Chapter 3

Coordinate and Reference Systems

This chapter describes coordinate systems and references frames, giving information about the various usages of these within the MPG.

3.1 Positional Conventions

A *coordinate system* is a method of locating points in a given space of given dimensions by means of numerical quantities specified with respect to a reference. These quantities are the *coordinates* of the point. Each coordinate system corresponds to a particular way of expressing the location of a point with respect to the given reference. Each set of coordinates corresponds to only one point in that coordinate system. In general, each position in space has three degrees of freedom, and is therefore represented by three coordinates. Coupled with a position in time measured from a reference epoch, the 4-tuple defines the spacetime coordinates of the point.

Although any specific coordinate system is useful for numerical calculations in a given space, the *space* itself is considered to exist independently of the particular choice of coordinate system.

The spatial coordinates of a point relative to the origin define a *position vector*. The time rate of change of that point relative to the coordinate axes defines the *velocity vector* of the point. The 6-tuple containing position and velocity vector components is called the *state vector* of the point. State vectors are normally assumed to be in rectangular component form, and this is the SPICE standard.

The use of coordinate systems permits geometrical objects, their relationships, and their motions to be described mathematically. The 3-dimensional coordinate systems used predominately within the MPG are the rectangular, (Cartesian), spherical (latitude-longitude-radius), and cylindrical systems. Two dimensional systems include rectangular, polar coordinates, azimuth/elevation, hour-angle/declination, right-ascension/declination, XY, and X'Y'. These will be discussed more fully later in this chapter.

A *reference frame*, also called a *coordinate reference frame*, is defined by (1) a designated location, called the *origin*, (2) a designated orientation, called the *reference plane*, and (3) a designated direction in the reference plane, from which all other locations and directions in the plane are reckoned, (4) a designated metric for distance measurement, and (5) a designated metric for time measurement. The reference plane itself is defined by its distance from the origin and a vector normal to the plane. The reference frame may also be associated with an epoch that defines the time origin in the frame.

Frames are classified into two major categories, *inertial* and *non-inertial* frames. An inertial frame is one in which Newton's laws (especially the first) are hypothesized to hold; a body at rest remains at rest, and a body in uniform motion retains that motion. The term *celestial frame* is also used to denote an inertial frame. A non-inertial frame is one in which Newton's laws are not assumed to hold. Examples of non-inertial frames are accelerating frames, rotating frames, and frames subject to gravitational fields or spacetime curvature.

Due to gravitation, which permeates the universe, there are no true physical inertial frames, but approximations within regions of space are possible. Such frames exhibit no perceptible short term rotation with respect to the star background, but certain adjustments in distances (light times) and apparent positions must be made due to relativistic effects.

3.1.1 Rectangular Coordinates

The concept of a rectangular coordinate system is attributed to the French philosopher and mathematician Rene Descartes in 1637. In this system, a set of mutually orthogonal axes are defined at a point of origin, from which the components of a given point are measured as orthogonal projections of the point onto each of the axes.

For three dimensional space, there are three such axes and three coordinate components per point. Such points are commonly designated as (x, y, z).

If the three orthogonal unit vectors defining the axes of a rectangular system have a designated numbering, and are such that $\mathbf{u}_1 \times \mathbf{u}_2 = \mathbf{u}_3$, then the system is said to be *right-handed*.

When applied to reference frames, the three axes are (1) the designated direction in the reference plane, (2) a direction in the reference plane that is a 90º rotation in a counter clockwise direction about the normal vector, and (3) the normal direction.

If (x, y, z) represents a vector based at the origin, then the angles (q_x, q_y, q_z) between the vector and each of the coordinate axes are called the *direction angles*, and are given by

$$
\begin{aligned}
q_x &= \arccos\left(\frac{x}{\sqrt{x^2+y^2+z^2}}\right) \\
q_y &= \arccos\left(\frac{y}{\sqrt{x^2+y^2+z^2}}\right) \\
q_z &= \arccos\left(\frac{z}{\sqrt{x^2+y^2+z^2}}\right)
\end{aligned}
\tag{3-1}
$$

The cosines of these angles are referred to as *direction cosines* and satisfy the relation

$$\cos^2 q_x + \cos^2 q_y + \cos^2 q_z = 1 \tag{3-2}$$

A unit length vector based at the origin is called a *pointing vector*. The Cartesian coordinates of a pointing vector are thus $(\cos q_x, \cos q_y, \cos q_z)$. For this reason, the term direction cosines is often used to designate a pointing vector in rectangular coordinates.

3.1.2 Spherical Coordinates

Points specified as spherical coordinates (r, l, j) also called spherical polar coordinates, are located by the distance r from the origin; the *longitude* angle l in the reference plane measured counter clockwise from the reference direction about the normal vector; and the *latitude* angle f measured from the origin and reference plane, positive toward the normal. In many cases the polar angle $(90^{\circ} - j)$, or complementary latitude (*colatitude*), is used.

Sometimes the angle is measured in the opposite direction and termed the *co-longitude*. It is also sometimes termed east longitude or west longitude to distinguish the direction of measure. The symbols used for longitude and latitude are often different in different contexts. Usage will clarify the conventions appearing in this document. Care should be exercised when applying a SPICE coordinate transformation utility to make sure that the input and output arguments match the assumed definitions of the parameters.

3.1.3 Cylindrical Coordinates

Points in cylindrical coordinates (r, l, z) are located by the length r of the projection of the point on the reference plane, the longitude l measured from the reference direction counterclockwise about the normal, and the distance z of the point from the reference plane, positive in the direction of the normal. Points are commonly designated by (r, l, z), although symbols and order of components tend to change according to the application. The context of usage will clarify the conventions used in this document.

Cylindrical coordinates are commonly used within the DSN to define station locations, where they use the convention (*CU*, *CV*, *LO*), denoting, respectively, the distance from Earth's polar[1] axis, the signed distance above the equator, and the geocentric longitude.

3.1.4 Coordinate Transformations

The MPG finds it necessary and convenient to represent objects in space sometimes in several different coordinate systems according to the context of the application. The basic transformations are (1) simple coordinate translations in which the axes represent the same frame, such as in rectangular-to-latitudinal conversion; (2) rotations, in which coordinates of one frame are translated into those of another frame in a way that preserves angles and distances, such as the transformation from the J2000 inertial frame to a topocentric frame at a deep space station; and (3) spacetime transformations, in which the relativistic relationships between space and time are accounted for, such as in the transformations between the solar system barycentric frame and local topocentric frames. Such relativistic effects were discussed in a previous chapter and are not further elaborated here.

[1] In NSS MP documentation, Earth's polar axis is referred to as the "spin axis".

Fortunately, the SPICE toolkit and NAIF utilities contain all the utilities needed to make such transformations, without the need to resort to the underlying mathematical formulas. There are geometrical translations among rectangular, spherical, and cylindrical coordinates, such as `RECLAT`, `RECSPH`, `RECCYL`, `LATREC`, `LATCYL`, `LATSPH`, `SPHREC`, `SPHCYL`, and `SPHLAT`. Here, of course, `REC` refers to rectangular, `SPH` to spherical, `CYL` to cylindrical, and `LAT` to latitudinal systems. The `LAT` utilities apply to spherical coordinates in latitude and longitude, whereas the `SPH` utilities apply to spherical coordinates in colatitude and longitude. The initial mnemonic refers to the system being transformed and the latter one to the target system.

SPICE also has utilities `GEOREC` and `RECGEO` for translating between geodetic and rectangular coordinates, treated later in this chapter.

Rotations from one recognized frame to another are provided in SPICE by the functions `SXFORM` and `PXFORM`, which return the rotation matrices required to transform vectors in one frame into vectors in another. The former is used for translation of state vectors, and the latter, for position vectors. The state vector between an observer and a given target in a given frame of reference and at a given ephemeris time is provided by the SPICE `SPKEZ`[2] function, which not only applies the geometric transformations, but also makes the special relativity correction (stellar aberration) and accounts for the relative time differences between observer and target (planetary aberration).

Explicit coordinate rotations, as at times are needed in the MPG, are made using SPICE rotation routines. One method of specifying a coordinate rotation that is particularly useful is through the use of Euler angles. The set of coordinates in one coordinate system may be uniquely transformed into those of another system by the application of three successive rotation angles about specified axes.

If the (rectangular) axes are designated 1, 2, 3, then the notation $[q]_n$ signifies the matrix that rotates transforms one coordinate system by an angle ? about axis n. Applying this matrix to a vector yields the vector's representation relative to the rotated coordinate system. The right-handed rule applies, so a counter-clockwise rotation is in the positive direction. The SPICE function `ROTATE` generates this matrix.

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[2] In generating predicted pointing angles, only the position vector of the state vector returned by `SPKEZ` is used. Aberration corrections applied by SPKEZ are under user control.

The composition of rotations $[q_1]_a[q_2]_b[q_3]_c$ is sometimes referred to as an *a-b-c* rotation with respect to the given Euler angles. For example, $[q_1]_3[q_2]_1[q_3]_3$ is a "3-1-3" rotation. The individual rotations are applied to a vector in the order *c-a-b*. Given the Euler angles and axes, the resulting composite rotation matrix may be found using the SPICE function `EUL2M`.

But while it is true that all rotation matrices can be decomposed into a set of Euler angles, this decomposition may not be unique. Given a rotation matrix and the set of axis designations, in which the second Euler angle axis differs from the first and third, the SPICE function `M2EUL` does produce a valid set of Euler angles. See the source code commentary for the method used in this case.

The NAIF high precision time conversion routines `HPT`*x*`2`*y*, where *x* and *y* specify the particular type of translation desired between `TA`(I) or `U`(TC) and `E`(phemeris) time, handle transformations between UTC, local atomic time, and solar system barycentric time.

General relativistic effects on light time of flight between target and observer are made in the NAIF `RLTIME` utility.

Hence, given the SPICE and NAIF programming environments, there is little need for MPG routines to implement their own mathematical equations of coordinate transformation. The interested reader may consult the SPICE and NAIF source code commentary and other information for further details on the conversion formulas, usage, restrictions, and limitations.

3.1.5 Frame Classifications

There are many celestial coordinate frames that are used to specify positions of objects. These are commonly named according to their origins or points of observation. The principal celestial frames are designated as

1. Topocentric: having its origin located at an observer's location, on the surface of Earth or other body.
2. Geocentric: having its origin at the Earth center.
3. Body-centric or planetocentric: having its origin at the center of a designated celestial body. There are corresponding designations for individual planets.
4. Selenocentric: having its origin at the center of the Moon.

5. Heliocentric : having its origin at the center of the Sun.
6. Barycentric : having its origin at the center of mass of a system, such as the solar system, or a system comprised by a planetary and its satellites.

The principal celestial reference planes are designated as

1. *Horizon*: the plane normal to the local vertical (apparent direction of gravity) with origin at an observer.
2. *Local meridian*: the plane with origin at an observer and containing the local vertical and Earth's axis of rotation.
3. *Planet meridian*: the local meridian of a designated planet.
4. *Celestial equator*: the plane with origin at the geocenter and normal to the axis of rotation.
5. *Planet equator*: the plane with origin a planet center normal to its axis of rotation.
6. *Ecliptic*: the mean plane of Earth's orbit around the Sun.
7. *Orbital plane*: the plane of an orbit of a body around another.
8. *Invariable plane* or *Laplacian plane*: the plane with origin at a system's barycenter and normal to the axis of angular momentum of the system.

The principal non-inertial frames of interest are

1. *Body-fixed* frame: the rotating frame with its origin at the center of mass of a designated body and its reference plane being the equatorial plane. The designated direction is toward an arbitrarily defined *prime meridian.* The spherical coordinate angles are longitude and latitude.
2. *Crustal-fixed* frame: the body fixed frame whose axis of rotation is the instantaneous axis of rotation, which is the *axis of figure*, or axis of maximum moment of inertia.
3. *Topocentric* frame: the rotating frame with its origin at a point on a body's surface and its reference plane perpendicular to the local vertical (i.e., the horizon). The designated direction is north. The spherical coordinate angles are azimuth and elevation[3].

[3] The preferred term in astronomical usage is *altitude.* However, the term elevation is used for

Body-fixed and topocentric frames rotate with respect to inertial frames according to the dynamical effects of diurnal and orbital motions.

3.2 Celestial Reference Systems

Reference systems are defined so as to provide consistent bases for observation and computation. Such systems specify the reference frame at a given epoch, called the *standard epoch*, together with all the necessary formulas, procedures, and constants required to transform from the reference epoch to any other date. The motions of objects in the solar system offer a number of possible bases for reference frames, the standard being the Earth equator and ecliptic. The choice of epoch and whether the planes are mean or dynamical offer further alternatives.

A celestial reference frame, however defined, involves a process of generating ephemerides in the chosen frame based on the equations of motion in that frame and determining the necessary transformations that make the computed ephemerides consistent with observations. This chapter does not elaborate on this process, but does discuss a few of the standard frames the MPG must handle.

The following material is meant to clarify the relationships among the various inertial frames used within the MPG. Since celestial reference systems are defined in terms of terrestrial features, it is instructive to elaborate on the particular characteristics of influence.

Terrestrial reference frames will then be more fully discussed in a subsequent section.

3.2.1 The International Celestial Reference System

Since antiquity, celestial and terrestrial coordinate systems have been tied to Earth's orientation in space, but not always in a coordinated way. The International Earth Rotation Service (IERS) was founded on 1 January 1988 as a replacement for the Earth-rotation section of the Bureau International de l'Heure (BIH) and the International Polar Motion Service (IPMS), with the goal of providing an interdisciplinary service to maintain the key connections between astronomy, geodesy, and geophysics. In particular, it was to coordinate the definitions of the IERS Celestial Reference Frame (ICRF) and IERS

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historic reasons.

Terrestrial Reference Frame (ITRF), and to oversee the generation and distribution of Earth orientation parameter (EOP) data.

The ICRF is a celestial coordinate system, updated yearly by the IERS, that is based on a set of VLBI-determined coordinates of compact extragalactic radio sources. The ITRF is a terrestrial coordinate system, updated yearly by the IERS, implicitly defined by a standard set of station-location coordinates. The directions of its axes are continuous with those of the previously used BIH Terrestrial System.

The basic spatial reference system for the MPG and SPICE is the J2000 system. This is an inertial reference frame specified by the orientation of Earth's mean equator and equinox at the J2000 epoch, which is Greenwich noon on January 1, 2000 Barycentric Dynamical Time (JD 2451545.0). The terminology J2000 is used to name both the fundamental inertial frame and its designated epoch. To avoid confusion, usage here will attempt to distinguish the context in which the term is used.

The ICRF epoch is that of J2000, its origin is the solar system barycenter, its reference plane is that of the mean equator at epoch, and its reference direction is the equinox, as determined by IERS VLBI sources. IERS conventions equate it with the frame of JPL Development Ephemeris DE-403, and SPICE documentation equates the frame of DE-403 with J2000. It is also designated as the basis of the fundamental catalog of stellar objects, FK5. Thus, the current ICRF, J2000, FK5, and the frames of the DE-4xx series of fundamental ephemerides, all refer to the same inertial frame of reference.

3.2.2 Equatorial and Ecliptic Frames

The intersection of the plane of Earth’s equator and the ecliptic is a line that defines the directions of equinoxes. In equatorial and ecliptic frames, the direction of the vernal equinox at a particular epoch is chosen as the origin of longitude. It is often denoted in the literature and almanacs by the symbol ♈. In ancient times the equinox was located in the constellation Aries[4], and the equinox was thus termed “the first point of Aries.” The symbol, depicting a ram’s head, became the standard notation of the equinox in the astronomy literature. Both celestial and ecliptic frames use this equinox as their designated direction in their respective reference planes.

[4] The autumnal equinox is called “the first point of Libra” because it was located in that constellation in ancient times.

But, whereas the ecliptic plane may be determined from observations of Earth in its orbit, determination of the equator depends on observations of Earth's axis of rotation.

Right ascension, or *RA*, is the angular distance of a celestial body or point on the celestial sphere, measured eastward from the vernal equinox along the celestial equator to the hour circle of the body or point. It is the longitudinal coordinate in the celestial (equatorial) frame.

Right ascension is commonly measured in hours, minutes, and seconds, 24 hours being equivalent to 360º. This convention makes it necessary to distinguish right ascension angular measure from regular angular units so as to avoid confusion. One hour in right ascension is 15 degrees of arc; one minute in right ascension is 15 minutes of arc, or ¼ degree of arc; and one second in right ascension is 15 seconds of arc.

Hour angle, or *HA*, is a topocentric measure of the angle, reckoned westward, from the local meridian to the hour circle passing through a given point on the celestial sphere. Hour angle, like right ascension, is commonly measured in hours, minutes, and seconds of time, where 24 hours corresponds to 360 degrees of arc.

The relationship between hour angle and right ascension is one between terrestrial timekeeping and celestial coordinates. Objects rise in the east, transit the local meridian, and set in the west. Hour angle is essentially the length of time between the object and the meridian, positive westward. Thus an object setting due west is at an hour angle of 6 hours, while an object rising due east is at an hour angle of -6 hours.

In contradistinction, right ascension (*RA*) increases to the east from the vernal equinox. The right ascension of a point on the meridian increases continuously with time. Therefore, if the right ascension of an object now on the meridian is *RA*, then an object just now rising due east has right ascension RA + 6 hours, and an object just now setting due west has right ascension *RA* – 6 hours. Since Local Sidereal Time (*LST*) is the right ascension of a point on the meridian, the relationship between *RA*, *HA*, and *LST* is

$$HA = LST - RA \tag{3-3}$$

If a target's location at a specified time is specified in right ascension, then it can be converted to local hour angle at that time by computing the local sidereal time and applying the formula above.

Declination, or *d*, or *DEC*, is measured from the equator, positive in the northerly direction, along an hour circle or circle of right ascension to the point. Declination is commonly measured in degrees, minutes, and seconds of arc.

Longitude in the ecliptic frame is termed *ecliptic longitude* and also *celestial longitude* (the latter sometimes being confusing, since it does not refer to the celestial frame). It is measured in radians or degrees.

Latitude in the celestial frame, measured from the equator, is termed *declination* and measured in radians or degrees, positive northward. *Ecliptic latitude*, measured from the ecliptic, is also termed *celestial latitude* (again causing some confusion). It is also measured in radians or degrees.

The vernal equinox is at the ascending node of the ecliptic on the equator. It is the direction at which the Sun crosses the equator from north to south. The angle between the two planes is known as the *obliquity of the ecliptic.* The equator and ecliptic are moving because of perturbing forces on the rotation and orbital motion of Earth. For this reason, both the location of the equinox and the value of obliquity change over time. The vernal equinox currently resides in the constellation Pisces.

In order to define an inertial frame based on the equinox, it is necessary to specify the standard epoch of the reference equinox position. Moreover, it is necessary to state the method by which the reference equinox is reckoned. The usual specification is the *mean equator and equinox* at the standard epoch, which ignores small variations of short period in the motions of the celestial equator and includes only precession effects.

The positions of the equator and ecliptic for a standard epoch are not observed directly, but are calculated from catalogued positions and motions of stars and other celestial objects that act as reference points in the sky. A number of such frames have been defined[5], such as those designated as J2000, FK5, and the DE-4*xx* series of ephemerides, all of which refer to the same inertial frame, and those related to B1950, such as FK4 and the frames of the DE-1xx series of ephemerides, which all slightly differ from one another. Others include the ECLIPB1950, ECLIPJ2000, and GALACTIC frames.

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[5] Oddly enough, the ICRF is not one of the frames explicitly listed in SPICE system documentation. However, it is currently the same as J2000.

Fortunately, as a standard, JPL ephemerides each contain identification of its frame of reference. The SPICE library recognizes both inertial and body-fixed frame identifiers. Its utilities automatically and transparently translate from the various ephemeris frames to J2000, so that the generation of predictions thereafter proceeds smoothly. The `PXFORM` and `SXFORM` routines return the position and state transformation matrices, respectively, for translating between any two recognized frames at a given ephemeris time. The `SPKEZ` routines produce state vectors in any requested inertial or body-fixed frame in a seamless manner.

Transformations between rectangular coordinates and right ascension, declination, and range coordinates may be made using the `RECLAT` and `LATREC` utilities.

3.2.3 Earth Precession, Nutation, and Polar Motion

The normal to the equatorial plane is the true celestial pole, as defined by the axis of Earth's rotation. As viewed in the background of stars and extragalactic radio sources at a given instant of time, its direction is not fixed in space. Its motion is due to gravitational forces, mainly from the Sun and Moon, acting on the nonuniform distribution of mass within Earth. Mathematically, this motion is composed of three effects: precession, nutation, and polar motion.

The term *precession* refers to the slow, periodic conical motion of the celestial pole about the ecliptic pole. The component of precession caused by the Sun and Moon acting on Earth's equatorial bulge is called *lunisolar* precession, and the component caused by the action of the planets is called *planetary* precession. The sum of the two effects is called *general* precession. Precession causes the equinox to move backward along the equator at a rate of about 50 arcseconds per year. Earth's rotational axis will return thus to its present location in about 26,000 years.

While precessing, Earth's axis wobbles slightly due to shorter term effects of the Moon's gravity on Earth's equatorial bulge. This effect, called *nutation*, is a short period motion of the true pole about the mean pole with amplitude of about 9 arcseconds and a variety of periods up to 18.6 years.

Whereas the effects of precession determine the location of the *mean equinox of date*, the added effects of nutation determine the location of the *true equinox of date*. The difference in right ascension between the true and mean equinoxes of date is called the *equation of the equinoxes*, and is the difference between true and mean sidereal time.

The combination of precession and nutation define a reference axis called the *Celestial Ephemeris Pole* (CEP). It is normal to the true equator and is the axis about which the diurnal rotation of Earth is applied in the transformation between celestial and terrestrial frames. However, it does not coincide with instantaneous axis of rotation, which is the Earth's *axis of figure*, or axis of maximum moment of inertia.

The difference between the axis of figure and CEP is known as *polar motion*. This motion is affected by unpredictable geophysical forces on the deformable Earth, and is determined from observations of stars, radio sources, the Moon, and Earth satellites, using Very Long Baseline Interferometry (VLBI), laser ranging, and other applicable techniques. The intersection of the axis of rotation with the Earth's surface appears to wander in a quasi-circular motion around the CEP with maximum amplitude of about 0.3 arcseconds, corresponding to a motion of about 9m on the surface and having principal periods of about 365 and 428 days.

The obliquity of the ecliptic is known to oscillate between about 22.0º - 24.6º, with a period of around 41,000 years. Its current value is about 23º26'.

Theories and formulas for precession and nutation, including changes in obliquity, may be found in the *Explanatory Supplement to the Astronomical Almanac*. They are implemented in the Navigation Ancillary Information Facility (NAIF) Precision Earth Model, discussed under Terrestrial Reference Systems, below.

Polar motion is unmodeled by SPICE and the MPG; that is, there are no mathematical models or ephemerides that characterize the motion. Rather, its effects are entered into the MPG by means of an ephemeris called the Precision Earth Model (PEM) which is generated by NAIF special MPG routines that make use of Earth Orientation Parameter (EOP) files and Universal Time and Polar Motion (UTPM[6]) files received by the Service Preparation Subsystem (SPS) from the Kalman Earth Orientation Software service, which processes the EOP data supplied by the IERS. The reader is referred to the refer-

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[6] Also known as the UTPM STOIC file format, created by the Standby Timing Operations In Contingencies program. This format contains information derivable from the EOP and is more limited in extent. The NSS was the predominant user of STOIC files.

enced DSN Interface Agreement for further details. The PEM is an implementation of ITRF93, discussed later.

Since polar motion is quasi random and cannot be accurately predicted very far into the future, the MPG requires frequent updates of EOP files in order to generate accurate products. Even with accurate current EOP files, it is not possible to guarantee that high accuracy predictions can extend into the more distant future. MPG predictions are accurate within the accuracy and validity of its inputs, but may not echo reality in cases where inputs do not represent reality.

3.2.4 Other Inertial Frames

3.2.4.1 Ephemeris-Defined Frames

Fundamental ephemerides of the positions and velocities of solar system bodies are computed using the basic dynamical equations of motion and fit to observational data. They are the bases for computing apparent ephemerides, representational ephemerides, phenomena, orbital elements, and stability characteristics of entities of interest.

The gravitational model used includes all the known relevant forces (i.e., those producing an observable or measurable effect) acting upon and within the solar system, with relativistic effects approximated to terms including $1/c^2$. The method is further elaborated in the ESAA.

The positions and velocities of objects in the ephemerides are referenced with respect to inertial space, since the equations of motion are defined with respect to inertial space. Associated with the ephemerides is the set of astronomical constants used in the creation of the ephemerides. These "constants" are "solved-for" parameters, as they must provide a best-fit of the ephemerides to the observational data. The constants are associated directly with the ephemerides and are considered to be an integral part of them.

Since the dynamical equinox is a position defined by motions of the solar system bodies, it is possible to determine its location using the ephemeris itself. The alignment of the ephemeris frame with the J2000 equinox of the ephemerides then becomes a relatively straightforward, but iterative task. Since the dynamical equinox depends on the set of observational data used to correct the ephemeris, the equinox found using an ephemerides based on constants derived from observations of solar system objects is not precisely equivalent to one based on observations of stars and radio-source catalogs

For this reason, the reference frames of JPL development ephemerides may vary somewhat from the standard reference frames used in prediction generation (B1950 for the NSS MP, or J2000 for the MPG), depending on the observational data applied. The SPICE required reading document on frames identifies the reference frames associated with JPL development ephemerides and other ephemeris-derived inertial frames, and also provides the rotation matrices required to transform states in the ephemeris frames to J2000.

Fortunately for the MPG, SPICE automatically translates recognized ephemeris frames to J2000, so these are largely transparent to MPG applications.

3.2.4.2 Star Catalog Frames

The fifth fundamental star catalog, denoted FK5, is a listing of the mean position and proper motions at equinox and epoch J2000 for a number of fundamental stars to magnitude of about 9.5. A previous version, FK4, which was referenced to B1950, was in effect prior to the adoption of the FK5 frame. It differed from B1950 by a rotation of 0.525 arc seconds about the polar axis.

Although referenced to the J2000 frame, FK5 positions differ slightly in optical and radio source observations by about 1 milliarcsecond. FK5 was used primarily before the introduction of the ICRS, which on January 1, 1998 superseded it.

3.2.4.3 Time and Standard Epochs

The NSS MP bases its computations on the standard B1950 frame, which corresponds to the equinox and mean equator of the Besselian epoch JD 2433282.423. A *Besselian* epoch, named after the German mathematician and astronomer Friedrich Bessel (1784 – 1846), is an epoch that is based on a tropical year of 365.242198781 days, measured at the point where Sun's longitude is exactly 280°.

Since 1984, however, Besselian epochs have been superseded by Julian epochs, the current standard epoch being J2000. Besselian and Julian epochs are related according to:

$$\mathrm{BesselEpoch} = 1900 + \frac{\mathrm{JulianEpoch\ -\ 2415020.31352}}{365.242198781} \qquad (3\text{-}4)$$

Even though the MPG bases its computations on the standard J2000 frame, nevertheless, since many older star catalogs are still useful, those having B1950 coordinates cannot just be shelved. However, these older positions must be corrected for precession and nutation to yield J2000 positions in order that they be used by the MPG. Even though the applicable Interface Agreement shows a field for epoch of observation (see References, below), it specifically states that all radio source RA/DEC coordinates are given in the ICRF frame.

Future versions of prediction generators will probably base their computations on standard Julian epochs that are spaced 50 years apart. In this way, the unit of time, viz., seconds past the reference epoch, will stay within precision bounds of the data type used in programming.

3.3 Terrestrial Reference Systems

The ITRF is an Earth-crust-fixed frame that is geocentric, with its center of mass being that of the whole Earth, including oceans and atmosphere. Its scale is that of a local Earth frame, in the meaning of a relativistic theory of gravitation. Its initial orientation was taken to be the same as that of the BIH Terrestrial Frame of 1984.0, and its evolution in time is such that there is no residual global rotation with regards to the crust.

The method of realization of the ITRF and the transformation formulas between ICRF and ITRF are detailed in the IERS conventions (see references), and do not appear here. However, the Navigation Ancillary Information Facility (NAIF) utility `I2TERR` generates transformation matrices from specified inertial frames to the ITRF. It also has a utility `WRTPEM`, which writes the Precision Earth Model ephemeris used by the MPG. The SPICE system now also contains a built-in implantation of the ITRF. By defining DSS locations relative to this frame, SPICE utilities are then able to develop DSS frames that the MPG can use to generate accurate topocentric predictions.

The particular terrestrial frame implemented is ITRF93, the particular version of the ITRF published in 1993. Time and polar motion data input to the NAIF model are consistent with this frame definition.

The SPICE system also implements a terrestrial model labeled IAU_EARTH, which does not have the accuracy required for MPG pointing and Doppler predictions. The IAU models are discussed in a later section.

3.3.1 Terrestrial Coordinate Systems

Earth is not spherical, is not flat, and is not uniform in makeup. In fact, it is a bumpy, somewhat elastic irregular glob of nonuniformly distributed matter, whose surface features change (slowly) over time. Most terrestrial coordinate systems for measuring positions near the Earth's surface use, as their reference, an abstract surface near that of Earth. There are several common abstract representations of the reference surface, such as the geoid and various ellipsoids. This section discusses the fundamentals of the various terrestrial coordinate systems that are used to define the coordinates of an object on or near Earth's surface.

3.3.1.1 Pole and Prime Meridian Coordinates

Points on Earth's surface can be expressed in rectangular coordinates (x, y, z), in which the z-axis is the rotational axis, the x-axis is in the prime meridian, and the y-axis is 90º eastward from the x-axis. The origin is the center of Earth. Other coordinate systems that translate to these values are also used, such as geocentric latitude, geocentric longitude, and distance from the geocenter, and such as geodetic latitude, geodetic longitude, and height above a reference surface.

The locations of deep-space stations are contained in the MPG Station Parameter File, and expressed in cylindrical coordinates, (*CU*, *CV*, *LO*), denoting, respectively, the distance from Earth's polar axis, the signed distance above the equator, and the geocentric east longitude. The SPICE function `CYLREC` can be used to convert the cylindrical coordinates to rectangular ones, if needed[7].

3.3.1.2 Geocentric, Geodetic, and Astronomical Coordinates

It is usual practice in some fields to specify locations relative to some useful surface, as opposed to an origin and axes. Cartography, geodesy, and navigation, for example, deal with coordinates derived from Earth's gravitational field. Points are specified by a location on the reference surface and a height above it.

Due its non-uniformity, an ellipsoid is often used as the first approximation to a surface of constant gravitational potential. However, a best-fitting triaxial

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[7] Besides prediction generators, the MPG also has several stand-alone utilities. One of these, `GPS_Translate`, implements a number of such coordinate transformations.

ellipsoid does not appear to have significant benefit over an ellipsoid of rotation, but does substantially complicate computations. Therefore, the oblate spheroid (a rotationally symmetric ellipsoid having its polar axis shorter than its equatorial diameter) is most often used because it does model the flattening of Earth at its poles and yet is still a fairly simple mathematical surface. Such ellipsoids are termed *local* or *terrestrial*, depending on whether they approximate a given localized area or the entire Earth.

Another abstract surface that proves useful when instruments sensitive to the local gravitational gradient are involved is the *geopotential* surface, or *geop*[8]. The geop defines a surface of equal gravity potential, including the effects of both gravitational and centrifugal forces. The gravity potential is everywhere perpendicular to the geop.

One geop of particular importance is the *geoid*, which is a geop whose potential is that of Earth's mean sea level. The geoid itself lies close to the reference ellipse, but differs by an amount called the *geoid undulation* (N), which is the height of the geoid above the ellipsoid.

An observer at a given point on Earth's surface lies on a geop above the geoid. The height of the observer above the ellipse is the *ellipsoidal height* (h), and the height of the observer above the geoid is called *mean sea level height* or *orthometric height* (H). These are related approximately by

$$N = h - H \tag{3-5}$$

This is only approximate because H is actually measured along the curved normal or plumb line between the observer and geoid.

An observer's longitude and latitude can be measured in a number of ways. If measured with respect to the geocenter, they are said to be *geocentric*. If measured with respect to a reference ellipsoid, they are said to be *geodetic*. And, if measured with respect to the observer's local vertical, they are said to be *astrometric*. The reader should not confuse the term geodetic here as having to do with the geoid.

Geocentric latitude is the angle as viewed at the center of the reference ellipsoid between the ellipsoid equator and the observer, positive in the northerly direction. Geodetic latitude is the angle between the ellipsoid equator and the

---

[8] The pronunciation of this term is not found in literature available to the authors. The presumption is that, since it refers to Earth, it would be pronounced *GEO-P*. However, the word geoid does not follow this rule, so the pronunciation could well be *GEE-OP*.

normal to the ellipsoid at the observer, also positive northward. Astronomical latitude is the angle between the Earth's equator and the local vertical. The reader will note that the line of the local vertical does not necessarily pass through the Earth's center or even intersect the polar axis.

The angle between the local vertical and normal to the ellipsoid at the observer is known as the *deflection of the vertical*. This angle is sometimes expressed as the combination of a meridian increment and an orthogonal increment along the meridian, positive northward. It is unused within SPICE and the MPG.

Geocentric longitude is the angle between the reference (prime) meridian and the observer's meridian. Geodetic longitude is the same as geocentric longitude, under the usual assumption that the reference axes and prime meridians are chosen to be the same. The astronomical longitude is somewhat more complicated; it is the angle between the prime meridian plane and the plane perpendicular to the equator that includes the observer and observer zenith vector.

If a and b are, respectively, the semimajor and semiminor axes of the reference ellipsoid, the *flattening factor* f is defined as

$$f = \frac{a - b}{a} \tag{1.6}$$

The height associated with geocentric measure is the distance between the observer and geocenter, the height associated with geodetic measure is the ellipsoidal height, and the height associated with astronomical measure is the *orthometric height*.

A geodetic frame of reference is referred to as a *datum*. Geodetic datums define the size and shape of Earth and the origin and orientation of the coordinate systems used to map it. Hundreds of different datums have been used to frame position descriptions since the first estimates of Earth's size were made by Aristotle. Datums have evolved from those describing a spherical Earth to ellipsoidal models derived from years of satellite measurements.

One such datum is the World Geodetic System of 1984 (WGS84), last revised in 2004) that is used by the Global Positioning Satellite (GPS) system. The coordinate system is essentially that of the ITRF and the reference ellipsoid is one having

$$
\begin{aligned}
a &= 6378.137 km \\
1/f &= 298.257223563
\end{aligned}
\tag{3-7}
$$

It is usual to find the flattening factor in geodetic models expressed as an inverse, because the resulting figure has an integer part that, to practitioners, appears to be a more meaningful representation. The flattening value is actually

$$
f = 0.0033528106647475 \tag{3-8}
$$

Datums also specify an Earth Gravitational Model (EGM), which is typically a spherical harmonic series of the gravitational potential from which a geoid undulation model is derived. The EGM96 series, for example, was of order and degree 360. The MPG and SPICE do not use gravity models, and hence do not compute heights relative to the geoid. Heights above the reference ellipsoid, however, are used.

The ESAA contains formulas for geocentric-geodetic transformations. These are not particularly enlightening and are omitted here. SPICE contains routines `GEOREC` and `RECGEO` that perform these functions in an equivalent, but seemingly more elegant manner. The interested reader is referred to the commentary in the source code for further details.

The conversion from a given geodetic longitude, geodetic latitude, and height output (? f, h) of a GPS (WGS84) receiver to geocentric coordinates (x, y, z) is found directly using `GEOREC` along with the Earth radius and flattening given above. The conversion of this point (x, y, z) into cylindrical coordinates is made using `RECCYL`, which outputs the values (R, $LONG$, Z), which, in the parameters of the Station Parameter File, are (CU, LO, CV).

3.3.2 Topocentric Coordinates

The SPICE convention for topocentric coordinates is the north-west-zenith frame, and the components are denoted (n, w, z). The MPG observes topocentric rectangular coordinates as north-west-zenith components, as well. The SPICE frame transformation utilities, such as `SXFORM` and `PXFORM`, and state vector functions such as `SPKEZ`, all observe this convention. These utilities rely on geodetic coordinates of tracking stations provided in the Topocentric Reference Frames file and Station Ephemeris File. Both these files are generated from the user-accessible Station Parameter file.

The PX6 prediction data type lists direction cosines in the order (z, e, n). For this reason, the Network Support Subsystem Metric Prediction (NSS MP) application used this convention internally. This notation forms a right-handed coordinate system, but is not a rotation of the SPICE and MPG frame. The generation of PX6 direction cosines in the MPG requires the transposition

$$(\cos q_N, \cos q_W, \cos q_Z) \rightarrow (\cos q_Z, -\cos q_W, \cos q_N) \qquad (3\text{-}9)$$

to provide the correct output format.

It should be noted that, while the NSS MP used the (z, e, n) frame convention, the JPL Orbit Determination Program applies a north-east-zenith convention for topocentric pointing vectors. The (n, e, z) frame, however, is a left-handed coordinate system. Right-handed coordinate conventions incorporating east are (e, n, z), (n, z, e), and (z, e, n).

3.3.2.1 Antenna Coordinate Systems

DSN DSS antennas are categorized depending on their construction. The principal differences among the various types of antennas are aperture, wave optics, and mount. The coordinate system of an antenna is defined by the orientations of its axes of motion and measures of rotation about each axis. The mounts are classified by the type of coordinate system most natural to the motion axes. There are hour-angle/declination (also called equatorial or HA-DEC), azimuth/elevation, and XY and X'Y' mounts. Transformations of pointing angles in the coordinate systems used by these mounts are discussed below. These transformations do not include the effects of atmospheric refraction and mount-specific range corrections, which are discussed in other chapters of this Supplement.

A *keyhole* is an area in the sky where an antenna cannot track a target because the required slew rate along one of its axes of motion would be too high, or because mechanical limitations prevent the antenna from pointing in that direction. Keyholes impose restrictions on an antenna's ability to serve its function. As will be seen, each mount type has differing keyhole constraints.

Another constraint on antennas is restricted pointing areas. These are sometimes not physical limitations, but ones imposed by safety or security. Horizon masks define the limits of reception from a target, while high-power transmitter masks define areas in which it is safe to radiate to a distant target.

3.3.2.2 Hour Angle/Declination Coordinates

Antennas with so-called equatorial or HA-DEC mounts have one axis parallel to Earth's polar axis and the other in a latitudinal direction that slews above and below the equator. With proper calibration and the application of the ITRS model, antenna coordinates may be related to those deriving from the true pole, prime meridian, and equinox of date. Elongations relative to the polar axis are thus hour angle, and those relative to the equatorial axis are declination.

Some of the older DSS antennas were equatorial mounts. To track an interplanetary spacecraft, the antenna would point to the spacecraft's known coordinates, and then, for the rest of the tracking period, it would simply rotate in hour angle about the tilted axis as the Earth turns.

While being a fine type of mount for a small instrument, it proved to be very unsuitable for large, heavy structures because the tilted polar bearing has to sustain large asymmetric loads. These loads include not only the whole reflector dish and its associated wavefront focusing apparatus, but also an HA counterweight heavy enough to balance the antenna, the DEC bearing, and its DEC counterweight. Also the structure has to be designed specifically for its location, since the polar bearing's angle depends on the station's latitude.

The DSN built such antennas at Goldstone, Madrid, and Canberra, but these are no longer in service. The Goldstone site has been converted to a radio telescope dedicated to educational use. The discussion here is included for historical purposes, because hour angle and declination coordinates are still used in pointing optical instruments, and because right ascension and declination still appear in star catalogs.

If the geocentric position of the DSS antenna, designated here as DSS, is $(x_{DSS}, y_{DSS}, z_{DSS})$ and that of a target in space is $(x_{tgt}, y_{tgt}, z_{tgt})$, then the declination and hour angle are given by

$$
\begin{aligned}
\mathbf{p} &= (x_{tgt} - x_{DSS}, y_{tgt} - y_{DSS}, z_{tgt} - z_{DSS}) \\
\mathbf{u} &= \frac{\mathbf{p}}{|\mathbf{p}|} \\
l_{tgt} &= \arctan(y_{tgt}, x_{tgt}) \\
l_{DSS} &= \arctan(y_{DSS}, x_{DSS}) \\
d &= \arcsin(u_z) \\
HA &= l_{DSS} - l_{tgt}
\end{aligned}
\qquad (3\text{-}10)
$$

where l denotes the longitude of the subscripted object. The arctangent function appearing here computes the quadrant-corrected $\arctan(y/x)$. The longitude of the station, of course, is fixed, and only needs to be computed once. The body-fixed direction to the target, however, changes continually, and must be reevaluated for each computation of hour angle and declination.

The inverse formulas are

$$
\begin{aligned}
u_x &= \cos(d)\cos(l_{DSS} - HA) \\
u_y &= \cos(d)\sin(l_{DSS} - HA) \\
u_z &= \sin(d)
\end{aligned}
\qquad (3\text{-}11)
$$

Conversion of a station location and pointing vector in rectangular coordinates to hour angle and declination may use the SPICE `RECLAT` function, which returns the elevation as the declination argument and the hour angle as the difference in longitude between the DSS and target. The inverse conversion may use `LATREC`, observing the same conventions.

For a HA-DEC antenna, the keyhole is large, in the northern hemisphere, and centered near the North Star. To track through that area the antenna would have to whip around prohibitively fast in hour angle.

3.3.2.3 Azimuth-Elevation Coordinates

Antennas with so-called azimuth-elevation or AZ-EL mounts have one axis along the local vertical so that they turn in the horizontal plane. The other axis lifts toward zenith. This design permits mechanical loads to be symmetric, resulting in less cumbersome, less expensive hardware that is easier to maintain. Most of the DSN antennas are of this type.

Such mounts locate a point in the sky by elevation (*el*) in degrees above the horizon, and azimuth (*az*) in degrees clockwise (eastward) from true north.

Given a topocentric unit vector (n, w, z) in the SPICE north-west-zenith coordinate convention, azimuth and elevation computations follow the familiar formulas

$$\begin{aligned} az &= \arctan(-w, n) \\ el &= \arcsin(z) \end{aligned} \tag{3-12}$$

The arctangent function appearing here computes the quadrant-corrected $\arctan(-w/n)$. The inverse formulas are

$$\begin{aligned} n &= \cos(az)\cos(el) \\ w &= -\sin(az)\cos(el) \\ z &= \sin(el) \end{aligned} \tag{3-13}$$

Conversion of a pointing vector in rectangular coordinates to azimuth and elevation may use the SPICE `RECLAT` function, which returns the elevation as the latitude argument and the negative of the azimuth as the longitude. The inverse conversion may use `LATREC`, observing the same conventions.

Such mounts have keyholes at zenith and cannot generally dip below a minimum elevation limit. If a spacecraft were to pass directly overhead, the AZ-EL antenna would rise in elevation until it reached its straight-up maximum near 90°. But then the antenna would have to whip around rapidly in azimuth as the spacecraft is first on the one side of the antenna, and then, a moment later, is on the other. When the antenna slew rate is not fast enough to track through this region, there will be an interruption in tracking until the link can be reacquired on the other side.

Certain AZ-EL antennas[9] require long cables that connect the dish electronics to the ground electronics. As the antenna tracks its target, the cable between the pedestal and alidade wraps around until its limit in that direction, clockwise or counterclockwise, is reached. The antennas are designed so that the entire traverse from counter-clockwise limit to clockwise limit is greater than 360°. Cable wrap limitations restrict the time-on-target that can be achieved for some missions. For this reason, the MPG antenna pointing predictions include cable-wrap status (pointing) and warnings (view period events).

[9] Antennas with beam waveguide technology avoid the use of such cables by the addition of five precision radio frequency mirrors that reflect signals along a beam waveguide tube from the vertex of the antenna to the equipment in the antenna pedestal. However, there remains a power cable connecting the alidade and pedestal to which the wrap limits apply.

3.3.2.4 X-Y and X'-Y' Coordinates

Two other mounting schemes for antennas are the X-Y and X'-Y' orientations. Like AZ-EL, and HA-DEC antennas, these mounts also have two perpendicular axes. They are mechanically similar to the HA-DEC antenna, but have their "polar" axes oriented horizontally, and not necessarily aligned to a cardinal direction.

An antenna having a so-called X-Y mount has one of its rotational axes fixed and oriented horizontally toward north. The angle X is then measured from zenith positive eastward. The other axis rotates perpendicularly to the first, so that the angle Y is measured as the northern elongation. Such mounts have keyholes at the northern and southern horizons. The conversion from (n, w, z) to (X, Y) is

$$\begin{aligned} n &= \sin(Y) \\ w &= -\sin(X)\cos(Y) \\ z &= \cos(X)\cos(Y) \end{aligned} \qquad (3\text{-}14)$$

and the inverse mapping is

$$\begin{aligned} X &= \arctan(-w/z) \\ Y &= \arcsin(n) \end{aligned} \qquad (3\text{-}15)$$

These formulas are of the same form as those for azimuth and elevation under the mapping *n*®*z*, *w*®*w*, *z*®*n*, *Y*®el, *X*®*az*.

An antenna having a so-called X'-Y' mount has one of its rotational axes fixed and oriented horizontally toward east. The angle X' is then measured from zenith positive southward. The other axis rotates perpendicularly to the first, so that the angle Y' is measured as the eastern elongation. Such mounts have keyholes at the eastern and western horizons. The conversion from (n, w, z) to (X', Y') is

$$\begin{aligned} n &= -\sin(X')\cos(Y') \\ w &= -\sin(Y') \\ z &= \cos(X')\cos(Y') \end{aligned} \qquad (3\text{-}16)$$

and the inverse mapping is

$$\begin{aligned} X' &= \arctan(-n/z) \\ Y' &= -\arcsin(w) \end{aligned} \qquad (3\text{-}17)$$

Again, these formulas are of the same form as those for azimuth and elevation under the mapping *w®z*, *n®w*, *z®n*, *Y'®–el*, *X'®az*.

These two antenna types have the advantage over HA-DEC and AZ-EL antennas in that they can rotate freely in any direction from the upward-looking zenith central position without any cable wrap-up issues. Another advantage is the location of keyholes. These antennas are oriented so that its keyholes are either at the northern and southern horizons, or at the eastern and western horizons. This leaves the whole sky open for tracking spacecraft without requiring high angular rates around either axis. Such mounts were first built for tracking Earth-orbiting spacecraft, which may require high angular rates and overhead passes.

The DSN is currently equipped with three X'-Y', 26-m aperture antennas (DSS-16, DSS-46, DSS-66), used primarily in tracking Earth orbiters, which usually have inclinations that avoid the east and west keyholes.

Of course, the 26-m antennas can also be used with interplanetary spacecraft. Such spacecraft do not typically pass overhead, but rather stay near the ecliptic plane in most cases, and may occasionally pass through a keyhole at rise or set. However, since their apertures are smaller than most other DSN stations, they are not deemed effective for most interplanetary craft.

3.4 Planetary Reference Systems and Frames

At regular intervals the IAU revises and publishes tables giving the directions of the north poles of rotation and the prime meridians of the planets, satellites, and asteroids. It also publishes revised tables giving their sizes and shapes, along with a summary of changes since the previous report.

These planetary body-fixed coordinate frames are defined relative to their mean axes of rotation and various definitions of longitude, depending on the body. The longitude systems of most of those bodies with observable rigid surfaces have been defined by references to a surface feature, such as a crater. These are generally simplified models in which the models of rotation, precession, and nutation are less complex than that found in the ITRF. The ICRF is the reference coordinate frame, with variable quantities expressed in units of days (86400 SI seconds) or Julian centuries (36525 days).

The SPICE system incorporates the IAU tables in defining reference frames for these objects with respect to the J2000 inertial coordinate system. The names of these frames are of the form IAU_*object*. For example, IAU_EARTH is the IAU Earth frame.

The MPG uses IAU frames, together with IAU estimates of body radii, in computing occultation and eclipse predictions, where bodies are treated as triaxial ellipsoids.

3.5 DSN and NAIF Frame Identification

The MPG recognizes two frame identification designations. The DSN ID system is used in user interfaces, while the NAIF ID system is used within the MPF and SPICE. The two bear similarities, but are also very dissimilar in many aspects. The two are different partly for historical reasons and for consistency with NSS identifiers.

Correspondences between the two are defined in the DSN_NAIF_Conv.txt file used by the MPG.

Basically, in the DSN ID system, planet barycenters are designated by single digits 0-9. Sun is 10, Earth is 300, Moon is 301, spacecraft are negative and deep space stations are positive integers less than 100.

SPICE files and subroutines internally refer to ephemeris objects, reference frames, and instruments by integer codes. The codes and conventions may be found in the SPICE required reading document NAIF_IDS. Spacecraft identifiers are negative and are usually assigned by a NASA control authority. This authority, at times, is forced into reusing some IDs, which can affect the way the SPICE system handles these codes.

As for NAIF numeric identifiers, the smallest positive codes are reserved for the solar system barycenter (0) and Sun (10). The nine integers in between refer to planet system barycenters in order of distance from Sun. Integers of the form *PNN*, where *P* is one of the planet indices and *NN* is the number of a satellite, refer to planets and satellites; a planet center is considered to be the 99^{th} satellite of its barycenter. Thus, 399 refers to the geocenter.

Spacecraft are assigned negative integer codes. The code assigned to an interplanetary spacecraft is normally the negative of the code assigned to the same spacecraft by the DSN, as determined by the NASA control authority at GSFC.

Earth orbiters not having a DSN identification code are assigned numbers equal to `-100000-US_Space_Command_code`.

The NAIF identification codes for tracking stations and landed spacecraft are of the form *P*99*NNN*, where *P* is the planet number, and *NNN* is the station or target number.

NAIF also has identification techniques for spacecraft instruments, comets, and asteroids.

SPICE subroutines permit textual names to be assigned to these integer codes. More than one name may be assigned to any particular numeric ID, and these names may be used to refer to that ID. However, if one asks for the name of a given ID, only the last-entered assignment is retrieved.

As the SPICE system has expanded, so has the number of objects requiring identifying codes. Many of these objects do not fit neatly into the schemes originally envisioned as needing ID codes. Needless to say, the particular set of ID codes recognized by SPICE now shows the wear that results from an expanding system.

The definition of frames corresponding to NAIF IDs is explained in the FRAMES required reading. Basically, there are a number of built-in frames, augmented by the means to define other frames, given the information by which to do so.

The built-in inertial frames include the Earth mean equator and equinox of J2000 (`'J2000'`), the mean ecliptic and equinox of J2000 (`'ECLIPJ2000'`), the Galactic System II frame (`'GALACTIC'`), and the Mars mean equator and IAU vector of J2000 frame (`'MARSIAU'`). The built-in body-fixed frames include those based on IAU rotation models, such as `'IAU_EARTH'` and `'IAU_MARS'`, as well as the high-precision Earth rotation model `'ITRF93'`.

SPICE also provides the means to define other reference frames using parameters and mathematical models defined in text or binary files.

DSS frames are defined by a combination of antenna location information found in the station parameters file and parameters in a frames kernel for generating the rotation matrix from the Earth model (ITRF93) to topocentric coordinates.

The interested reader is directed to the SPICE required reading files for further information.

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