments. The error status (-1) protects against (unrealistic) cases that would lead to arithmetic exceptions. If an error occurs, `xyz` is unchanged.
5. The inverse transformation is performed in the function `iauGc2gde`.
6. The transformation for a standard ellipsoid (such as WGS84) can more conveniently be performed by calling `iauGd2gc`, which uses a numerical code (1 for WGS84) to identify the required `a` and `f` values.

REFERENCES :

1. Green, R.M., 1985, *Spherical Astronomy*, Cambridge University Press, Section 4.5, p96.
2. Seidelmann, P.K. (Ed.), 1992, *Explanatory Supplement to the Astronomical Almanac*, University Science Books, Section 4.22, p202.

iauFk52h — *FK5 to Hipparcos* — iauFk52h

CALL :

```
iauFk52h ( r5, d5, dr5, dd5, px5, rv5, &rh, &dh, &drh, &ddh, &pxh, &rvh )
```

ACTION :

Transform FK5 (J2000.0) star data into the Hipparcos system.

GIVEN (all FK5, equinox J2000.0, epoch J2000.0) :

r5	`double`	RA (radians)
d5	`double`	Dec (radians)
dr5	`double`	proper motion in RA (radians/Jyear)
dd5	`double`	proper motion in Dec (radians/Jyear)
px5	`double`	parallax (arcsec)
rv5	`double`	radial velocity (km/s, +ve = moving away)

RETURNED (all Hipparcos, epoch J2000.0) :

rh	`double*`	RA (radians)
dh	`double*`	Dec (radians)
drh	`double*`	proper motion in RA (radians/Jyear)
ddh	`double*`	proper motion in Dec (radians/Jyear)
pxh	`double*`	parallax (arcsec)
rvh	`double*`	radial velocity (km/s, +ve = moving away)

NOTES :

1. This function transforms FK5 star positions and proper motions into the system of the Hipparcos catalog.

2. The proper motions in right ascension are $\Delta\alpha/\Delta t$ rather than $\Delta\alpha\cos\delta/\Delta t$, and are per year rather than per century.

3. The FK5 to Hipparcos transformation is modeled as a pure rotation and spin; zonal errors in the FK5 catalog are not taken into account.

4. See also `iauFK52H`, `iauFk5hz`, `iauHfk5z`.

REFERENCE :

F.Mignard & M.Froeschle, Astron.Astrophys., **354**, 732-739 (2000).

iauHfk5z — *Hipparcos to FK5, zero PM* — iauHfk5z

CALL :

```
iauHfk5z ( rh, dh, date1, date2, &rh5, &dh5, &dr5, &dd5 )
```

ACTION :

Transform a Hipparcos star position into FK5 (J2000.0), assuming zero Hipparcos proper motion.

GIVEN :

rh	`double`	Hipparcos RA (radians)
dh	`double`	Hipparcos Dec (radians)
date1	`double`	TDB as a 2-part...
date2	`double`	...Julian Date (Notes 1,2)

RETURNED :

r5	`double*`	FK5 RA (radians), equinox J2000.0, at date
d5	`double*`	FK5 Dec (radians), equinox J2000.0, at date
dr5	`double*`	FK5 RA proper motion (rad/year, Note 4)
dd5	`double*`	FK5 Dec proper motion (rad/year, Note 4)

NOTES :

1. The TDB date `date1+date2` is a Julian Date, apportioned in any convenient way between the two arguments. For example, JD(TDB) = 2450123.7 could be expressed in any of these ways, among others:

`date1`	`date2`	
2450123.7	0.0	(JD method)
2451545.0	−1421.3	(J2000 method)
2400000.5	50123.2	(MJD method)
2450123.5	0.2	(date & time method)

   The JD method is the most natural and convenient to use in cases where the loss of several decimal digits of resolution is acceptable. The J2000 method is best matched to the way the argument is handled internally and will deliver the optimum resolution. The MJD method and the date & time methods are both good compromises between resolution and convenience.

2. The proper motion in right ascension is $\Delta\alpha/\Delta t$ rather than $\Delta\alpha\cos\delta/\Delta t$.

3. The FK5 to Hipparcos transformation is modeled as a pure rotation and spin; zonal errors in the FK5 catalog are not taken into account.

4. It was the intention that Hipparcos should be a close approximation to an inertial frame, so that distant objects have zero proper motion; such objects have (in general) non-zero proper motion in FK5, and this function returns those fictitious proper motions.

5. The position returned by this function is in the FK5 J2000.0 reference system but at date `date1+date2`.

6. See also `iauFk52h`, `iauH2fk5`, `iauFk5hz`.

REFERENCE :

F.Mignard & M.Froeschle, Astron.Astrophys., **354**, 732-739 (2000).

iauIcrs2g — *ICRS to Galactic coordinates* — iauIcrs2g

CALL :

```
iauIcrs2g ( dr, dd, &dl, &db )
```

ACTION :

Transformation from ICRS to Galactic coordinates.

GIVEN :

dr	`double`	ICRS right ascension (radians)
dd	`double`	ICRS declination (radians)

RETURNED :

dl	`double*`	Galactic longitude (radians)
db	`double*`	Galactic latitude (radians)

NOTES :

1. The IAU 1958 system of Galactic coordinates was defined with respect to the now obsolete reference system FK4 B1950.0. When interpreting the system in a modern context, several factors have to be taken into account:

   - The inclusion in FK4 positions of the E-terms of aberration.
   - The distortion of the FK4 proper motion system by differential Galactic rotation.
   - The use of the B1950.0 equinox rather than the now-standard J2000.0.
   - The frame bias between ICRS and the J2000.0 mean place system.

   The Hipparcos Catalogue (Perryman & ESA 1997) provides a rotation matrix that transforms directly between ICRS and Galactic coordinates with the above factors taken into account. The matrix is derived from three angles, namely the ICRS coordinates of the Galactic pole and the longitude of the ascending node of the galactic equator on the ICRS equator. They are given in degrees to five decimal places and for canonical purposes are regarded as exact. In the Hipparcos Catalogue the matrix elements are given to 10 decimal places (about 20 μas). In the present SOFA function the matrix elements have been recomputed from the canonical three angles and are given to 30 decimal places.

2. The inverse transformation is performed by the function `iauG2icrs`.

REFERENCE :

Perryman M.A.C. & ESA, 1997, ESA SP-1200, *The Hipparcos and Tycho catalogues. Astrometric and photometric star catalogues derived from the ESA Hipparcos Space Astrometry Mission.* ESA Publications Division, Noordwijk, Netherlands.

iauMoon98 *Moon geocentric position+velocity* iauMoon98

CALL :

`iauMoon98 ( date1, date2, pv )`

ACTION :

Approximate geocentric position and velocity of the Moon.

GIVEN :

date1	`double`	TT as a 2-part...
date2	`double`	...Julian Date (Note 1)

RETURNED :

pv	`double[2][3]`	Moon position/velocity, GCRS (au, au/d, Note 5)

NOTES :

1. The TT date `date1+date2` is a Julian Date, apportioned in any convenient way between the two arguments. For example, JD(TT) = 2450123.7 could be expressed in any of these ways, among others:

`date1`	`date2`	
2450123.7	0.0	(JD method)
2451545.0	−1421.3	(J2000 method)
2400000.5	50123.2	(MJD method)
2450123.5	0.2	(date & time method)

   The JD method is the most natural and convenient to use in cases where the loss of several decimal digits of resolution is acceptable. The J2000 method is best matched to the way the argument is handled internally and will deliver the optimum resolution. The MJD method and the date & time methods are both good compromises between resolution and convenience. The limited accuracy of the present algorithm is such that any of the methods is satisfactory.

2. This function is a full implementation of the algorithm published by Meeus (see reference) except that the light-time correction to the Moon's mean longitude has been omitted.

3. Comparisons with ELP/MPP02 over the interval 1950-2100 gave RMS errors of 2.9 arcsec in geocentric direction, 6.1 km in position and 36 mm/s in velocity. The worst case errors were 18.3 arcsec in geocentric direction, 31.7 km in position and 172 mm/s in velocity.

4. The original algorithm is expressed in terms of "dynamical time", which can either be TDB or TT without any significant change in accuracy. UT cannot be used without incurring significant errors (30 arcsec in the present era) due to the Moon's 0.5 arcsec/sec movement.

5. The result is with respect to the GCRS (the same as J2000.0 mean equator and equinox to within 23 mas).
6. Velocity is obtained by a complete analytical differentiation of the Meeus model.
7. The Meeus algorithm generates position and velocity in mean ecliptic coordinates of date, which the present function then rotates into GCRS. Because the ecliptic system is precessing, there is a coupling between this spin (about $1^\circ\!.4$ per century) and the Moon position that produces a small velocity contribution. In the present function this effect is neglected as it corresponds to a maximum difference of less than 3 mm/s and increases the RMS error by only 0.4%.

REFERENCES :

Meeus, J., *Astronomical Algorithms*, 2nd edition, Willmann-Bell, 1998, p337.

Simon, J.L, Bretagnon, P., Chapront, J., Chapront-Touzé, M., Francou, G., and Laskar, J., 1994, Astron.Astrophys., **282**, 663.

iauPlan94 — *planet ephemerides, approximate* — iauPlan94

CALL :

```
status = iauPlan94 ( date1, date2, np, pv )
```

ACTION :

Approximate heliocentric position and velocity of a nominated planet: Mercury, Venus, EMB, Mars, Jupiter, Saturn, Uranus or Neptune (but not the Earth itself). *n.b.* Not IAU-endorsed and without canonical status.

GIVEN :

date1	`double`	TDB as a 2-part...
date2	`double`	...Julian Date (Note 1)
np	`i`	planet (1=Mercury, 2=Venus, 3=EMB ... 8=Neptune)

RETURNED :

pv	`double[2][3]`	planet position/velocity (heliocentric, J2000.0, au, au/d)

RETURNED (function value) :

`int`	status: −1 = illegal `NP` (outside 1-8)
	0 = OK
	+1 = warning: date outside 1000-3000 CE
	+2 = warning: failed to converge

NOTES :

1. The TDB date `date1+date2` is a Julian Date, apportioned in any convenient way between the two arguments. For example, JD(TDB) = 2450123.7 could be expressed in any of these ways, among others:

`date1`	`date2`	
2450123.7	0.0	(JD method)
2451545.0	−1421.3	(J2000 method)
2400000.5	50123.2	(MJD method)
2450123.5	0.2	(date & time method)

   The JD method is the most natural and convenient to use in cases where the loss of several decimal digits of resolution is acceptable. The J2000 method is best matched to the way the argument is handled internally and will deliver the optimum resolution. The MJD method and the date & time methods are both good compromises between resolution and convenience. The limited accuracy of the present algorithm is such that any of the methods is satisfactory.

2. If an `np` value outside the range 1-8 is supplied, an error status of −1 is returned and the `pv` vector set to zeroes.

3. For `np=3` the result is for the Earth-Moon barycenter. To obtain the heliocentric position and velocity of the Earth, use instead the SOFA function `iauEpv00`.

4. On successful return, the array `pv` contains the following:

`pv[0][0]`	x	
`pv[0][1]`	y	heliocentric position, au
`pv[0][2]`	z	
`pv[1][0]`	$\dot{x}$	
`pv[1][1]`	$\dot{y}$	heliocentric velocity, au/d
`pv[1][2]`	$\dot{z}$	

The reference frame is equatorial and is with respect to the mean equator and equinox of epoch J2000.0.

5. The algorithm is due to J. L. Simon, P. Bretagnon, J. Chapront, M. Chapront-Touzé, G. Francou and J. Laskar (Bureau des Longitudes, Paris, France). From comparisons with JPL ephemeris DE102, they quote the following maximum errors over the interval 1800-2050:

	λ	β	r
Mercury	4	1	300
Venus	5	1	800
EMB	6	1	1000
Mars	17	1	7700
Jupiter	71	5	76000
Saturn	81	13	267000
Uranus	86	7	712000
Neptune	11	1	253000
	arcsec	*arcsec*	*km*

Over the interval 1000-3000, they report that the accuracy is no worse than 1.5 times that over 1800-2050. Outside 1000-3000 the accuracy declines.

6. Comparisons of `iauPlan94` with the JPL DE200 ephemeris give the following RMS errors over the interval 1960-2025:

	position	*speed*
Mercury	334	0.437
Venus	1060	0.855
EMB	2010	0.815
Mars	7690	1.98
Jupiter	71700	7.70
Saturn	199000	19.4
Uranus	564000	16.4
Neptune	158000	14.4
	km	ms^{-1}

Comparisons against DE200 over the interval 1800-2100 gave the following maximum absolute differences (the results using DE406 were essentially the same):

	λ	β	r	$\dot{r}$
Mercury	7	1	500	0.7
Venus	7	1	1100	0.9
EMB	9	1	1300	1.0
Mars	26	1	9000	2.5
Jupiter	78	6	82000	8.2
Saturn	87	14	263000	24.6
Uranus	86	7	661000	27.4
Neptune	11	2	248000	21.4
	arcsec	*arcsec*	*km*	ms^{-1}

7. The returned status indicates the most serious condition encountered during execution of the routine. Illegal `np` is considered the most serious, overriding failure to converge, which in turn takes precedence over the remote epoch warning.

REFERENCE :

Simon, J.L, Bretagnon, P., Chapront, J., Chapront-Touzé, M., Francou, G., and Laskar, J., 1994, Astron.Astrophys., **282**, 663.