Reading STEREO ephemerides as SPICE kernels

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1 Introduction

The STEREO orbit and attitude data will be distributed as SPICE kernel files. SPICE (**S**pacecraft, **P**lanet, **I**nstrument, **C**-matrix (pointing), and **E**vents) is a software package developed by the Jet Propulsion Laboratory's Navigation and Ancillary Information Facility (NAIF), and is used by many missions which navigate through the solar system.

SPICE data files are known as "kernels", and come in a wide variety. Mission specific kernels provide information about the orbital position and orientation of the spacecraft as a function of time. On top of these are more generic kernels, such as a general solar system ephemeris, planetary constants, and so on. The SPICE system puts these various elements together into a common integrated system.

SPICE is available as both FORTRAN and C libraries. The CSPICE library can also be used from IDL as a Dynamically Loadable Module (DLM), and software has bee placed in the Solar Software Library (SolarSoft, or SSW) to take advantage of that fact. This document describes the implementation of SPICE within SolarSoft for the STEREO mission.

We anticipate that SPICE will be used by the STEREO instrument teams in planning their observations, and in processing their telemetry. However, the resulting scientific data files should have sufficient position and orientation information in them that one shouldn't need SPICE for data analysis.

2 Installing SPICE

The IDL software developed for STEREO, and the necessary SPICE kernels, are distributed as part of SolarSoft. Information about SolarSoft, including how to install it, can be found at

> `http://stereo-ssc.nascom.nasa.gov/software.shtml`

We've also now worked out the legal details to distribute the part of SPICE which supports IDL as part of SolarSoft. Compiled versions are available for Windows, Mac OSX, Linux, and Solaris.

One can also download the complete SPICE package, including the source code, directly from the NAIF website at

> `http://naif.jpl.nasa.gov/naif/`

Follow the "Toolkit" link to download the software based on the software environment (e.g. IDL) and the operating system (e.g. Linux). The files can be unpacked into a suitable location, for example `/usr/local/icy`. No compilation should be needed, but the file `makeall.csh` can be

used to recompile the software if necessary. Other SPICE resources are also available from the above website.

The IDL-CSPICE (also known as "Icy") tar package will include the following directories:

`data`	Sample data files used with the "cookbook" routines
`doc`	Documentation, in both plain-text and HTML formats
`exe`	Executable utility files
`lib`	Object libraries and `idl.dlm`
`src`	Source code, and some sample IDL "cookbook" procedures

plus several others. SPICE consists of two parts: the library itself in the `lib` directory, and a collection of stand-alone utilities in the `exe` directory. The latter are mainly used for managing the contents of kernel files. For example, the `toxfer` program converts binary kernel files into an ASCII transfer format, while `tobin` does the reverse.

In order to use the SPICE library in IDL, the DLM needs to be registered. This should now be automatic, but one can also control which DLM is used by defining the environment variable `SPICE_ICY_DLM`, e.g.

```
setenv SPICE_ICY_DLM /usr/local/icy/lib/icy.dlm
```

Normally, though, one shouldn't have to do this.

SPICE toolkit version N0058 introduced parameterized dynamic frames, which are used to implement some of the heliospheric coordinate system used by STEREO. Users with earlier versions of the SPICE toolkit should upgrade to N0058 or later. As of this writing, the version delivered as part of SolarSoft is N0060.

3   SolarSoft routines

The SPICE software for the STEREO project are found within the `stereo/gen/idl/spice` sub-directory of the SolarSoft distribution. The principal routines are listed below:

GET_STEREO_COORD: Returns the x, y, z (and v_x, v_y, v_z) coordinates of one of the two STEREO spacecraft in one of the supported coordinate systems described in section 4. The default coordinate system is Heliocentric Inertial (HCI). This routine can also be used to return the position of a solar system body, such as the Sun, Earth, or Moon.

CONVERT_STEREO_COORD: Converts x, y, z positions (and v_x, v_y, v_z) between coordinate systems.

GET_STEREO_LONLAT: Calls `GET_STEREO_COORD`, and converts the x, y, z positions into angular longitude and latitude, plus radial distance.

CONVERT_STEREO_LONLAT: Converts longitude and latitude (and optionally radial distance) between coordinate systems.

GET_STEREO_SEP_ANGLE: Returns the three-dimensional heliocentric separation angle between two bodies. (Note that this can be slightly different than the angular extent along the ecliptic plane.)

GET_STEREO_CARR_ROT: Returns the decimal Carrington rotation number associated with disk center as seen from one of the two STEREO spacecraft, or from Earth.

STEREO_COORD_INFO: Calls the other routines discussed above, and prints out a simple summary of the positions of the two spacecraft. Sample output is shown in Figure 1.

GET_STEREO_CMAT: Returns the 3×3 (or 6×6) transformation matrix to convert between instrument and standard coordinate frames. The default coordinate system is Radial-Tangential-Normal (RTN).

GET_STEREO_HPC_POINT: Returns the spacecraft pointing in helioprojective-cartesian coordinates (θ_x, θ_y) as described in Thompson (2006), as well as the roll angle (ψ) as used in FITS files.

LOAD_STEREO_SPICE: Loads all the various SPICE kernels needed to derive orbit and attitude information. Normally, the user shouldn't need to call this routine directly, as the other routines will call this routine automatically. However, there are some optional parameters that can be used to call up kernel files from the preflight mission simulations, and sample ephemerides for different launch dates.

SPICE_KERNEL_REPORT: Reports which SPICE kernels are currently loaded.

GET_STEREO_SPICE_RANGE: Reports the time range covered by a STEREO ephemeris or attitude history file.

GET_STEREO_SPICE_KERNEL: Reports which currently loaded kernel contains the ephemeris or attitude history information for a given date and spacecraft.

Detailed information can be found in the documentation headers within each IDL procedure.

Some comments should be made about the input parameters to these routines. Date and time values are expressed as Coordinated Universal Time (UTC), and are processed through the SolarSoft routine `ANYTIM2UTC` to be put into the right format for SPICE. A separate software document ("CDS Time Conversion Software") describes the time handling software available within Solarsoft.

The STEREO SPICE routines also allow some latitude in the way that the spacecraft can be identified, as shown in Table 1. Most routines also allow the name of a solar system body, such as "Sun", "Earth", or "Moon". Strings are case-insensitive, including those in Table 1.

4   Coordinate systems

The coordinate systems used by the STEREO project are based on Russell (1971), Hapgood (1992), and Fränz and Harper (2002), with special emphasis on the last. The various coordinate systems are summarized below. Two axes are chosen to define each coordinate system, and the missing axis satisfies the right-hand rule.

```
                        STEREO-B          Earth         STEREO-A

Heliocentric distance (AU)   1.048914       0.983286        0.918217
Semidiameter (arcsec)         914.877        975.939        1045.099

HCI longitude                  15.477         24.143          34.435
HCI latitude                   -1.806         -2.980          -4.134

Carrington longitude           90.049         98.714         109.006
Carrington rotation number   2051.750       2051.726        2051.697

Heliographic (HEEQ) longitude  -8.666          0.000          10.292
Heliographic (HEEQ) latitude   -1.806         -2.980          -4.134

Earth Ecliptic (HEE) longitude -8.736         -0.000          10.336
Earth Ecliptic (HEE) latitude   0.139         -0.000          -0.017

Separation angle with Earth            8.737          10.336
Separation angle A with B             19.073
```

Figure 1: Sample output from STEREO_COORD_INFO.

Table 1: Spacecraft identifiers recognized by the SolarSoft routines.

A	B
STA	STB
Ahead	Behind
STEREO Ahead	STEREO Behind
STEREO-Ahead	STEREO-Behind
-234	-235

GEI: Geocentric Equatorial Inertial. The X axis points toward the first point of Aries (i.e. the vernal equinox), and the Z axis is aligned with the geographic north pole. When expressed in terms of longitude and latitude, this is the well known celestial coordinate system of right ascension and declination. This is realized with the J2000 ecliptic.

GEO: Geographic. X is the intersection of the Greenwich meridian and the geographic equator, and Z is the geographic North Pole. This is usually expressed as geographic longitude and latitude. (However, see Appendix C for a discussion of the distinction between planetographic and planetocentric coordinates.)

GSE: Geocentric Solar Ecliptic. X is the Earth-Sun line, and Z is aligned with the north pole for the ecliptic of date.

MAG: Geomagnetic. Z is Earth's north dipole axis, and Y is the intersection between the geographic equator, and the geographic meridan 90° east of the meridian containing the dipole axis. In other words, the geomagnetic meridian containing X also passes through the south geographic pole. The dipole axis is defined as the centered dipole approximation to the International Geomagnetic Reference Frame (IGRF) model, as described in Fränz and Harper (2002).

GSM: Geocentric Solar Magnetospheric. X is the Earth-Sun line, and Z is the projection of the north dipole axis.

SM: Solar Magnetic. Z is Earth's north dipole axis, and X is the projection of the Earth-Sun line. Although not evident in the name, this is a geocentric coordinate system. Users should be aware that the acronym SM has sometimes in the past been used for what is now referred to as GSM.

HCI: Heliocentric Inertial. Z is the solar north rotational axis, and X is the solar ascending node on the J2000 ecliptic.

HAE: Heliocentric Aries Ecliptic. X is in the direction of the first point of Aries, and Z is the ecliptic North Pole. This can be realized with either the J2000 ecliptic (default), or the ecliptic of date.

HEE: Heliocentric Earth Ecliptic. X is the Sun-Earth line, and Z is the north pole for the ecliptic of date.

HEEQ: Heliocentric Earth Equatorial. Z is the solar rotation axis, and X is in the plane containing the Z axis and Earth, at the intersection of the solar central meridian, and the heliographic equator. When converted to longitude and latitude, this is known as Stonyhurst heliographic coordinates. In FITS files, this coordinate system is abbreviated as "HEQ", so that variation is also recognized by the software.

Carrington heliographic. Z is the solar rotational axis. The X axis is at the intersection of the Carrington prime meridian and the heliographic equator. The coordinate system rotates with a sidereal period of 25.38 days. This coordinate system is usually expressed in terms of longitude and latitude.

HGRTN/RTN: Radial-Tangential-Normal. X axis points from Sun center to the spacecraft, and the Y axis is the cross product of the solar rotational axis and X, and lies in the solar equatorial plane (towards the West limb). For the STEREO Ahead spacecraft, this is realized

through the dynamic coordinate frame `STAHGRTN`, while for STEREO Behind it is realized through `STBHGRTN`. When the Sun is used as the origin, the designation is HGRTN—with the spacecraft as origin, it's simply RTN. RTN coordinates are closely related to helioprojective-cartesian coordinates (Thompson, 2006)).

SCI: STEREO Science Pointing. X axis points at center of the Sun, while the $+Z$ axis points away from Earth such that the X-Z plane contains the observatory, Sun, and Earth. The origin is at the observatory center of mass. Defines the nominal pointing reference frame used by the flight operations team during science operations.

References

Fränz, M. and Harper, D. (2002). Heliospheric coordinate systems. *Planetary and Space Science*, **50**, 217–239.

Hapgood, M. A. (1992). Space physics coordinate transformation: A user guide. *Planetary and Space Science*, **40**, 711–717.

Russell, C. T. (1971). Geophysical coordinate transformations. *Cosmic Electrodynamics*, **2**, 184–196.

Thompson, W. T. (2006). Coordinate systems for solar image data. *Astron. Astrophys.*, **449**, 791–803.

Appendices

A SPICE internals

In this section, we discuss some of the internal workings of the SPICE system as it applies to STEREO. Although oriented towards IDL, the discussion is also applicable to the FORTRAN and C libraries with little modification.

A.1 SPICE kernels

The term "kernels" is used to denote data files used by the SPICE system. An early sample STEREO orbit kernel is `stereo_20060211a_nominal.xsp` with a creation date of February 6, 2004. This is an example of what is called an SPK, or Spacecraft and Planet Kernel. The file extension `.xsp` means that it's in a platform-independent ASCII transfer format. This needs to be converted into a binary file before it can be used. The `tobin` utility in the `exe` directory will convert the ASCII file into a binary file with the extension `.bsp`. These binary files are platform-specific, but modern versions of SPICE can read binary files from other platforms, with the exception of OpenVMS.

The `brief` program can be used to get a brief summary of the contents of a binary SPK file. The results for the sample STEREO ephemeris file are shown in Figure 2. This tells us that the file contains ephemerides for two bodies, named "STEREO AHEAD" and "STEREO BEHIND", with ID numbers -234 and -235 respectively. (Spacecraft ID numbers are always negative in SPICE, while planets and other solar system bodies have positive ID numbers.) Also, we have the date and time ranges that the file is valid for. (SPICE uses ephemeris time (ET) which has a small offset from TAI or UTC—this will be discussed in more detail later.) The `spacit` utility can be used to display more detailed information about the file.

Although the file `stereo_20060211a_nominal.bsp` contains all the ephemeris data needed for the two STEREO spacecraft, it cannot be used by itself; it needs to be put into its context within the solar system. Specifically, the positions of the two STEREO are defined relative to Earth early in the mission, and relative to the Sun later in the mission, while SPICE internally needs to relate all of these to the solar system barycenter. Thus, a solar system ephemeris needs to be loaded.

```
> /usr/local/icy/exe/brief stereo_20060211a_nominal.bsp
Brief.  Version: 2.2.0         (SPICE Toolkit N0057)


Summary for: stereo_20060211a_nominal.bsp

Bodies: STEREO AHEAD (-234)   STEREO BEHIND (-235)
        Start of Interval (ET)            End of Interval (ET)
        ------------------------------    ------------------------------
        2006 FEB 11 09:29:17.165          2013 JAN 01 00:01:04.183
```

Figure 2: Synopsis of the contents of the sample STEREO ephemeris file.

There are several generic solar system kernels available, but the correct one to use is `de405.bsp`, because that was the kernel that was used to generate the STEREO ephemeris.

Another data file required by SPICE is a Leapseconds Kernel (LSK), to support various time conversions, e.g. `naif0007.tls`.

A Planetary Constants Kernel (PCK) allows coordinates to be expressed in longitude and latitude, e.g. `pck00007.tpc`. Using this file allows one to extract either geographic or heliographic (i.e. Carrington) coordinates.

All of the generic kernels discussed above can be downloaded from the NAIF website. Also, the STEREO Science Center will organize and make available all SPICE kernels needed to process the orbit and attitude data, including the STEREO-specific and relevant NAIF generic kernels.

A.2 Basic software calls

A.2.1 Loading SPICE kernels

SPICE kernels are loaded with calls to `CSPICE_FURNSH`, one for each kernel file. For example, to load the STEREO ephemeris, together with the generic planet ephemeris and leapseconds, one would type

```
cspice_furnsh, 'naif0007.tls'
cspice_furnsh, 'de405.bsp'
cspice_furnsh, 'stereo_20060211a_nominal.bsp'
```

Assuming that each of these files are in the current directory. Similarly, calls to `CSPICE_UNLOAD` can be used to unload kernels once they are no longer needed.

A.2.2 Time

Internally, SPICE uses Ephemeris Time (ET), also known as Barycentric Dynamical Time (TDB). This time varies from TAI time by 32.184 seconds plus a small annual variation on the order of a few milliseconds. In SPICE, ET is expressed as the number of dynamical seconds since 1-Jan-2000 12:00 ET.

The routine `CSPICE_STR2ET` converts a wide variety of time string formats into double precision ET values. A simple way to convert time values into ET format is to first use the SolarSoft routine `ANYTIM2UTC` with the `/CCSDS` keyword to convert date/time values into ISO 8601 format, which SPICE is able to ingest, e.g.

```
utc = anytim2utc(date_time, /ccsds)
cspice_str2et, utc, et
```

(The `CCSDS` keyword refers to the Consultative Committee for Space Data Systems, which endorsed a specific subset of the wider ISO-8601 standard.)

Similarly, the routine `CSPICE_ET2UTC` can be used to convert from ephemeris time into a UTC character string. For example, the call

Table 2: NAIF ID names and numbers for various solar system objects, and the two STEREO spacecraft. Character string names are case-insensitive.

MERCURY BARYCENTER	1	SATURN BARYCENTER	6	MERCURY	199
VENUS BARYCENTER	2	URANUS BARYCENTER	7	VENUS	299
EARTH BARYCENTER	3	NEPTUNE BARYCENTER	8	MOON	301
MARS BARYCENTER	4	PLUTO BARYCENTER	9	EARTH	399
JUPITER BARYCENTER	5	SUN	10	MARS	499
STEREO AHEAD	-234	SOLAR SYSTEM BARYCENTER (or SSB)			0
STEREO BEHIND	-235	EARTH MOON BARYCENTER (or EMB)			3

```
cspice_et2utc, et, 'ISOC', 3, utcstr
```

would return a string such as "2000-01-01T12:00:00.000", which is easily ingested into SolarSoft. The "ISOC" tells the software to use ISO 8601 calendar format, and the "3" tells the software to return seconds to three significant figures past the decimal point.

The above SPICE calls allow the input times to be either scalars or one-dimensional arrays.

SPICE has a separate mechanism for keeping track of spacecraft clock values, which will be discussed in Section A.5.1.

A.2.3   Spacecraft and planet identifiers

Spacecraft and planets are identified within SPICE in one of two ways: either by a character string name, or by an ID number. Table 2 shows the ID numbers for various solar system objects, and the two STEREO spacecraft. By convention, spacecraft IDs are always negative.

Internally, SPICE uses ID numbers to track spacecraft and solar system objects, and lower level routines take the ID numbers as input parameters. Higher level routines, however, use character string names, such as "Earth" or "Sun". A few high level routines can take either the name or the ID number, provided that the ID number is formatted as a character string.

A.2.4   Reference frames

SPICE incorporates two basic kinds of reference frames: inertial and body-fixed frames. Examples of inertial frames include:

J2000: Celestial reference frame, with Z aligned with Earth's rotational axis, and X aligned with the direction of the vernal equinox, at the dynamical epoch of J2000.

ECLIPJ2000: Ecliptic coordinates based upon the J2000 frame.

among others. Note that these inertial frames are based on the Earth's rotational axis and ecliptic for a specific date, and do not take precession into account. This is discussed in more detail in Appendix B.

Body-fixed frames include geographic and Carrington heliographic, as well as spacecraft and instrument-based frames. The reference frames for geographic and Carrington heliographic coordinates are IAU_EARTH and IAU_SUN respectively.

Versions N0058 and later of the SPICE toolkit also allows one to define additional non-inertial reference frames based on certain kinds of parameters. This facility is used to realize certain standard heliospheric coordinate systems, discussed below.

The routine `CSPICE_SPKEZR` provides a simple interface to extract coordinate frame data of objects. The calling sequence is

```
CSPICE_SPKEZR, TARGET, ET, REF, ABCORR, OBS, STATE, LTIME
```

where the input parameters are

TARGET: Target body name.

ET: Ephemeris time(s) of the observation.

REF: Reference frame, e.g. 'ECLIPJ2000' or 'IAU_SUN'.

ABCORR: Aberration correction. Possible values include:
      'NONE'   No aberration correction
      'LT'   Correct for one-way light travel time
      'LT+S'   Correct for one-way light travel time, and stellar aberration
One can also use 'XLT' and 'XLT+S' in the transmission case, where ET then refers to the time of transmission, and ET+LTIME is the observation time.

OBS: The name of the observing body; i.e. the origin of the coordinate system.

and the output parameters are

STATE: The six-element state vector of the target. The first three parameters are the position in kilometers, and the last three are the velocity in km/sec. (Note that velocities expressed in rotating coordinate frames have different magnitudes than velocities expressed in inertial coordinate frames.)

LTIME: The one-way light travel time from the target to the observer.

The target and observer parameters can be either their character string names, or their ID numbers formatted as a character string. For example, the call

```
cspice_spkezr, '-234', et, 'J2000', 'LT+S', 'Earth', state, ltime
```

returns the state vector of the STEREO Ahead spacecraft as seen from Earth in the J2000 celestial coordinate system. The complete process from loading to unloading the kernels is presented in Figure 3.

```
pro stereo_a_demo, date, state, ltime
;
cspice_furnsh, 'naif0007.tls'
cspice_furnsh, 'de405.bsp'
cspice_furnsh, 'pck00007.tpc'
cspice_furnsh, 'stereo_20060211a_nominal.bsp'
;
utc = anytim2utc(date,/ccsds)
cspice_str2et, utc, et
;
cspice_spkezr, 'STEREO AHEAD', et, 'IAU_SUN', 'None', 'Sun', state, ltime
;
cspice_unload, 'stereo_20060211a_nominal.bsp'
cspice_unload, 'pck00007.tpc'
cspice_unload, 'de405.bsp'
cspice_unload, 'naif0007.tls'
;
end
```

Figure 3: Sample IDL program for deriving the position and velocity of the STEREO A spacecraft in Carrington heliographic coordinates at a given date.

A.3   Coordinate systems

It is possible to use the SPICE software to derive coorinates in a number of standard coordinate systems, described in Section 4. Table 3 gives the values for the REF and OBS parameters in the CSPICE_SPKEZR call.

Some coordinate systems require that an appropriate parameterized dynamic frame be loaded. These dynamic frames are defined in the files heliospheric.tf, and in stereo_rtn.tf.

A.3.1   Longitude and latitude

Any of the above coordinate systems can be converted into longitude and latitude, and vice-versa, by using the CSPICE calls

```
cspice_reclat, vector, radius, lon, lat
cspice_latrec, radius, lon, lat, vector
```

Where VECTOR is a three-element array, e.g. either the position or velocity portion of the STATE vector. These are equivalent to the IDL calls

```
radius = sqrt(total(vector^2))
lon = atan(vector[1], vector[0])
lat = atan(vector[2], sqrt(total(vector[0:1]^2)))
```

and

Table 3: `REF` and `OBS` values to be used in `CSPICE_SPKEZR` to realize various standard coordinate systems. Coordinate systems marked with the "J2000" subscript are referenced to the ecliptic plane at the J2000 epoch; those marked with the "D" subscript are referenced to the ecliptic of date. An asterisk (*) means that a dynamic frame needs to be loaded.

System			REF	OBS
GEI	J2000		J2000	Earth
GEO			IAU_EARTH	Earth
GSE	D	*	GSE	Earth
HCI	J2000	*	HCI	Sun
HAE	J2000		ECLIPJ2000	Sun
HAE	D	*	ECLIPDATE	Sun
HEE	D	*	HEE	Sun
HEEQ		*	HEEQ	Sun
Carrington			IAU_SUN	Sun
STEREO-A RTN		*	STAHGRTN	Sun (or STEREO Ahead)
STEREO-B RTN		*	STBHGRTN	Sun (or STEREO Behind)
STEREO-A SCI		*	STASCPNT	STEREO Ahead
STEREO-B SCI		*	STBSCPNT	STEREO Behind

```
vector = [radius * cos(lat)*cos(lon), $
          radius * cos(lat)*sin(lon), $
          radius * sin(lat)]
```

respectively. An advantage of using the SPICE calls is that the parameters can be vectorized: `VECTOR` can be a $3 \times N$ array, and `RADIUS`, `LON`, and `LAT` can each be arrays of N elements.

SPICE, like IDL, expresses angles in radians. Therefore, a conversion is needed if degrees or arc seconds are desired. The SPICE calls `CSPICE_DPR()` and `CSPICE_RPD()` return the double-precision values $180/\pi$ and $\pi/180$ respectively. For example, to convert the output of `CSPICE_RECLAT` from radians to degrees, one could use the commands

```
lon = lon * cspice_dpr()
lat = lat * cspice_dpr()
```

A.4 Coordinate conversions

Because all coordinate systems are implemented as frames, either internal or dynamic, the process to convert from one coordinate system to another is the same for all. There are two basic routines used for converting between coordinate frames, `CSPICE_SXFORM` and `CSPICE_PXFORM`. The only difference between them is that `CSPICE_SXFORM` works on 6-element state vectors containing both position and velocity, which `CSPICE_PXFORM` works only on 3-element position vectors. The parameters are:

FROM: Name of the reference frame one is converting from.

TO: Name of the reference frame one is converting to.

ET: Ephemeris time(s) of the observation.

XFORM: Output transformation matrix. If ET is an array, then this will be either a $6 \times 6 \times N$ array, or a $3 \times 3 \times N$ array, depending on whether one is calling `CSPICE_SXFORM` or `CSPICE_PXFORM`.

For the `FROM` and `TO` parameters, use the `REF` field from Table 3 for the coordinate systems in question.

The following example demonstrates the conversion from GEI to HEEQ coordinates, which involves both rotation of the coordinate axes, and a shift of the shift of the origin. Note that both internal and dynamic reference frames are involved.

```
cspice_spkezr, 'STEREO AHEAD', et, 'J2000', 'None', 'Earth', gei, ltime
cspice_spkezr, 'Sun', et, 'J2000', 'None', 'Earth', gei_sun, ltime_earth
cspice_sxform, 'J2000', 'HEEQ', et, xform
heeq = transpose(xform) # (gei - gei_sun)
```

A.5   Pointing

STEREO's Attitude History files will also be stored as SPICE data, in the form of C-Kernels. In this section, we will discuss how to read and interpret STEREO C-Kernels. We will use the sample file `ahead_2006_070_00.ah.xc` created during Mission Simulation #1. The file extension `.xc` means that it's in a platform-independent ASCII transfer format. As in Section A.1, the `tobin` utility can be used to convert it into a binary file with the extension `.bc`. These binary files are platform-specific, but modern versions of SPICE can read binary files from other platforms, with the exception of OpenVMS.

A.5.1   Spacecraft clocks

SPICE pointing files are somewhat different from ephemeris files, in that the data are organized by spacecraft clock time, instead of the ephemeris time used for the spacecraft and planetary positions. The relationship between the spacecraft clock and other kinds of time is given by a spacecraft clock (SCLK) text kernel. For the STEREO project, these are static kernels, and have names like `ahead_science_03.sclk` and `behind_science_03.sclk`.

Spacecraft times can be given as strings, e.g. "1/100007:76:1", which are directly related to the way that the spacecraft reports time values, or encoded into a double precision number representing the number of "ticks" since spacecraft clock start. A "tick" is defined to be the shortest time interval that a spacecraft clock is capable of—for the STEREO project, this is $1/256^{th}$ of a second. It is this latter double precision format which is used by the C-Kernel files.

Thus, in order to use C-Kernel files, one must be able to convert between ephemeris time and spacecraft clock values. This is done through the routines `CSPICE_SCE2C` and `CSPICE_SCT2E`. For example, to convert an ephemeris time to an onboard clock value for the STEREO Ahead spacecraft, use

```
CSPICE_SCE2C, -234, ET, SCLKDP
```

The conversion between ephemeris time and UTC was discussed in Section A.2.2.

A.5.2 Deriving the C-matrix

The routine `CSPICE_CKGP` ("CK get pointing") is used to get pointing information from C-Kernel files. The calling sequence is

```
CSPICE_CKGP, INST, SCLKDP, TOL, REF, CMAT, CLKOUT, FOUND
```

where the input parameters are

INST: The instrument code. For STEREO, the code is -234000 for the Ahead spacecraft, and -235000 for the Behind spacecraft, i.e. 1000 times the spacecraft ID numbers.

SCLKDP: The double precision spacecraft clock time.

TOL: The tolerance on SCLKDP, in "ticks".

REF: Reference frame, e.g. 'ECLIPJ2000' or 'IAU_SUN'.

and the output parameters are

CMAT: The transformation matrix from the base reference frame to the instrument-fixed frame.

CLKOUT: The clock time associated with CMAT.

FOUND: Either 0 or 1.

(The routine `CSPICE_CKGPAV` also returns the angular velocity 3-vector. See the SPICE documentation for more information.)

The following example shows the use of `CSPICE_CKGP` with the sample attitude history file from Mission Simulation #1.

```
IDL> cspice_str2et, '2006-03-11T12:00:00', et
IDL> cspice_sce2c, -234, et, sclkdp
IDL> cspice_ckgp, -234000, sclkdp, 128, 'GSE', cmat, clkout, found
IDL> print,cmat
      0.99999999    0.00010445802   -7.6697726e-05
   -1.9779502e-05      0.70793446       0.70627814
    0.00012807338     -0.70627813       0.70793445
```

The rows of CMAT are the respective coordinates of the spacecraft X, Y, and Z axes in the GSE coordinate frames. Without doing any further calculation, one can see that the main spacecraft axis X is almost completely aligned with the Sun-Earth line (the [0,0] element is close to 1), while the Y and Z axes are rolled by close to 45° (the 2×2 lower-right elements are all close to $\pm\sqrt{1/2}$). The matrix can be converted into roll, pitch, and yaw angles with the call

```
cspice_m2eul, cmat, 1, 3, 2, roll, pitch, yaw
```

Here, roll is defined as a right-handed rotation about the $+X$ axis, with pitch and yaw defined around the $+Z$ and $+Y$ axes respectively. For the C-Matrix shown above, the roll is $44°93$, the pitch is 21.55 arcsec, and the yaw is 15.82 arcsec.

If VEC_GSE contains the (x, y, z) positions of a point in the GSE reference frame, then the coordinate transformation

```
vec_sta = transpose(cmat) # vec_gse
```

will rotate this coordinate into the spacecraft reference frame. (A change in origin may also be required.) The inverse transformation, from spacecraft reference frame to the GSE reference frame, is given by

```
vec_gse = cmat # vec_sta
```

There are two alternate forms for the above equations, namely

```
cspice_mxv, cmat, vec_gse, vec_sta
cspice_mtxv, cmat, vec_sta, vec_gse
```

and

```
vec_sta = cmat ## vec_gse
vec_gse = transpose(cmat) ## vec_sta
```

respectively. The "`##`" forms differ in that they return column vectors (dimensions 1×3) instead of simple row vectors. The SPICE routines require row vectors, so the "`##`" notation may not be desirable.

B   Precession

Internally, SPICE works within the J2000 inertial reference frame. However, Earth's rotational axis slowly precesses around the pole of the ecliptic at a rate of about $50''$ per year, with a period of about 26,000 years. Also, the plane of the ecliptic itself precesses at a rate of about $47''$ per century. There may be situations where these effects need to be taken into account.

Fränz and Harper (2002), discuss the effects of precession on the standard heliospheric coordinate systems, and distinguish between three different versions of the Geocentric Equatorial Inertial system:

GEI_{J2000} Earth mean equator at J2000.
GEI_D Earth mean equator of date, i.e. corrected for precession.
GEI_T Earth true equator of date, i.e. corrected for precession and nutation.

SPICE returns GEI_{J2000}. On the other hand, geographic coordinates (GEO) are defined relative to the true equator of date, which is how they are implemented in SPICE.

Similarly, Fränz and Harper distinguish between two versions of Heliocentric Aries Ecliptic:

HAE$_{\text{J2000}}$	Earth mean ecliptic at J2000.
HAE$_{\text{D}}$	Earth mean ecliptic of date.

Again, SPICE natively returns HAE$_{\text{J2000}}$. However, the other ecliptic systems, GSE and HEE, are explicitly defined by Fränz and Harper in terms of the mean ecliptic of date, while SPICE wants to work within the J2000 reference frame. The use of parameterized dynamic frames, introduced in SPICE toolkit version N0058, gets around this problem. Table 3 lists which coordinate systems are based on the J2000 ecliptic, and which use the ecliptic of date.

Precession is not a concern for HEEQ, RTN, or Carrington heliographic coordinates.

C Planetographic versus planetocentric coordinates

In cartography, a distinction is made between planetocentric and planetographic coordinates. Planetocentric latitude is the angle between the equatorial plane and a line drawn from the center of mass to the reference point. Planetographic latitude, however, is defined in terms of a line which is normal to a spheroidal reference surface for the body in question. For spherical bodies, such as the Sun, there is no distinction between these two kinds of latitudes, but there is a difference for an oblate spheroid such as Earth. For the STEREO spacecraft, the distinction between geocentric and geographic latitude varies between about $\pm 0°.15$. The coordinates returned by the `CSPICE_SPKEZR` call in Section A.3 are in the planetocentric system.

There's also a distinction between planetocentric and planetographic longitude when the body's rotation is retrograde, but this does not apply to either Earth or the Sun.

Fränz and Harper (2002) explicitly define the GEO coordinate system as a planetographic system. However, Russell (1971) and Hapgood (1992) describe the GEO system in terms of X, Y, Z coordinates, where the distinction between planetocentric and planetographic does not apply. One should therefore be careful when comparing geographic longitudes and latitudes to X, Y, Z systems.

Although SPICE returns planetocentric coordinates, the routines `CSPICE_BODVAR` and `CSPICE_RECGEO` can be used to derive planetographic longitude and latitude (in degrees), as well as the altitude above the surface, e.g.

```
cspice_spkezr, 'STEREO Ahead', et, 'IAU_EARTH', abcorr, 'Earth', state, ltime
cspice_bodvar, 399, 'RADII', radii
flat = (radii[0]-radii[2]) / radii[0]
cspice_recgeo, state[0:2], radii[0], flat, lon, lat, alt
lon = lon * cspice_dpr()
lat = lat * cspice_dpr()
```

Note that `CSPICE_BODVAR` requires the body ID number, and that 'RADII' must be uppercase.

The inverse routine is `CSPICE_GEOREC`, e.g.

```
lon_r = lon * cspice_rpd()
lat_r = lat * cspice_rpd()
cspice_georec, lon_r, lat_r, alt, radii[0], flat, vector
```

where `LON_R` and `LAT_R` are the longitude and latitude converted back into radians, and `VECTOR` is the output position vector.

The parameters can be vectorized, with `VECTOR` being a $3 \times N$ array, and `LON`, `LAT`, and `ALT` each being arrays of N elements.

D   Using `CSPICE_SUBPT`

An alternative way to derive heliographic coordinates is to use `CSPICE_SUBPT`, which returns the sub-observer point on a spheroidal body. The advantage of using it over `CSPICE_SPKEZR` is that `CSPICE_SUBPT` treats the STEREO spacecraft as an observer rather than as a target, which influences how aberration corrections are handled. The calling sequence is

```
CSPICE_SUBPT, METHOD, TARGET, ET, ABCORR, OBS, SPOINT, ALT
```

where the input parameters are

> **METHOD:** Calculation method. Possible values are:
> > 'NEAR POINT'   Nearest point on surface to observer
> > 'INTERCEPT'   Intercept point along line from target center
>
> > For a spherical object like the Sun, the two methods return the same result. The 'INTERCEPT' method is less computationally intensive.
>
> **TARGET:** Target body name, e.g. 'Sun'.
>
> **ET:** Ephemeris time of the observation (scalar).
>
> **ABCORR:** Aberration correction. (See Section A.2.4.)
>
> **OBS:** The name of the observing body, e.g. 'STEREO AHEAD'.

and the output parameters are

> **SPOINT:** Planetocentric coordinates of the sub-observer point on the target surface.
>
> **ALT:** The altitude, calculated as the distance from the sub-observer point to the observer.

The following example shows the derivation of Carrington heliographic longitude and latitude (in degrees) using `CSPICE_SUBPT`

```
cspice_subpt, 'Intercept', 'Sun', et, 'lt+s', 'STEREO Ahead', spoint, alt
cspice_reclat, spoint, radius, lon, lat
lon = lon * cspice_dpr()
lat = lat * cspice_dpr()
```

The radius returned by `CSPICE_RECLAT` will be the solar radius of 696,000 km, and the sum radius+alt will be the heliocentric distance. Without aberration correction, the results will be identical with those from `CSPICE_SPKEZR`.

17