PURPOSE:

The **Horizons On-Line Ephemeris System** provides access to key solar system data and dynamic production of highly accurate ephemerides for solar system objects. This includes 611,000+ asteroids, 3200 comets, 176 natural satellites, all planets, the Sun, more than 60 select spacecraft, and dynamical points such as Earth-Sun L1, L2, L4, L5, and system barycenters. Users may conduct parameter searches of the comet/asteroid database, finding objects matching combinations of up to 42 different parameters. Users may define and integrate their own objects. Rise, transit and set may be identified to the nearest minute. When used with Sun and Moon sky-brightness data, observing windows can be identified. Close-approaches by asteroids and comets to the planets, Ceres, Pallas, and Vesta, can be rapidly identified along with the encounter uncertainties and impact probabilities. Orbital uncertainties can be computed for asteroids and comets.

More than 100 different observational and physical aspect quantities can be requested as a function of time for both topocentric and geocentric observers, in one of 9 coordinate systems and 4 time scales (CT, TT, UT, Civil). 1500 Earth station locations are available, along with sites on other major bodies. Users may search for (or define) topocentric site coordinates on any planet or natural satellite with a known rotational model. Spacecraft-based observations are also supported. Output is suitable for observers, mission planners and other researchers, although this determination is ultimately the user's responsibility. The underlying planet/satellite ephemerides and small-body osculating elements are the same ones used at JPL for radar astronomy, mission planning and spacecraft navigation.

In addition to **parameter searches**, **object data summaries**, and **close-approach tables**, four types of customizable ephemerides can be requested:

> 1) Observables (RA/DEC, Az/El, physical aspect, separation angles, uncertainty ellipses,etc.)
> 2) Osculating elements
> 3) Cartesian state vectors
> 4) SPK binaries (asteroids and comets only)

The first three are ASCII tables; output is returned to the user via browser, e-mail, FTP or Kermit protocols and may be requested in a format suitable for spreadsheet import. SPK binary files allows user programs to reproduce the integrated target state at any instant and may be used as plug-ins to existing visualization and mission-design software.

ACCESS METHODS:

> **A) Telnet** (full access via an interactive prompt-based interface):
> > 1) Connect directly to system (**telnet ssd.jpl.nasa.gov 6775**, or **telnet://ssd.jpl.nasa.gov:6775**).
> > 2) Specify an object to get a summary data screen.
> > 3) Follow prompts. At any prompt, type ? or ?! for short and long explanations
> > 4) Transmit results to your system by e-mail, FTP or Kermit

> **B) E-mail** (full access batch interface; allows up to 200 discrete times for 200 objects at once):
> > 1) Send e-mail to "**horizons@ssd.jpl.nasa.gov**" with subject "**BATCH-LONG**".
> > 2) An example command file will be mailed back to you.
> > 3) Edit this text file, then mail it back with the subject header "**JOB**".
> > 4) Results of your request are mailed back to you.

> **C) Web** (access a small subset of program functions with a passive-interactive GUI interface):
> > Point your browser to **http://ssd.jpl.nasa.gov/horizons.html**

Horizons was intended to be easy to use, with a step-function learning curve. The remainder of this documentation summarizes system capabilities, but is not necessary for successful use. **While using the telnet system, type "?" or "?!" at any prompt for an explanation of options. See the "Acknowledgments" section for contact information.** Complete documentation (this file) may also be retrieved at **ftp://ssd.jpl.nasa.gov/pub/ssd/Horizons_doc.pdf**

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1. CONNECTING TO THE SYSTEM

TELNET:

The Horizons on-line ephemeris and data system is available as a telnet service. This is suitable for people who want full access to program features in an interactive prompt-based way. From a telnet-capable machine running a "VT100" type terminal emulation, telnet to "**ssd.jpl.nasa.gov 6775**", where 6775 is a port number. From within a web-browser, such as Netscape, enter location "**telnet://ssd.jpl.nasa.gov:6775**". The system will start a terminal session automatically. No user-ID or password is required.

If a user-name/password is requested, the port number was not specified. A few PC-type telnet programs do not fully implement the telnet protocol and may not pass the port number to the network, or may need to be reconfigured to function properly, or may have a different syntax for specifying port numbers. Consult your system users's guide if there is a problem.

If there is a firewall restriction at your end, contact your local computer system administrator. Since no password or security information is exchanged, you may be able to request a firewall exception from your institution.

Once you connect, Horizons will also attempt to determine your window size. If it cannot, it will default to a 24 row by 79 column screen display. If this is inappropriate, and your display paging is choppy, manually set your screen size by using the command "TTY {rows} {columns}", where {rows} and {columns} are replaced by appropriate integers. **Window sizes less than 79 columns aren't recommended since data-screen displays are formatted with that minimum size in mind and may be difficult to read on something smaller.**

Access may be automated. Example scripts may be found in the anonymous FTP directory "ftp:// ssd.jpl.nasa.gov/pub/ssd" and include:

Automate SPK file production:
    ftp://ssd.jpl.nasa.gov/pub/ssd/smb_spk

Automate observer table production:
    ftp://ssd.jpl.nasa.gov/pub/ssd/obs_tbl
    ftp://ssd.jpl.nasa.gov/pub/ssd/obs_tbl.inp (sample input file for 'obs_tbl')

Automate osculating element table production:
    ftp://ssd.jpl.nasa.gov/pub/ssd/osc_tbl
    ftp://ssd.jpl.nasa.gov/pub/ssd/osc_tbl.inp (sample input file for 'osc_tbl')

WEB:

Point your browser to **http://ssd.jpl.nasa.gov/horizons.html.** This graphical interface is intended for the more casual user, or general public, and offers access to a subset of program features using pull-down menus, fill-in boxes and buttons to click. Verify default settings for time and coordinate systems are as intended for the run.

E-MAIL:

The program can also be controlled by sending e-mail messages to the program at the address "**horizons@ssd.jpl.nasa.gov**". Response is determined by the **subject** of the message you send. This method is for those who want access to program features without the overhead of answering prompts or manipulating graphical interfaces; generally those already familiar with what the program does and who know what they want. It has the additional capability of allowing users to specify up to 10000 discrete times (to aid astrometric reduction) and up to 200 objects at once. It does not allow SPK file production available via telnet.

To get started, send e-mail to the above address with the subject "BATCH-LONG". The latest, fully-commented example run-stream will be mailed back. Edit this file to produce the results you want, then mail back with the subject "JOB". Output is returned by e-mail. Recognized e-mail subject commands are:

SUBJECT HEADER	MEANING
JOB	Execute the following Horizons run-stream
BATCH-LONG	Retrieve latest fully commented example batch file
BATCH-BRIEF	Retrieve latest example batch file without comments
DOC-TEXT	Retrieve ASCII version of current documentation
DOC-PS	Retrieve PostScript version of current documentation
QUESTION	Message forwarded to cognizant engineer

2. GENERAL DEFINITIONS

RA

Right ascension; the angular distance on the celestial sphere eastward along the celestial equator from the reference equinox to the meridian of the object. RA is analogous to longitude, with the plane containing the equinox defining zero RA much as the Greenwich meridian defines zero longitude. Expressed in units of hours, minutes and seconds or degrees, as requested.

DEC

Declination; the angular distance on the celestial sphere north (positive) or south (negative) of the celestial equator. It is analogous to latitude. Usually expressed in degrees.

AZ

Azimuth; the angle measured eastward along the "horizon" (the plane perpendicular to the local zenith) from the North to the point where the meridian passing through local zenith and the object intersects the horizon plane.

EL

Elevation; the angular distance above or below the plane perpendicular to the local zenith.This plane is not necessarily the visible horizon, due to station elevation ("horizon dip" effect).

Geometric coordinates

Geometric coordinates are the true, or instantaneous states of a body at a particular ephemeris time.

Astrometric coordinates

Accounts for the finite but varying amount of time it takes light to travel from the target to the observer.

Apparent coordinates

Takes into account factors which appear to change target position with respect to the background stars and inertial coordinate system: light-time, stellar aberration, the relativistic deflection of light. Usually, a final rotation to some "of-date" coordinate system is performed, such as precession-nutation to Earth true-equator and equinox-of-date.

Refracted coordinates

Apparent coordinates approximately corrected for atmospheric refraction. Available for Earth-based sites only.

Small body

Refers to a comet or asteroid for which the trajectory is integrated from orbital elements. Typically no cartographic coordinate system is available, with the exceptions, so far, being Gaspra and Ida.

Major body

Refers to a spacecraft, planet, natural satellite, or the Sun. In special cases, a comet or asteroid can be redefined as a major body. Only major bodies can be coordinate centers (observing sites). State vectors are interpolated from previously defined ephemerides, such as DE-405 (or later), which are stored as Chebyshev coefficients. Interpolation recovers the integrator state to the mm level.

Target body

Refers to the object of interest, selected by the user. It can be a major-body or small-body.

Primary body

Refers to closest body about which a target body orbits. For natural satellites, this would be a planet, although they orbit the Sun as well. For planets and small-bodies, the primary body is the Sun.

Interfering body

The largest other body in the system. Such a body can visually complicate observations at the site due to its

brightness or by covering up the target. On the Earth, the "interfering body" is the Moon. On Io, it would be Jupiter. On Mars, it would be Phobos (largest body, though unlikely to genuinely interfere). Mercury and Venus have no interfering bodies.

Deflecting body

This is the Sun plus the most massive object in the planet/satellite system (e.g. the system barycenter). These two masses are used to compute the relativistic deflection of light that can change the apparent position of the target body.

3. OBJECT SELECTION

After connecting by telnet, the prinmary thing one has to learn to use Horizons effectively is how to select objects. You will be prompted for everything else.

There are two categories of objects to select:

1. MAJOR BODIES ... defined as planets, natural satellites, spacecraft,and some "special cases"
2. SMALL BODIES ... comets and asteroids.

This division is a result of the objects being stored differently. Major bodies are represented in pre-computed trajectory files which are interpolated very accurately to retrieve position and velocity at any instant. Small-bodies have their position and velocity at one instant (only) compactly stored in a database and are then numerically integrated "on-the-fly" by Horizons to other times of interest (also very accurately), using all known physics.

When an object is specified, the user's request is first examined for "keywords" that tell the system more about what is wanted. If there aren't any keywords, the system will then try to match against the major body list. If no match is found among the major bodies, it will then match against the small-body database.

For example, if you simply input "Io", it will return a list of matches from among the major bodies, including the moon of Jupiter, and then stop, waiting for a unique specification that matches just one object. To uniquely specify Io, enter it's IAU number, "501", which was displayed on the previous list of multiple matches.

To instead select the small-body named Io, provide more information by specifying it one of these ways:

Horizons> Io;	(semi-colon tells Horizons its a small-body look-up)
Horizons> 85	(no match on major body [at least right now], so search "falls through" to the small-body number look-up)
Horizons> 85;	(semi-colon tells Horizons its a small-body look-up)
Horizons> NAME= Io	(keyword "NAME" tells Horizons its an asteroid or comet small-body look-up)
Horizons> ASTNAM= Io	(keyword "ASTNAM" tells Horizons its an asteroid name)

Further details, discussion, and examples follow.

SELECTING MAJOR BODIES:

Type 'MB' as a command in the telnet system to obtain a general list of all major-body strings that can be used to search on. To select a major body, enter **one** of the following ...

     (1) String to search on ("Mars" or "Trit")
     (2) JPL ID integer code or fragment
     (3) An IAU code

Examples (at the main prompt):

Horizons> mars bary	(uniquely select Mars system barycenter; '4' does same)
Horizons> mars	(list all major bodies with 'mars' in an ID field)
Horizons> 501	(uniquely select Io)
Horizons> N*	(list all major bodies with 'n' in an ID field)

Major bodies names may have two associated integer ID's. Those >100, ending in 99 (such as 199, 299, 399, etc.) refer to planet CENTERS. To select planet SYSTEM BARYCENTERS, use the codes less than 10 (1, 2, 3).

For example, "399" specifies the Earth's center, "3" the Earth-Moon Barycenter and "301" the center of the Moon. For Mercury, Venus and Mars, there is no significant difference between planet-center and system barycenter (1=199, 2=299, 4=499).

If a planet name is entered, it may not be considered unique if a distinct system barycenter is defined. For example, if "Saturn" is entered, a list containing "Saturn" and the "Saturn Barycenter" will be returned (6 and 699). To specify Saturn (the planet-center), you must use its unique ID code, "699".

System barycenters are available over longer time-spans than planet-centers because planet-centers are defined relative to the barycenter by satellite solutions. These satellite solutions are based on shorter data arcs than the entire system and can therefore be extrapolated only over shorter time-spans. For example, the planet Jupiter (599) might be available over the interval 1600-2500, while the Jupiter system barycenter (5) is available over 3000 B.C. to A.D. 3000.

Surface Targets:

To specify an arbitrary target point on the surface of a major body having a defined shape and rotation model, the most general target specification form allows two types of coordinate-type inputs, both in units of degrees and km:

Geodetic/planetographic coordinatess:

{g: E.Long, latitude, h@}BODY

Or, in cylindrical coordinates:

{c: E.Long,   DXY, DZ@}BODY

... where the brackets {} indicate optional components of the general specification.

 For example, while "301" specifies the target to be the center of the Moon, and "Apollo 11 @ 301" specifies the Apollo 11 landing site as target,the following ....

g: 348.8, -43.3, 0 @ 301

... specifies the crater Tycho on the Moon (body 301), at geodetic (planetographic) coordinates 348.8 degrees east longitude, -43.3 degrees latitude (south), and zero km altitude with respect to the IAU reference triaxial ellipsoid surface.

To alternatively input cylindrical coordinates, DXY is distance from the spin axis in the body equator plane in km, DZ is distance above (+) or below (-) that plane, also in km.

When a surface target is specified, two new markers are placed in observer table output. They indicate if the point on the target surface is lit (by the Sun) and if it is on the near or far-side of the target body relative to the observer.

Altered descriptions are printed at the end of the tables as necessary to describe the output.

SELECTING SMALL BODIES (ASTEROIDS & COMETS):

To select an asteroid or comet, enter a list of parameters to search on **SEPARATED BY A SEMI-COLON** (;). Type 'SB' for a list of the 42 field keywords that can be matched or consult the list later in this document. Match symbols are from the set { >, <, <>, = }. For example, from the main prompt:

        Horizons> A < 2.5; IN > 7.8; STYP = S; GM <> 0;   (match parameters)
        Horizons> Vesta;   (or "ASTNAM = Vesta;" for faster search)
        Horizons> DES = 1993*;   (Objects with designations containing 1993)
        Horizons> 1;   (Object in file position #1)
        Horizons> ;   (Enter your own elements)

For example, "A < 2.5; IN > 7.8; STYP = S; GM <> 0; " searches for all S-type small-bodies with semi-major axis less than 2.5 AU and inclination greater than 7.8 degrees with a known (non-zero) GM. Spaces in the command are not considered, nor are upper/lower-case distinctions.

Exceptions are object names and designations. Name searches consider spaces. Designation searches consider spaces AND upper/lower-case. If you want to match a fragment of a name or designation, end it with a '*' (e.g. DES = 1993*;). Otherwise, it is assumed a complete name or designation is specified and the search must match exactly and completely. For example:

        NAME = CERES;   (matches only if object name is "Ceres")
        NAME = CER*;   (match "Ceres", "Lucerna", "Cicero", etc.)

The same keyword can be used more than once in a search command. For example, "IN > 10; IN < 20;" will list those objects possessing an inclination between 10 and 20 degrees. If the directive "LIST;" is in the search request, the matched parameters will be displayed. For example, "IN > 150; LIST" will display the inclination of each object with inclination greater than 150 degrees. If LIST is input on the command-line by itself, the default is toggled and matching quantities will be output without the need to specify the keyword on each subsequent search.

Once a small-body is uniquely identified, a screen of data will be displayed. **If more than one small-body matches given parameters, a list of matching objects is displayed. Individual objects from the matched list can then be requested by giving the displayed record number followed by a semi-colon.**

The command-line semi-colon is used to indicate a small-body request and resolve number ambiguities. For example, if you enter '1' you will select Mercury Barycenter. Enter '1;' to retrieve the small-body in record #1 (Ceres).

Osculating elements for more than one comet apparition may be listed ("apparition" refers to a particular perihelion passage), since out-gassing near perihelion can alter the orbit for each passage. Select an apparition from the list with the closest epoch prior to the date of interest for the ephemeris, or add the "CAP" directive to the search to automatically select the closest apparition of interest:

        CAP;   (return last apparition before the current date)
        CAP < JD#;   (return last apparition before the specified Julian Day Number)
        CAP < YEAR;   (return last apparition before the given integer year)

If the number after a '<' is less than 10000, it is assumed to be a year integer. Otherwise, the number is taken to be a Julian Day Number. If "CAP;" is specified, the search is automatically recognized as being a comets-only search.

The record (or file) number of unnumbered asteroids and comet apparitions should NOT be considered constants; they may change as the database is updated, until an updated small-body storage system is implemented.

 To enter your own heliocentric ecliptic elements, type ";" at the main prompt. This capability is described in more detail in a later section.

Example small-body queries follow. Where more than one example is given, the first is most likely to complete as intended. For example, "ASTNAM = Vesta;" will always return the asteroid while, if the more convenient and permitted form "Vesta" is used, it is possible that a future natural satellite name will someday include that string and there will no longer be a unique match. A good habit is to include at least one semi-colon in all small-body searches to be most specific when looking for a comet or asteroid.

Search for objects matching a set of parameters:

    Horizons> A < 2.5; IN > 7.8; STYP = S; GM <> 0;   (asteroid & comets)
    Horizons> A < 2.5; IN > 7.8; STYP = S; GM <> 0; AST;   (asteroids only)
    Horizons> A < 2.5; IN > 7.8; STYP = S; GM <> 0; COM;   (comets only)

Match by exact name:

    Horizons> ASTNAM= Vesta;
    Horizons> Vesta;
    Horizons> Vesta

Match by name fragment:

    Horizons> NAME= Cer*;
    Horizons> Cer*;

"Wildcard" match designation:

    Horizons> DES = 1993*; (match all objects with designations containing 1993)
    Horizons> 1993*;
    Horizons> 1993*

NOTE: The '*' must be at the end. It toggles searches on sub-strings of characters and is not a true positional or "regular expression" wildcard. For example, '19*3;' is not a recognized search in Horizons.

Match exact designation:

    Horizons> DES= 1990 MU;
    Horizons> 1990 MU;
    Horizons> 1990 MU

Select numbered asteroid:

    Horizons> 1;   (Object in database record #1 ["1 Ceres"])

Define an arbitrary object not in database:

    Horizons> ;

Comet searches:

    Horizons> COMNAM= HER*;   (Comet names (only) containing "her")
    Horizons> DES= 73P;   (Request comet 73P apparitions, includingfragments, if any)
    Horizons> DES= 73P; NOFRAG   (Request apparitions of comet 73P, excluding fragments)
    Horizons> DES= 73P; CAP   (Request comet 73P apparition solution closest to present date, including any fragments)
    Horizons> DES= 73P; NOFRAG; CAP   (Request comet 73P apparition solution closest to present date, excluding any fragments)
    Horizons> COM; NOFRAG; CAP   (List the apparition solutions closest to the present date for all comets, excluding fragments)
    Horizons> NAME=Halley;CAP<1690; (Request last Halley apparition solution prior to the year 1690)

SPACECRAFT TRAJECTORIES IN HORIZONS

Horizons was generally intended to make the natural-body dynamics work of the JPL Solar System Dynamics Group accessible to astronomers and mission planners. However, it is often convenient to make spacecraft trajectory information available through the same mechanism, especially for space-based telescopes.

Sources of the spacecraft trajectory data in Horizons include navigation teams at JPL, flight projects at other NASA centers, ESA, as well as TLE-based orbits from the Joint Space Operations Center (JSOC).

While Horizons will always have the latest comet/asteroid/natural satellite solutions, keeping current with the externally produced spacecraft trajectories is problematic; there is no mandate or funding or staff for this, and maneuvers and mission planning changes can occur without notification.

Some flight projects do set up a regular delivery schedule to keep Horizons current (some mission science teams use Horizons for planning). More typically, a spacecraft is added if its inclusion is requested by a researcher with a specific need. The flight project might provide on request an initial planning trajectory prior to launch and a final historical trajectory after end of mission.

This is often sufficient for spaceraft in interplanetary phases, since the spacecraft are maneuvered to such reference trajectories, which are often designed years in advance.

However, spacecraft trajectories can get 'orphaned' in Horizons if updates stop happening. Always check the revision date in the upper left corner of the Horizons spacecraft datasheet to determine the last time the spacecraft's trajectory was updated, and read the data-sheet comments for mission status information.

Spacecraft in low Earth orbit in particular (such as ISS, HST, Swift, GALEX) need frequent updates to maintain high accuracy. Predicts more than a few days into the future can have 10s or 100's of km of error. If more accurate predicts are needed, and the last update was more than a few days ago, an update to Horizons can be done on request.

For interplanetary missions, users having high-precision applications (such as mission data reduction) should contact JPL Solar System Dynamics to verify the status of the specific trajectory in Horizons if there is doubt as to the available trajectory's revision status:

> Donald.K.Yeomans@jpl.nasa.gov (Supervisor, 818-354-2127)
> Jon.D.Giorgini@jpl.nasa.gov   (SSDG analyst)

Some archival mission trajectories are available. These spacecraft trajectories are often expressed relative to older, target-body trajectories such that multi-km offsets can appear if output is instead requested relative to a modern target-body trajectory. This is because the modern solutions are derived from different measurement datasets and dynamical models (planetary ephemerides), introducing inconsistencies.

To avoid this, Horizons usually includes the original mission-target ephemeris to permit consistent reconstruction with the archived spacecraft trajectory.

For example, the NEAR spacecraft trajectory during the Eros mapping phase was expressed relative to the asteroid Eros within the dynamical system of the DE200 planetary ephemeris, and has not been updated, while Eros' trajectory is now expressed in Horizons relative to the Sun in the system of the DE405 planetary ephemeris.

To obtain the historically accurate position of NEAR with respect to Eros as it was during the mission, select the archived Eros trajectory along with the archived NEAR trajectory. How to do this is explained in the Horizons data-sheet for NEAR, but amounts to specifying the SPK ID of the archived target body instead of integrating it from the database of orbital elements.

For example, to obtain historical spacecraft ephemerides of ....

1) NEAR wrt historical Eros orbit solution (#177):
Specify target as "NEAR" with observing center "@2000433"

2) NEAR wrt current Eros orbit solution:
Not available

3) Eros historical orbit solution (#177) wrt to NEAR:
Specify target as "2000433" with observing center "@NEAR"

4) Eros current orbit solution wrt NEAR (offset wrt to historical):
Specify target as "Eros;" or "2000433;", observing center "@NEAR"

4. COORDINATE CENTER (OBSERVING SITE) SELECTION

While osculating element tables may be generated with respect to a major body center only, vector and observer tables may additionally be produced with respect to an arbitrary observing site, defined with respect to a major body center.

EARTH SITES

For the Earth, a list of 1500+ sites is predefined. The list generally matches that of the Minor Planet Center, expanding on radar sites (which have negative ID numbers on this system) as necessary. Station "500" is the geocenter.

NON-EARTH SITES

For non-Earth major bodies, station 500 also represents the body center. For those major bodies with IAU rotational models, additional topocentric sites may be defined. Spacecraft landing sites are typically predefined on non-Earth bodies.

USING A PREDEFINED SITE

There are several equivalent ways of specifying a location. The most general form is ...

site @ body

... where "site" is a numeric code or name fragment to match, and "body" is a numeric major body code or name fragment to match. A list of major body codes follows later in this document.

Here are four equivalent ways of searching for the same Earth location:

Code	Meaning
675@399	Site #675 on Earth (Palomar Mountain)
palomar@399	"
675@	"
Palomar	" (observer table only)

If an observer table has been requested, the @ may be dropped; the Earth will be assumed if an integer like "675" or a name fragment like "Palom" is input. For a vector table, the DIFFERENT assumption is made that a coordinate center request lacking a "@" symbol is a major body. For example, '10' would mean the Caussols site for an observer table, but "Sun" for a vector table. '10@' or '10@399' would mean the Caussols site for both table types.

If your specification returns more than one possible match, the list of matched sites is returned. Refine your site request to be more specific, by using numeric codes for example, and try again.

While one can spell out the names of the bodies and sites, it is possible unique matches won't be returned. Thus, use the unique ID numbers when known. For example, "675@Earth" will first look for the body, find both the Earth & Earth-Moon barycenter, thus have to quit before finding specific Palomar site coordinates. "675@399" is unique and avoids this problem. Spaces & upper/lower case are ignored.

Here are examples for sites on bodies other than the Earth:

Code	Meaning
Viking@499	List all defined Viking lander sites on Mars
Viking 1@499	Select Viking 1 landing site on Mars
1 @301	Site #1 on the Moon
500 @ 501	Io body center
3 @ 499	Site #3 on Mars

The asterisk ('*') can be used to generate lists:

Code	Meaning
*@301	List all predefined sites on the Moon
*@Phobos	List all predefined sites on the Martian moon Phobos
*@399	List all predefined sites on Earth
*@	List all predefined sites on Earth (observer/vector table)
*	List all predefined sites on Earth (observer/vector table)
*	List all major bodies (element table only)

There are a several ways to request a body-centered site for a major body. For example:

Code	Meaning
500@601	Mimas body center
geo@601	"
g@601	"
g@Mimas	"
500@Deimos	Deimos body center
geo	Earth Geocenter
g@399	Earth Geocenter

INPUT OF TOPOCENTRIC SITE COORDINATES

Many small or recently discovered natural satellites do not have defined rotation models, thus do not support topocentric site definition. Only body-centered observers can be defined.

However, for sites with IAU rotation models, topocentric sites may be input by the user as follows:

Code	Meaning
c @ Europa	Request prompting for user location on satellite Europa
coord @ 502	(same)

After coordinate input is requested, the site location may be entered as either geodetic or cylindrical coordinate triplets, separated by commas:

GEODETIC (generally this means map coordinates)
- E-long - Geodetic east longitude (DEGREES)
- lat - Geodetic latitude (DEGREES)
- h - Altitude above reference ellipsoid (km)

CYLINDRICAL
- E-long - Angle eastward from XZ plane (DEGREES)
- DXY - Distance from Z axis (KM)
- DZ - Height above XY equator plane (KM)

This system always uses planetographic/geodetic coordinates. This is typically the one used on maps, such as those by the USGS, unless the map says otherwise. In these coordinates, the rotational pole of the body that lies on the positive (north) side of the invariable plane of the solar system (the plane perpendicular to the solar system's angular momentum vector) is called the "north pole".

Northern latitudes are positive, southern are negative. The planetographic latitude takes into account body oblateness and, for a point on the surface, is the angle between the body equatorial plane and the normal to the reference surface at that point. For a point not on the reference surface, the geodetic latitude is the latitude of the point on the reference surface where the normal passes through the point at some altitude (h) above the reference surface.

Prograde (or direct) rotation of a body is rotation eastward, or counter-clockwise, as seen from the north pole. For such bodies, east longitude is measured negatively to the east (0 to -360 degrees) from the prime meridian. Retrograde rotation is rotation clockwise (westward) as seen from the north pole. East longitude is measured positively to the east (0 to 360 degrees) from the prime meridian.

Exceptions are the Earth, Moon and Sun where longitude has historically been measured both east and west of the prime meridian 0 to 180 degrees. Though these bodies are direct rotators, longitude is nonetheless measured positively to the east on this system, 0 to 360 degrees, due to historical precedence. If the positive west longitude of a site on these 3 bodies is given, it should be input here as positive east longitude, which would be (360 - West Longitude). If the negative east longitude is given instead, input (360 + East Longitude).

The following major bodies are either retrograde or exceptions and require site input with positive east longitude:

Retrograde (+ east longitude):

Venus (299), Arial (701), Umbriel (702), Titania (703),
Oberon (704), Miranda (705), Cordelia (706), Ophelia (707),
Bianca (708), Cressida (709), Desdemona (710), Juliet (711),
Portia (712), Rosalind (713), Belinda (714), Puck (715),
Uranus (799), Pluto (999), Charon (901)

Also + east longitude (prograde exceptions):

Sun (10), Earth (399), Moon (301)

All others are prograde and must be input with negative longitude east of the adopted prime meridian. Since such sites are usually expressed in terms of positive west longitude on maps, negative east longitude would be ...

(West longitude - 360)

INTERPRETING NON-EARTH OBSERVER TABLES

When placing a site on a body other than the Earth, some definitions become useful:

Visually interfering body:

The largest other body in the system. Such a body can visually complicate observations at the site due to its brightness or by covering up the target. On the Earth, the "interfering body" is the Moon. On Io, it would be Jupiter. On Mars, it would be Phobos (largest body, though unlikely to genuinely interfere). Mercury and Venus have no interfering bodies.

Observer tables provide some optional quantities that can be used to characterize the effect of the interfering body (or IB): how far is the target from the IB in the plane-of-sky, is it obscured by the IB, what fraction of the IB is lit by the Sun as seen from the observing site, and so on.

Deflecting body:

This is the Sun PLUS the most massive object in the planet/satellite system (e.g. the system barycenter). These two masses are used to compute the relativistic deflection of light that can change the apparent position of the target body.

Other changes:

REFRACTION

There are no refraction effects modeled for non-Earth sites. Any request for refraction is ignored and the refraction angle will be zero. This affects rise-set determination on non-Earth bodies as well.

AIRMASS

There is no airmass model or airmass cut-off available for non-Earth sites. Any request for airmass computation is ignored.

APPARENT RA & DEC

The origin of Right Ascension for apparent coordinates on NON-EARTH sites with rotational models is the meridian containing the Earth equinox of J2000.0. Apparent declination is with respect to the particular body's true equator-of-date. This allows an observer to align axes with the pole and use the local apparent sidereal time output by this system to set the RA origin and acquire the target.

For objects lacking a pole & prime meridian rotational model (spacecraft and certain asteroids that may have been redefined as "major bodies"), the reference frame (ICRF or FK4/B1950.0) coordinate system is used to compute apparent places. That is, apparent RA and DEC are defined with respect to the Earth mean-equator and equinox of the frame epoch.

TIME

The print-time output by this system for observer tables (UT or TT) is the instantaneous time on Earth. For non-Earth sites, it is unrelated to the rotation of the body. Local apparent solar time at the observing site can be requested, as can the instantaneous light time from Earth to the non-Earth site.

LIMITATIONS OF NON-EARTH/MOON ROTATION MODELS

For bodies outside the Earth-Moon system, precession and nutation effects are usually not known to high accuracy. Thus, the **non-**Earth/Moon IAU rotation models, used by this system to determine topocentric site motion relative to the inertial frame as a function of time, are good to about 0.1 degree in the present era.

For many satellites, the official IAU pole direction was simply assumed perpendicular to the body's mean orbit plane, lacking better information. For many satellites in the IAU model, the rotation rate was assumed equal to the mean orbital period.

Some small satellite rotational models are strictly valid only at the time of the Voyager spacecraft flyby; extrapolation to other times is hazardous. Topocentric results for such bodies (610-614, for example) should be used cautiously if at all. Results in these cases reflect only the best available model, which is a suspect one.

As rotation models are refined through observation of surface features by visiting spacecraft (Cassini, etc.), Horizons will be updated to use the best officially sanctioned models available.

5. OTHER COMMANDS

For the telnet interface:

Program information:
- MB .... — Show planet/natural-satellite (major-body) ID fields.
- SB .... — Show small-body search-field names & meanings.
- NEWS .... — Display program news (new capabilities, updates, etc.).
- ?! .... — Extended help ('?' for brief help).

Program controls:
- LIST .... — Toggle display of small-body match-parameter values.
- PAGE .... — Toggle screen paging (scrolling) on or off.
- EMAIL {X}.... — Set your email address to {X} for output delivery.
- TTY {R} {C}.. — Check or reset screen size; "tty" or "tty 24 79" to set.
- X .... — Exit JPL on-line system (also "QUIT" or "EXIT").
- - .... — Return to the previous prompt (back-up!).

Storing format default settings:
- LOAD {macro} .... — Load previously SAVED output-format {macro}.
- SAVE {macro} ...... — Save/replace output-format macro with current settings.
- DELETE {macro} .. — Delete previously saved output-format macro.

Useful short-cuts:

1) Move backward through the prompts by typing "-".

2) Quit from any prompt by entering 'q'.

3) To use a default, or previously entered value, press return.

4) After selecting an object, enter "e+" to produce an ephemeris
   format like the last one, without additional prompting.

6. SAVING PROGRAM SETTINGS

Telnet (interactive) users may go through program options once, then save all settings for recall during future sessions. This can save time, by reducing the the time devoted to changing the same defaults or routinely defining the same output format each time you connect. Others in your organization may load and use the same pre-defined format settings by name.

To save program settings, go through the prompts and define the settings as you require. Then return to the main "Horizons>" prompt.

    #1) Type "SAVE {NAME}", where {NAME} contains 1-12 characters.
    #2) Input a password that allows you to later DELETE or REPLACE the macro
    #3) Next time you telnet to Horizons, type "LOAD {NAME}".

Your output preferences will then be loaded in as the new defaults.

If a mistake is made, or it is desirable to change a setting later, two commands are relevant: DELETE and SAVE

DELETE a macro with command "DELETE {NAME}". Alternatively, change specific settings manually, then replace the stored macro with a SAVE to an existing name. Delete and replace operations require input of a confirming password. LOAD does not. Thus, anyone can use your settings if they know the macro name. Only those who know the password can change or delete a macro.

Start/stop dates are also saved in the macro, as is observing location. You need only load the macro and select the target. Remaining defaults will be as defined in the format macro. If the macro is for an individual (personal use), you may want to set the e-mail address prior to saving. Otherwise don't, so users of the macro will be prompted for it in the future.

A macro may be loaded, then specific settings overruled by responding to the program prompts. For example, if your last table prior to saving the macro was a "vector" table, that table type will be saved as the default.

Settings for the other table types are saved as well so, to access them, manually respond to the prompt requesting table type, over-riding the macro's "vector" default on that issue. Start and stop times are also macro settings that may commonly be overruled as necessary.

Ideally, macro names would be something clean and logical:

    "OBS670-1" for macro #1 for Observatory Code 670, etc.

    ... but the name is up to you.

The use of macros may make it less likely to stumble upon new capabilities as they are added, though they will described here and in the system news, as necessary.

7. INTEGRATOR DISPLAY

Comet and asteroid ephemerides are integrated from initial conditions called "osculating elements". These describe the 3-dimensional position and velocity of the body at a specific time. The integrator starts with this state and takes small time steps, summing the perturbing forces at each step before taking another step. A variable order, variable step-size integrator is used to control error growth. In this way, the gravitational attraction of other major solar system bodies on the target body trajectory is taken into account.

The integrator will thus start at the epoch, or time, of the osculating elements. It then integrates forward or backward, as necessary, to the start of the requested table. Once it reaches the table start time, it may have to reverse direction and go forward in time to generate the table.

Every 50th step will be displayed so one can get some sense of the progress of the ephemeris. Direction reversals are also displayed. If you request output at small time intervals, the integrator may proceed rapidly to the start of your table. There may then be long (apparent) pauses, as numerous interpolations within a given integration step are performed to compute states at closely spaced print times.

The last number on the integrator display line is the most recent step size in days.

8. SPECIFICATION OF TIME

ACCEPTED FORMATS:

        Time may be specified many ways, in addition to the primary form "YYYY-MMM-DD HH:MM". Of particular note are Julian day number and day-of-year forms. Input start times may be specified to 1/1000th of a second. Examples are shown below.

        Generally, if the input start time has more digits of precision specified than the output format selected, start time will be truncated to the appropriate level. For example, if a start time of 23:45:12.4 is specified, but the output format is set to minutes, start time will automatically be changed to 23:45(:00.000).

	User Input	Program Interpretation
Recommended:	1997-May-5 12:30:23.3348	(5 MAY 1997 12:30:23.334)
Acceptable:	1/9/96 3 12 59.2	(9 JAN 1996 03:13)
	1 9 96 3,12,59.2	(9 JAN 1996 03:13)
	2 jan 91 3:00 12.2	(2 JAN 1991 03:00)
	91 MAR 10 12:00:00	(10 MAR 1991 12:00)
	29 February 1975 3:00	(1 MAR 1975 03:00)
	10 October 29 3:58	(29 OCT 2010 03:58)
	dec 31 86 12	(31 DEC 1986 12:00)
	86-365 // 12	(31 DEC 1986 12:00)
	JUL 98	(1 JUL 1998 00:00)
	JD 2451545.	(1 JAN 2000 12:00)
	JD2451545.	(1 JAN 2000 12:00)
	278bc-jan-12 12:34	(B.C. 12 JAN 278 12:34)
	AD 99-Aug-12 12:34	(A.D.12 AUG 99 12:34)
	bc 278-Jan-12 12:34	(B.C. 12 JAN 278 12:34)

        The program will interpret other forms as well, but if you get too casual, you may end up with a surprise interpretation.

        The program's time-span prompts indicate the earliest & latest dates that may be used for the selected target/ center combination, as well as the type of time assumed being input (UT, CT, or TT).

        For cartesian coordinates or osculating elements tables, only CT may be used. For "observer tables", output may be either UT or TT. **To change the UT default for <u>observer tables</u>, append a "TT" when entering the <u>START</u> time. To switch back, append a "UT" to the start time.**

The three time systems are described as follows:

     CT: Coordinate Time. typically for cartesian and osculating element tables. The uniform time scale, or independent variable, of the ephemerides. CT is the same as the IAU's current TDB time-scale ("Barycentric Dynamical Time").

     TT : Terrestrial (Dynamic) Time. Called TDT prior to 1991. Used for observer quantity tables. This is proper time as measured by an Earth-bound observer and is directly related to atomic time, TAI. TT periodically differs from CT by, at most, 0.002 seconds.

     UT: Universal Time. This can mean one of two non-uniform time-scales based on the rotation of the Earth. For this program, prior to 1972, UT means UT1. After 1972, UT means UTC or "Coordinated Universal Time". Future UTC leap-seconds are not known yet, so the closest known leap-second correction is used over future time-spans.

TIME ZONE CORRECTIONS

Output time-tags may also be in local civil time. When specifying start time, enter your time-zone correction in the format:

YYYY-Mon-Dy HH:MM UT{s}HH{:MM}

... where

{s} .... optional sign (+ or -). If unspecified, it is assumed "+".
HH .... integer hours time-zone difference from UT
{:MM} .... optional minutes offset (usually 0)

North American standard time (winter) zone corrections are as follows:

Atlantic Standard Time (AST)   = UT-4 hours
Eastern Standard Time (EST)   = UT-5 hours
Central Standard Time (CST)   = UT-6 hours
Mountain Standard Time (MST)   = UT-7 hours
Pacific Standard Time (PST)   = UT-8 hours

If daylight savings is in effect (summer), add one hour to above offsets. For example, "1999-jun-2 12:30 UT-8" produces a table in Pacific Standard Time. A "-7" would provide Pacific Daylight Time (or MST, if it is winter).

GREGORIAN AND JULIAN CALENDAR DATES

Input calendar dates 1582-Oct-15 and after are taken to be expressed in the extended Gregorian calendar system. Prior dates are assumed to be in the Julian proleptic calendar. Historically, not all regions switched calendars at the same time (or even in the same century). Thus, the user must be aware of which calendar was in effect for a particular historical record. It should NOT be assumed this system's calendar automatically correlates with a date from an arbitrary historical document.

Here is the progression near the calendar switch point. Note that Julian calendar dates are different than (and unrelated to) Julian day numbers.:

Calendar Type	Calendar Date	Julian Day Number
Julian	1582-Oct-03	2299158.5
Julian	1582-Oct-04	2299159.5 ---------->
(skipped)	"1582-Oct-05"	2299160.5 |
(skipped)	"1582-Oct-06"	2299151.5 |
(skipped)	"1582-Oct-07"	2299152.5 |
(skipped)	"1582-Oct-08"	2299153.5 |
(skipped)	"1582-Oct-09"	2299154.5 |
(skipped)	"1582-Oct-10"	2299155.5 |
(skipped)	"1582-Oct-11"	2299156.5 |
(skipped)	"1582-Oct-12"	2299157.5 |
(skipped)	"1582-Oct-13"	2299158.5 |
(skipped)	"1582-Oct-14"	2299159.5 |
Gregorian	1582-Oct-15	2299160.5 <---------
Gregorian	1582-Oct-16	2299161.5
Gregorian	1582-Oct-17	2299162.5

Examination of this table shows that the date labels from Oct 5, 1582 through Oct 14, 1582 don't exist. Of course, the days themselves do, as is shown in the continuous Julian day number column; it's just a matter of what one calls them. If a non-existant calendar date label is specified, this program will automatically use a day number, as shown above, that maps into the previous Julian calendar system. For example, requesting a date of 1582-Oct-14 (skipped) is the same as requesting the Julian calendar date 1582-Oct-04.

ANCIENT DATES

Objects 0-10, 199, 299, 301, 399 and 499 (planet barycenters, their equivalents and the Sun & Moon) are available over a 3000 B.C. to A.D. 3000 interval. When specifying ancient calendar dates, this system requires input in the "BC/AD" scheme. If no "BC" marker is input with a calendar date, it is assumed to be "AD". Exceptions are AD years less than 100 which must have an AD symbol in the date in order to be recognized as a valid year. For example, "66ad-jan-27" will be accepted, but "66-Jan-27" cannot be parsed. On output, observer-table lines begin with a 'b' in column 1, to indicate B.C. dates, and a space (" ") to indicate A.D. dates.

In this system, there are no negative years. The progression is as follows:

Julian Day Number	Labeling-convention	
(Jan 1 00:00)	BC/AD	Arithmetical
1720327.5	3bc	-2
1720692.5	2bc	-1
1721057.5	1bc	0
1721423.5	1ad	1
1721788.5	2ad	2

From this, one can see that no days (in the arithmetical year "0", for example) are skipped in the BC/AD scheme, but they do have a different label than in the corresponding arithmetical system.

OUTPUT STEPPING:

Fixed time steps:
Output time steps are specified as integers with some associated units from the set {days, hours, minutes}. Example responses to the prompt include"30 days", "1 day", "10 min", and so on. To get half day steps, specify "12 hour".

It is possible to obtain output at less than 1 minute intervals (telnet & e-mail interfaces only). After specifying a start and stop time, give a positive integer as the "time-step" without giving units, such as"10". This will divide the time span into 10 parts. For example, if start and stop times are one hour (3600 seconds) apart, specifying a step of "240" will produce output every 15 seconds (3600/15 = 240 intervals). "3600" will produce output every second.

Rise/set and satellite eclipse circumstances may not be accurate to less than a minute since factors such as the primary's oblateness and atmosphere are not currently modelled.

Time-varying steps:
Output is typically at fixed time intervals. However, observer tables may additionally be requested at time-varying steps based on an angular shift specification. That is, "output only if the object has moved at least X arcseconds in the plane-of-sky".

When specifying the step-size, with the telnet or e-mail interfaces, respond with something like "VAR ####", where '####' is an integer from 60 to 3600 arcseconds. This will trigger output whenever the object's position is predicted to be '####' arcseconds different from the current output step in the observer's plane-of-sky.

To preserve system performance, the time-varying output mode uses a simple linear extrapolation to predict the time when the object should have moved the requested distance. Due to non-linearities in the object's actual motion in the plane-of-sky, this projection can be off by .1 to 5 (or more) arcsecs. Thus the angular-motion print criteria you give should be considered approximate.

Computed quantities will be exact for the given time in the output, but the particular output time may not be exactly that required for the requested angular change.

9. REFERENCE FRAMES

It is necessary to adopt a commonly agreed-upon coordinate system for describing the position and velocity of an object in three-dimensional space. This program has two basic frames available:

"J2000" refers to the frame of the current planetary ephemeris. This is closely aligned with the International Celestial Reference Frame (ICRF). The planetary ephemeris coordinates differ from ICRF by at most 0.001 arcseconds, while the ICRF is thought to differ from the FK5 optical catalog system by at most 0.01 arcseconds.

The planetary ephemeris (and ICRF) coordinate directions are defined purely with respect to external radio sources (quasars), but can be thought of as closely corresponding to these basis directions:

+Z coordinate is normal to Mean Earth Equator of Epoch J2000.0
+X coordinate is parallel to Mean Earth Dynamical Equinox of Epoch J2000.0
+Y coordinate completes the right-handed system

"B1950" selects an inertial reference frame based on Earth Mean-Equator and FK4 optical catalog Equinox of Epoch B1950.0 (FK4/B1950.0), where the Epoch of B1950.0 is the Julian date at the start of the Besselian year B1950.0 (2433282.42345905). The Fricke equinox correction at Epoch is applied.

10. Coordinate Systems

   Cartesian vectors and osculating elements may be requested in one of three available coordinates systems derived from the selected basic reference frame. These systems are defined with respect to the reference frames (above) as follows:

Earth mean equator and equinox of reference epoch ("frame"):
   Reference epoch: J2000.0 or B1950.0
   xy-plane : plane of the Earth's mean equator at the reference epoch
   x-axis : out along ascending node of the instantaneous plane of the Earth's orbit and the Earth's
        mean equator at the reference epoch
   z-axis : along the Earth mean north pole at the reference epoch

Ecliptic and mean equinox of reference epoch ("ecliptic")
   Reference epoch: J2000.0 or B1950.0
   xy-plane : plane of the Earth's orbit at the reference epoch
   x-axis : out along ascending node of instantaneous plane of the Earth's orbit and the Earth's mean
        equator at the reference epoch
   z-axis : perpendicular to the xy-plane in the directional (+ or -) sense of Earth's north pole at
        the reference epoch.

Body mean equator and node of date ("body")
   Reference epoch: "of date"
   Reference plane: ICRF or FK4/B1950.0
   xy-plane : central-body mean equator plane at reference epoch
   x-axis : out along the ascending node of the central-body mean equator plane on the reference plane at the
        reference epoch
   z-axis : along the central-body mean north pole at the reference epoch

Observer table coordinates, such as RA and DEC, may be with respect to two possible coordinate systems:

Earth mean equator and equinox of reference epoch (astrometric coordinates):
   Reference epoch: J2000.0 or B1950.0
   xy-plane : plane of the Earth's mean equator at the reference epoch
   x-axis : out along ascending node of the instantaneous plane of the Earth's orbit and the Earth's
        mean equator at the reference epoch
   z-axis : along the Earth mean north pole at the reference epoch

Earth true equator and equinox of date (apparent coordinates)
   Reference epoch: "of date"
   xy-plane: plane of the Earth's true equator at the reference epoch
   x-axis : out along ascending node of instantaneous plane of the Earth's orbit and the Earth's true equator
        plane at the reference epoch
   z-axis : along the Earth's true north pole at the reference epoch

11. SEARCHING FOR SMALL-BODIES

Search for small-bodies with following keywords (Type R=real, I=integer, C=char). Use comparisons from the set { <, >, <>, = }. **Separate each field with a semi-colon.** Example search formulation at main prompt:

A < 2.5; IN > 7.8; STYP = S; GM <> 0;

The first group of keywords are common to asteroids AND comets:

Type	Keyword	Description
C	NAME	Asteroid OR comet name fragment
C	DES	Object designation
R	EPOCH	Julian Date of osculating elements
R	CALEPO	Calendar date of osc. elements; YYYYMMDD.ffff
R	A	Semi-major axis (AU)
R	EC	Eccentricity
R	IN	Inclination of orbit plane (DEG) wrt ecliptic
R	OM	Longitude of Ascending Node (DEG) wrt ecliptic/equinox
R	W	Argument of Perihelion (DEG) wrt ecliptic/equinox
R	TP	Perihelion Julian Date
R	CALTP	Perihelion calendar date; YYYYMMDD.ffff
R	MA	Mean anomaly (DEG)
R	PER	Orbital period (YRS)
R	RAD	Object radius (KM)
R	GM	Object GM (KM^3/S^2), only a few are known
R	QR	Perihelion distance (AU)
R	ADIST	Aphelion distance (AU)
R	ANGMOM ...	Specific angular momentum (AU^2/DAY)
R	N	Mean motion (DEG/DAY)
R	DAN	Heliocentric dist. (AU) of ascending node
R	DDN	Heliocentric dist. (AU) of descending node
R	L	Ecliptic longitude of perihelion (DEG)
R	B	Ecliptic latitude of perihelion (DEG)
I	NOBS	Number of astrometric determinations in solution

The next parameters are ASTEROID SPECIFIC. If one or more is used, the search will conclude faster by examining asteroids only. For example, including something like "H > -10;" will limit search to asteroids only:

C	ASTNAM	Asteroid name fragment (designation if unnamed)
R	B-V	B-V color (asteroid)
R	H	Absolute magnitude parameter (asteroid)
R	G	Magnitude slope parameter; can be < 0 (asteroid)
R	ROTPER	Rotational period, hrs (asteroid)
R	ALBEDO	Geometric albedo (asteroid)
C	STYP	Spectral type, Tholen scheme (asteroid)

The next parameters are COMET SPECIFIC. If one or more is used, the search will conclude faster by examining comets only. For example, including something like "M1 > -10;' will limit search to comets only:

C	COMNAM	Comet name fragment (designation if unnamed)
I	COMNUM	Comet number
R	M1	Total absolute magnitude (comet)
R	M2	Nuclear absolute magnitude (comet)
R	K1	Total magnitude scaling factor (comet)

R	K2	Nuclear magnitude scaling factor (comet)
R	PHCOF	Phase coefficient for k2=5 (comet)
R	A1	Radial non-grav accel (comet), 10^-8 AU/DAY^2
R	A2	Transverse non-grav accel (comet), 10^-8 AU/DAY^2
R	A3	Normal non-grav accel (comet), AU/d^2
R	DT	Non-grav lag/delay parameter (comet), days

If one of the keywords 'ASTNAM', 'COMNAM', 'NAME' or 'DES' is used, no other parameter may be specified for that search.

Directives:

There are 5 directives that may be used to limit or control searches:

Directive	**Description**
COM	Limit search to comets only
AST	Limit search to asteroids only
LIST	Display parameter values for matched objects. (This may be set as a default for all subsequent searches by typing "LIST" at the main system prompt "Horizons>".)
NOFRAG	Exclude/skip comet fragments
CAP	Select the closest comet apparition of interest:

CAP;   (return last apparition before the current date)
CAP < JD#;   (return last apparition before the specified Julian Day Number)
CAP < YEAR; (return last apparition before the given integer year)

If the number after a '<' is less than 10000, it is assumed to be a year integer. Otherwise, the number is taken to be a Julian Day Number. If "CAP;" is specified, the search is automatically recognized as being a comets-only search.

For example,

"A < 2.5; IN > 10; AST;"	Match parameters against asteroids ONLY.
"A < 2.5; IN > 10; AST; LIST;"	Match AND display values of the parameters.
"NAME= Halley; CAP;"	Return latest apparition elements for Halley's comet

Contents of the Small-body Database:

Excluded from the database are single opposition asteroids with observational data arcs less than 30 days. Exceptions are NEO's, PHA's, TNO's, spacecraft targets, radar targets and periodic comets which are included immediately and updated on an hourly basis as new discoveries and observations are made and reported. Users can also input their own objects, as described in the next section.

Except for "PHA's" and NEOs, which are usually included within a couple hours of announcement, there can be a delay of a few days to a couple weeks before newly discovered objects (that meet the filter criteria) are added. Users can input their own objects, as described in the next section. The database is updated hourly with new objects and orbit solutions.

12. USER-SPECIFIED SMALL-BODIES

It is possible to define an object not in the database by inputting its **HELIOCENTRIC ECLIPTIC** elements and some other parameters. Type ';' at the main prompt to enter input mode. It is also possible to display a database object, then "cut-and-paste" elements back into the program, varying parameters (such as magnitude), as needed. Cut-and-paste is a function of your local terminal capability.

PRESS <return> ON A BLANK LINE WHEN DONE. Input format is:

    LABEL= VALUE   LABEL= VALUE ...
    LABEL= VALUE ...
        .
        .

... where acceptable label strings are defined as follows:

    EPOCH ...   Julian ephemeris date (CT) of osculating elements
    EC ....   Eccentricity
    QR ....   Perihelion distance in (AU)
    TP ....   Perihelion Julian date
    OM ....   Longitude of ascending node (DEGREES) wrt ecliptic
    W ....   Argument of perihelion (DEGREES) wrt ecliptic
    IN ....   Inclination (DEGREES) wrt ecliptic

Instead of {TP, QR}, {MA, A} or {MA,N} may be specified (not both):

    MA ....   Mean anomaly (DEGREES)
    A ....   Semi-major axis (AU)
    N ....   Mean motion (DEG/DAY)

Note that if you specify elements with MA, {TP, QR} will be computed from them. The program always uses TP and QR.

OPTIONAL INPUTS

    RAD ......   Object radius (KM)
    AMRAT ....   Area-to-mass ratio (m^2/kg). Total absorption is assumed, so scale the value to account for
                  reflectivity. For example, if 15% of light is reflected, specify a value for AMRAT in which the
                  actual value is multiplied by 1.15.

For asteroids, additional OPTIONAL parameters can be given:

    H ....   Absolute magnitude parameter (asteroid)
    G ....   Magnitude slope parameter; can be < 0 (asteroid)

For comets, additional OPTIONAL parameters can be given:

    M1 ....   Total absolute magnitude (comet)
    M2 ....   Nuclear absolute magnitude (comet)
    K1 ....   Total magnitude scaling factor (comet)
    K2 ....   Nuclear magnitude scaling factor (comet)
    PHCOF ...   Phase coefficient for k2=5 (comet)
    A1 ....   Radial non-grav accel (comet), AU/DAY^2
    A2 ....   Transverse non-grav accel (comet), AU/DAY^2
    A3 ....   Normal non-grav accel (comet), AU/d^2
    DT ....   Non-grav lag/delay parameter (comet), days

You may enter each value on a separate line or several on one line. If you make a mistake, re-entering the label on another line will over-ride the previously specified value. To erase a value, enter something like "H=", where

no value is given. To cancel all input, enter "-" as the first character on a line. To log-out, enter a "q" or "x" as first character on a line.

When done, after having pressed <return> on a blank line, you will be asked whether the reference frame of the elements is FK5/J2000.0 or FK4/B1950.0. You will also be asked the object name.

Here is an example of input to define a new object (in this case, a comet with out-gassing):

```
 EPOCH= 2450200.5
         EC= .8241907231263196 QR= .532013766859137 TP= 2450077.480966184235
         OM= 89.14262290335057 W = 326.0591239257098 IN= 4.247821264821585
         A1= -5.113711376907895D-10 A2= -6.288085687976327D-10
```

13. CUSTOMIZING REQUESTED EPHEMERIDES

Keys are embedded in output ephemerides to assist with automated reading of the output by user's own software. The keys are defined as follows:

$$SOE	Start of ephemeris
$$EOE	End of ephemeris

Ephemerides may be customized by changing output default flags. The '*' symbols below denote login defaults. All tables may be optionally output in a "comma-separated-value" format for import into spreadsheets.

1. **Cartesian state vector table** (Any object with respect to any major body site):

Reference frame:
* J2000 (ICRF)
  B1950 (FK4/B1950.0)

Coordinate system:
    Earth mean equator and equinox of reference system (J2000, B1950)
* Ecliptic and mean equinox of reference system (J2000 or B1950)
  Central body mean equator and node of date

Aberration corrections:
* NONE   (geometric state vectors)
  LT   (light-time)
  LT+S   (light-time & stellar aberration)

Units:
    KM and seconds
    KM and days
    AU and days

Quantities Output:

	Format	Output
	1	Position components {x,y,z} only
	2	State vector {x,y,z,vx,vy,vz}
*	3	State vector + 1-way light-time + range + range-rate
	4	Position + 1-way light-time + range + range-rate
	5	Velocity components {vx, vy, vz} only
	6	1-way light-time + range + range-rate

2. **Osculating elements table (**an object with respect to a planet, barycenter or the Sun):

   Note: In general satellite osculating elements output by Horizons should NOT be used to initialize a separate integration or extrapolation outside of Horizons. Such elements assume Keplerian motion (two point masses, etc.) which usually DOES NOT MATCH any kinematic model of the satellite orbit Horizons uses (which may be a precessing ellipse, for example). Extrapolation for satellites is better done using mean orbital elements at **http://ssd.jpl.nasa.gov.sat_elem.html**.

   Reference frame:
   *   J2000 (ICRF)
         B1950 (FK4/B1950.0)

   Coordinate system:
         Earth mean equator and equinox of reference system (J2000, B1950)
   *   Ecliptic and mean equinox of reference system (J2000 or B1950)
         Central body mean equator and node of date

   Units:
         KM and seconds
         KM and days
         AU and days

   *   Output quantities (fixed):
         JDCT   Epoch Julian Date (Coordinate Time)
         EC   Eccentricity
         QR   Periapsis distance
         IN   Inclination w.r.t. xy-plane (degrees)
         OM   Longitude of Ascending Node (degrees)
         W   Argument of Perifocus (degrees)
         Tp   Time of periapsis (users selects periapse-relative or absolute date)
         N   Mean motion (degrees/DU)
         MA   Mean anomaly (degrees)
         TA   True anomaly (degrees)
         A   Semi-major axis
         AD   Apoapsis distance
         PER   Orbital period

3. **Observer table (**any object with respect to major body center or observing site on any major body):

Default quantities that are output without request, as appropriate:
Time
Solar-presence
Lunar-presence (or rise/transit/set marker)

Selectable quantities. Output in order requested. No initial default exists. You will be prompted at least once. A detailed definition of these values follows, with the '*' symbols marking those quantities affected by user selection of airless or refraction-corrected apparent quantities. Quantities preceded by a '>' are statistical uncertainties that can be computed for asteroids and comets if a covariance is available, either in the database or supplied by the user. Numbers could change if new quantities are added:

1. Astrometric RA & DEC	15. Sun sub-longitude & sub-latitude	29. Constellation ID
*2. Apparent RA & DEC	16. Sub-Sun position angle & distance	30. Delta-T (CT - UT)
3. Rates; RA & DEC	17. North Pole position angle & distance	*31. Observer ecliptic lon. & lat.
*4. Apparent AZ & EL	18. Heliocentric ecliptic lon. & lat.	32. North pole RA & DEC
5. Rates; AZ & EL	19. Heliocentric range & range-rate	33. Galactic longitude & latitude
6. Satellite X & Y, pos. angle	20. Observer range & range-rate	34. Local apparent SOLAR time
7. Local apparent sidereal time	21. One-way (down-leg) light-time	35. Earth->obs. site light-time
8. Airmass	22. Speed wrt Sun & observer	>36. RA & DEC uncertainty
9. Visual mag. & surface brght.	23. Sun-Observer-Target ELONG angle	>37. Plane-of-sky error ellipse
10. Illuminated fraction	24. Sun-Target-Observer PHASE angle	>38. POS uncertainty (RSS)
11. Defect of illumination	25. Target-Observer-IB / IB_Illum%	>39. Range & range-rate 3-sigmas
12. Satellite angular separ/vis.	26. Observer-Primary-Target angle	>40. Doppler & delay 3-sigmas
13. Target angular diameter	27. Sun-Target pos. angle; radius & -vel.	41. True anomaly angle
14. Observer sub-lon & sub-lat	28. Orbit plane angle	42. Local apparent hour angle

... or select one of the pre-defined alphabetic formats below:

A = All quantities	B = Geocentric only	C = Small-body geocentric
D = Small-body topocentric	E = Spacecraft geocentric	F = Spacecraft topocentric

The alphabetic assignments specifically mean:

A = 1-42	B = 1-3, 6, 9-33,41	C = 1-3,9-11,13,18-29,33,36-41
D = 1-5,8-10,11,13,18-29,33-34,36-42	E = 1-3, 8,10,18-25,29,41	F = 1-5, 8,10,18-25,29,41-42

... with the small-body cases primarily skipping cartographic dependent quantities. Note that Ida and Gaspra are exceptions, having IAU-defined mapping grids, so that C & D options won't provide all available data for such objects. Below, a '*' indicates program initial defaults:

Reference frame:
* J2000 (ICRF)
B1950 (FK4/B1950.0)

Time scale:
* UT (Universal Time)
TT (Terrestrial Time)

* Time zone correction (used for UT-based output only); default = +00:00

Time format
* Calendar
JD (Julian date)
Both

Time output precision (calendar format only)
*   MINUTES (HH:MM)
     SECONDS (HH:MM:SS)
     FRACSEC (HH:MM:SS.fff)

Right-ascension format
*   Hours, minutes, seconds of arc (DEC degrees, minutes, seconds)
     Decimal degrees

High-precision RA/DEC output
*   No (~ 10^{-2} arcsec; HH MM SS.ff DD MM SS.f)
     Yes (~ 10^{-4} arcsec; HH MM SS.ffff DD MM SS.fff)

Apparent coordinate corrections
*   Airless apparent
     Refracted apparent

*   Minimum elevation (integer values only); default = -90 degrees (no cut-off)

*   Maximum airmass (real value); default = -38.0 (no cut-off)

*   Rise/Transit/Set (RTS) ONLY print; default= NO

Skip Daylight Print
*   No
     Yes

*   Solar Elongation Angle Cut-off; default= 0, 180.0 degrees (no cut-off)

Comma-separated-value spreadsheet output
*   No
     Yes

14. DEFINITION OF OBSERVER TABLE QUANTITIES

The menu of observer table output quantities was shown above. The format of the table is as follows. "Labels" refers to possible column headings:

TIME

One output line for each step. The line begins with a 'b' if the date is BC, a blank (" ") if AD. This is followed by the date and time, which is either UT or TT, in calendar or JD format (or both), depending on user defaults.

SOLAR PRESENCE

Time tag is followed by a blank, then a solar-presence symbol:

'*' Daylight (refracted solar upper-limb on or above apparent horizon)
'C' Civil twilight/dawn
'N' Nautical twilight/dawn
'A' Astronomical twilight/dawn
' ' Night OR geocentric ephemeris

INTERFERING BODY/LUNAR PRESENCE

The solar presence symbol is immediately followed by another marker symbol:

'm' Refracted upper-limb of Moon/IB on or above apparent horizon
' ' Refracted upper-limb of Moon/IB below apparent horizon OR geocentric ephemeris
'r' Rise   (target body on or above cut-off RTS elevation)
't' Transit (target body at or past local maximum RTS elevation)
's' Set   (target body on or below cut-off RTS elevation)

The 'rts' codes will be displayed under two conditions only: if the print interval is less than or equal to 30 minutes or the RTS-only print option has been selected.

For non-Earth observing sites, no twilight/dawn codes (C, N, or A) are output, refraction is not modelled and the interfering body marker is 'x' instead of the 'm' reserved for Earth's Moon.

NOTE: "n.a." is output if a requested quantity is not available for selected object. For example, azimuth and elevation for a geocentric ephemeris.

STATISTICAL UNCERTAINTIES

Asteroid and comet output can include formal +/- 3 standard-deviation statistical orbit uncertainty quantities if a covariance is available. Such output indicates there is a 99.7% chance the actual value is within given bounds. These statistical calculations assume observational data errors are normally (randomly) distributed. If there are systematic biases (such as timing, reduction or star-catalog errors), results can be optimistic. Because the epoch covariance is mapped using linearized variational partial derivatives, results can also be optimistic for times far from the solution epoch, particularly for objects having close planetary encounters.

QUANTITY DEFINITIONS

1. Astrometric RA & DEC
Adjusted for light-time only. With respect to the Earth mean equator and equinox of the reference Epoch. If FK4/B1950.0 frame output is selected, elliptic aberration terms are added.

Labels: R.A._(ICRF/J2000.0)_DEC   (HMS/DMS format)
R.A._(FK4/B1950.0)_DEC   (HMS/DMS format)
R.A._(J2000.0)_DEC.   (degree format)
R.A._(B1950.0)_DEC.   (degree format)

2. Apparent RA & DEC
Apparent right ascension and declination of the target with respect to the center/site body's true-equator and Earth equinox of-date. For non-Earth sites with rotational models, the origin of RA is the meridian containing the Earth equinox of J2000.0. For non-Earth sites without rotational models, RA and DEC are with respect to the REFERENCE FRAME (FK4/B1950 or ICRF/J2000.0) coordinate system. Adjusted for light-time, the gravitational deflection of light, stellar aberration, precession and nutation. There is an optional (approximate) correction for atmospheric refraction (Earth only).

Labels: R.A._(a-apparent)__DEC.   (airless, HMS/DMS format)
R.A._(r-apparent)__DEC.   (refracted, HMS/DMS format)
R.A._(a-appar)_DEC.   (airless, degrees format)
R.A._(r-appar)_DEC.   (refracted, degrees format)

3. Rates; RA & DEC
The rate of change of apparent RA and DEC (airless). d(RA)/dt is multiplied by the cosine of the declination. Units are ARCSECONDS PER HOUR.

Labels: dRA*cosD d(DEC)/dt

4. Apparent AZ & EL
Apparent azimuth and elevation of target. Adjusted for light-time, the gravitational deflection of light, stellar aberration, precession and nutation. There is an optional (approximate) correction for atmospheric refraction (Earth only). Azimuth measured North(0) -> East(90) -> South(180) -> West(270). Elevation is with respect to plane perpendicular to local zenith direction. TOPOCENTRIC ONLY. Units: DEGREES

Labels: Azi_(a-appr)_Elev   (airless)
Azi_(r-appr)_Elev   (refracted)

5. Rates; AZ & EL
The rate of change of apparent azimuth and elevation (airless). d(AZ)/dt is multiplied by the cosine of the elevation angle. TOPOCENTRIC ONLY. Units are ARCSECONDS PER MINUTE.

Labels: dAZ*cosE d(ELV)/dt

6. X & Y satellite offset & position angle
Satellite differential coordinates WRT the central body along with the satellite position angle. Differential coordinates are defined in RA as X=[(RA_sat - RA_primary)*COS(DEC_primary)], and in DEC as Y=(DEC_sat-DEC_primary). Non-Lunar satellites only. "SatPANG" is CCW angle from the North Celestial Pole to a line from planet center to satellite center. Units: ARCSECONDS (X & Y) and DEGREES (position angle)

Labels: X_(sat-primary)_Y SatPANG

7. Local Apparent Sidereal Time
        The angle measured westward in the body true equator-of-date plane from the meridian containing the body-fixed observer to the meridian containing the true Earth equinox (defined by intersection of the true Earth equator of date with the ecliptic of date). For non-Earth sites, a somewhat different definition is used. The value returned is measured from the observer meridian to the meridian containing the Earth equinox of the J2000.0 system. TOPOCENTRIC ONLY. Units are HH MM SS.ffff or decimal hours (HH.fffffffffff)

        Labels: L_Ap_Sid_Time

8. Airmass
        Relative optical airmass; a measure of extinction. The ratio between   the absolute optical airmass at target refracted elevation to the absolute optical airmass at zenith. Based on work of Kasten and Young (Applied Optics, vol. 28 no. 22, 15-Nov-1989). TOPOCENTRIC, ABOVE HORIZON ONLY.   Unitless.

        Labels: a-mass

9. Visual magnitude & Surface Brightness
        Approximate (apparent) visual magnitude & surface brightness, where surface brightness is the average visual magnitude of a square-arcsecond of the illuminated portion of the apparent disk).

Planets & satellites: Value for Pluto includes Charon. The Sun's altitude above the Saturn ring-plane is not considered for Saturn. When the Moon is at phase angles < 7 deg. (within 1 day of full), the computed magnitude tends to be ~ 0.12 too small. For observing sites not on the Earth or Moon, planet and satellite magnitudes are not available (but Sun, comet and asteroid values are). For planets and satellites, values are available only for solar phase angles in the range generally visible from Earth. This is to avoid extrapolation of models beyond their valid (data-based) limits.

 Asteroids & comets: Surface brightness is returned for asteroids only if a radius is known. Magnitudes are, in principle, accurate to about +/- 0.1 magnitude. However, measurement and calibration issues mean values should be treated as uncertain at the +/- 1.0 magnitude level. In practice, for solar phase angles > 90 deg, the error could exceed 1 magnitude. No values are output for phase angles greater than 120 degrees, since the errors could be large and unknown. Some comets have custom magnitude laws that are described at the end of the requested ephemeris output.

        Units are MAGNITUDES and VISUAL MAGNITUDES PER SQUARE ARCSECOND.

        Magnitude laws:

Sun:	APmag= M - 5 + 5*log10(d), where M=4.83, d=distance from Sun (parsecs)
Asteroids:	APmag= H + 5*log10(delta) + 5*log10(r) -2.5*log10((1-G)*phi1 + G*phi2)
Comets:	T-mag=M1 + 5*log10(delta) + k1*log10(r)
	N-mag=M2 + 5*log10(delta) + k2*log10(r) + phcof*beta
Chiron:	Computed using asteroid magnitude law with H= 6.5, G=0.15
Wilson-Harrington:	Computed using asteroid magnitude law, H= 15.99, G= 0.15
Elst-Pizzaro:	Computed using asteroid magnitude law, H= 14.0, G= 0.15

        Surface brightness: S-brt= V + 2.5*log10(k*PI*a*b')

      Labels: APmag S-brt (Non-comet with known dimensions)
          APmag   (Non-comet with unknown dimensions)
          T-mag N-mag (comets; total & nuclear magnitudes)

10. Illuminated fraction
        Percent of target object circular disk illuminated by Sun (phase), as seen by observer. Units are PERCENT.

        Labels: Illu%

11. Defect of illumination

Angular width of target circular disk diameter not illuminated by Sun. Available only if target radius is known. Units are ARCSECONDS.

Labels: Def_illu

12. Angular separation/visibility

The angle between the center of a non-lunar target body and the center of the primary body it revolves around, as seen by the observer. Units are ARCSECONDS.

Non-lunar natural satellite visibility codes (limb-to-limb):
/t = Transitting primary body disk,   /O = Occulted by primary body disk,
/p = Partial umbral eclipse,   /P = Occulted partial umbral eclipse,
/u = Total umbral eclipse,   /U = Occulted total umbral eclipse,
/- = Target is the primary body,   /* = None of above ("free and clear")

... the radius of major bodies is taken to be the equatorial value (max) defined by the IAU2009 system. Atmospheric effects and oblateness aspect are not currently considered in these computations. Light-time is included.

Labels: ang-sep/v

13. Target angular diameter

The angle subtended by the disk of the target seen by the observer, if it was fully illuminated. The target diameter is taken to be the IAU2009 equatorial diameter. Oblateness aspect is not currently included. Units are ARCSECONDS.

Labels: Ang-diam

14. Observer sub-longitude & sub-latitude

Apparent planetographic ("geodetic") longitude and latitude (IAU2009 model) of the center of the target seen by the OBSERVER at print-time. This is NOT exactly the same as the "sub-observer" (nearest) point for a non-spherical target shape, but is generally very close if not an irregular body shape. Light travel-time from target to observer is taken into account. Latitude is the angle between the equatorial plane and the line perpendicular to the reference ellipsoid of the body. The reference ellipsoid is an oblate spheroid with a single flatness coefficient in which the y-axis body radius is taken to be the same value as the x-axis radius. For the gas giants only (Jupiter, Saturn, Uranus and Neptune), these longitudes are based on the Set III prime meridian angle, referred to the planet's rotating magnetic field. Latitude is always referred to the body dynamical equator. Note there can be an offset between the dynamical pole and the magnetic pole. The direction of positive longitude (east or west) will be indicated in the description at the end of the requested ephemeris. Units are DEGREES.

Labels: Ob-lon Ob-lat

15. Solar sub-longitude & sub-latitude

Apparent planetographic ("geodetic") longitude and latitude of the Sun (IAU2009) as seen by the observer at print-time. This is NOT exactly the same as the "sub-solar" (nearest) point for a non-spherical target shape, but is generally very close if not an irregular body shape. Light travel-time from Sun to target and from target to observer is taken into account. Latitude is the angle between the equatorial plane and the line perpendicular to the reference ellipsoid of the body. The reference ellipsoid is an oblate spheroid with a single flatness coefficient in which the y-axis body radius is taken to be the same value as the x-axis radius. For the gas giants only (Jupiter, Saturn, Uranus and Neptune), these longitudes are based on the Set III prime meridian angle, referred to the planet's rotating magnetic field. Latitude is always referred to the body dynamical equator. Note there can be an offset between the dynamical pole and the magnetic pole. The direction of positive longitude (east or west) will be indicatedin the descripton at the end of the requested ephemeris. Units are DEGREES.

Labels: Sl-lon Sl-lat

16. Sub-solar position angle & angular distance from disk center

      Target sub-solar point position angle (CCW with respect to direction of true-of-date Celestial North Pole) and angular distance from the sub-observer point (center of disk) at print time. Negative distance indicates the sub-solar point is on the hemisphere hidden from the observer. Units: DEGREES and ARCSECONDS

    Labels: SN.ang SN.ds

17. North pole position angle & distance

      Target's North Pole position angle (CCW with respect to direction of true-of-date celestial North) and angular distance from the sub-observer point (center of disk) at print time. Negative distance indicates N.P. on hidden hemisphere. Units: DEGREES and ARCSECONDS

    Labels: NP.ang NP.ds

18. Heliocentric ecliptic longitude & latitude

      Geometric heliocentric (ICRF/J2000 or FK4/B1950) ecliptic longitude and latitude of target at the instant light leaves it to be observed at print time(at print time minus 1-way light-time). Units: DEGREES

    Labels: hEcl-Lon hEcl-Lat

19. Heliocentric range & range-rate

      Heliocentric range ("r", light-time adjusted) and range-rate ("rdot") of the target center or surface point at the instant light seen by the observer at print-time would have left the target (print-time minus down-leg light-time). The Sun-to-target distance traveled by a ray of light emanating from the center of the Sun that reaches the target at some instant and is recordable by the observer one down-leg light-time later at print-time. Units: AU and KM/S

    Labels: r   rdot

20. Observer range & range rate

      Range ("delta") and range-rate ("delta-dot") of the target center or surface point with respect to the observer at the instant light seen by the observer at print-time would have left the target (print-time minus down-leg light-time); the distance traveled by a light ray emanating from the the target and recorded by the observer at print-time. "deldot" is a projection of the velocity vector along this ray, the light-time-corrected line-of-sight from the coordinate center, and indicates relative motion. A positive "deldot" means the target is moving away from the observer (coordinate center). A negative "deldot" means the target s moving toward the observer. Units are AU or KM and KM/S

    Labels: delta deldot

21. One-Way Light-time

      Target 1-way down-leg light-time, as seen by observer. The elapsed time since light (observed at print-time) left or reflected off the target. Units: MINUTES

    Labels: 1-way_LT

22. Speed wrt Sun & observer

      Magnitude of velocity of target with respect to the Sun center and the observer at the time light left the target to be observed. Units are KM/S.

    Labels: VmagSn VmagOb

23. Sun-Observer-Target angle

Target's apparent <u>solar elongation</u> seen from observer location at print-time. If negative, the target center is behind the Sun. Units are DEGREES.

For observing centers with defined rotation models, an additional marker is output under the column labelled '/r' (for relative position). If there is no rotation model associated with the observing center, no /r column will be present. Under this column,

/T indicates target trails Sun (evening sky)
/L indicates target leads Sun (morning sky)

 NOTE: The S-O-T solar elongation angle is the total separation in any direction. It does not indicate the angle of Sun leading or trailing.

Labels: S-O-T /r

24. Sun-Target-Observer angle; phase angle; phase angle bisector direction

"S-T-O" is the Sun->Target->Observer angle; the measurable interior vertex angle at target center formed by a vector to the apparent center of the Sun at reflection time on the target and a vector to the observer at print-time.

"phi" is the PHASE ANGLE at the observer's location at print time. The difference with S-T-O is due to down-leg stellar aberration affecting apparent target position but not apparent solar illumination direction. When computing phase, Horizons uses "phi", not "S-T-O".

"PAB-LON" and "PAB-LAT" are the ICRF/J2000 or FK4/B1950 ecliptic longitude and latitude of the phase angle bisector direction; the outward directed angle bisecting the arc created by the apparent vector from Sun to target center and the astrometric vector from observer to target center. For an otherwise uniform ellipsoid, the time when its long-axis is perpendicular to the PAB direction approximately corresponds to lightcurve maximum (or maximum brightness) of the body. PAB is discussed in Harris et al., Icarus 57, 251-258 (1984). Units: DEGREES, DEGREES, DEGREES, DEGREES

Labels: S-T-O   phi PAB-LON PAB-LAT

25. Target-Observer-Interfering_Body / IB_Illum%

Apparent elongation angle, seen by the observer, between the target body center and the center of a potential visually interfering body (such as the Moon but, more generally, the largest body in the system except for the one the observer is on). Also output is the fraction of the lunar (or IB) disk that is illuminated by the Sun. A negative elongation angle indicates the target center is behind the interfering body. The specific interfering body for an observing site is given in the output header. Units are DEGREES and PERCENT.

Labels: T-O-M / Illu%   (Earth observer, 'M' denoting "Moon")
              T-O-I / Illu%   (Non-Earth observer)

26. Observer-Primary-Target angle

Apparent angle between a target, its primary's center and an observer at print time. Units: DEGREES.

Labels: O-P-T

27. Sun-Target position angle; radius & -velocity vector

The position angles of the extended Sun->target radius vector   ("PsAng") and the negative of the target's heliocentric velocity vector ("PsAMV"), as seen in the plane-of-sky of the observer, measured CCW from reference frame North Celestial Pole. Small-bodies only. Units are DEGREES.

Labels: PsAng PsAMV

28. Orbit plane angle
        Angle between observer and target orbital plane, measured from center of target at the moment light seen at observation time leaves the target. Positive values indicate observer is above the object's orbital plane, in the direction of reference frame +z axis. Small-bodies only.   Units: DEGREES.

        Labels: PlAng

29. Constellation ID
        The 3-letter abbreviation for the constellation name of target's astrometric position, as defined by the IAU (1930) boundary delineation.

        Labels: Cnst

30. CT-UT
        Difference between uniform Coordinate Time scale ("ephemeris time" or TDB) and Earth-rotation dependent Universal Time. Prior to 1972, the difference is with respect to UT1 (CT-UT1). For 1972 and later, the delta is with respect to UTC (CT-UTC). Values beyond the next July or January 1st may change if a leap-second is introduced at later date. Units: SECONDS

        Labels: CT-UT

31. Observer Ecliptic Longitude & Latitude
        Observer-centered Earth ecliptic-of-date longitude and latitude of the target's apparent position, corrected for light-time, the gravitational deflection of light, stellar aberration and possibly atmospheric refraction (if requested). Although centered on the observer, the values are expressed relative to coordinate basis directions defined by the Earth's true equator-plane, equinox direction, and ecliptic plane at print time. Units: DEGREES

        Labels: ObsEcLng   ObsEcLat

32. Target North Pole RA & DEC
         Right Ascension and Declination (IAU2009 rotation model) of target body's North Pole direction at the time light left the body to be observed at print time. Consistent with requested reference frame; ICRF/J2000.0 or FK4/ B1950.0 RA and DEC. Units: DEGREES.

        Labels: N.Pole-RA N.Pole-DC

33. Galactic Latitude
        Observer-centered Galactic System II (post WW II) latitude of the target's apparent position (adjusted for light-time, the deflection of light due to the Sun and Earth and stellar aberration). Units: DEGREES.

        Labels: GlxLon GlxLat

34. Local Apparent Solar Time
        Local Apparent SOLAR Time at observing site. This is the time indicated by a sundial. TOPOCENTRIC ONLY. Units are HH.fffffffffff (decimal hours) or HH MM SS.ffff

35. Earth to Site Light-time
         Instantaneous light-time of the station with respect to Earth center at print-time. The geometric (or "true") separation of site and Earth center, divided by the speed of light. Units: MINUTES

        Labels: 399_ins_LT

36. Plane-of-sky RA and DEC pointing uncertainty
        Uncertainty in Right-Ascension and Declination. Output values are the formal +/- 3 standard-deviations (sigmas) around nominal position. Units: ARCSECONDS

        Labels: RA_3sigma DEC_3sigma

37. Plane-of-sky error ellipse

Plane-of-sky (POS) error ellipse data. These quantities summarize the target's 3-dimensional 3-standard-deviation formal uncertainty volume projected into a reference plane perpendicular to the observer's line-of-sight.

Labels:

SMAA_3sig = Angular width of the 3-sigma error ellipse semi-major axis in POS. Units: ARCSECONDS.

SMIA_3sig = Angular width of the 3-sigma error ellipse semi-minor axis in POS. Units: ARCSECONDS.

Theta = Orientation angle of the error ellipse in POS; the clockwise angle from the direction of increasing RA to the semi-major axis of the error ellipse, in the direction of increasing DEC. Units: DEGREES.

Area_3sig = Area of sky enclosed by the 3-sigma error ellipse. Units: ARCSECONDS $^\wedge$ 2.

38. Plane-of-sky ellipse RSS pointing uncertainty

The Root-Sum-of-Squares (RSS) of the 3-standard deviation plane-of-sky error ellipse major and minor axes. This single pointing uncertainty number gives an angular distance (a circular radius) from the target's nominal position in the sky that encompasses the error-ellipse. Units: ARCSECONDS.

Labels: POS_3sigma

39. Uncertainties in plane-of-sky radial direction

Range and range rate (radial velocity) formal 3-standard-deviation uncertainties. Units: KM, KM/S

Labels: RNG_3sigma   RNGRT_3sig

40. Radar uncertainties (plane-of-sky radial direction)

Doppler radar uncertainties at S-band (2380 MHz) and X-band (8560 MHz) frequencies, along with the round-trip (total) delay to first-order. Units: HERTZ and SECONDS

Labels: DOP_S-sig   DOP_X-sig   RT_delay-sig

41. True Anomaly angle

Apparent true anomaly angle of the target's heliocentric orbit position; the angle in the target's instantaneous orbit plane from the orbital periapse direction to the target, measured positively in the direction of motion. The position of the target is taken to be at the moment light seen by the observer at print-time would have left the center of the object. That is, the heliocentric position of the target used to compute the true anomaly is one down-leg light-time prior to the print-time. Units: DEGREES

Labels: Tru_Anom

41. Local apparent hour angle

Local apparent HOUR ANGLE of target at observing site. The angle between the observer's meridian plane, containing Earth's axis of-date and local zenith direction, and a great circle passing through and Earth's axis-of-date and the target's direction, measured westward from the zenith meridian to target meridian along the equator. Negative values are angular times UNTIL transit. Positive values are angular times SINCE transit. Exactly 24_hrs/360_degrees. EARTH TOPOCENTRIC ONLY. Units: sHH.fffffffff or sHH MM SS.fff (decimal or sexagesimal angular hours)

Labels: L_ap_Hour_Ang

15. CLOSE-APPROACH TABLES

For asteroids and comets, a close-approach table may be requested. Output is produced only when the selected object reaches a minimum distance within a set spherical radius from a planet, Ceres, Pallas, or Vesta.

User-specifications for this table can include the time-span to check, the radius of detection for planets and asteroids, the maximum uncertainty in time-of-close-approach before the table is automatically cut-off, and whether to output optional error ellipse information projected into the B-plane

The B-plane mentioned above is defined by the three orthogonal unit vectors T, R, and S (the origin being the body center). T lies in the B-plane, pointing in the direction of decreasing celestial longitude. R lies in the B-plane, pointing in the direction of decreasing celestial latitude (south). S is directed along the relative velocity vector at body encounter, perpendicular to the B-plane, and thus R and T. The B vector is the vector in the plane from the body to the point where the incoming object's velocity asymptote pierces the R-T plane. Note the B-plane is defined only when the incoming object is hyperbolic with respect to the body.

For objects with covariances, statistical quantities are output for each close-approach. All tabulated statistical quantities (MinDist, MaxDist, TCA3Sg, SMaA, SMiA, Gamma, Nsigs and P_i/p) are based on a linearized covariance mapping in which higher-order (small) terms in the variational partial derivatives of the equations of motion are dropped.

Due to possible non-linearities in any given object's actual dynamics, this can result in significant errors at epochs distant in time from the solution epoch. Consequently, long linearized mappings (hundreds, dozens, or sometimes just several years from the present time) should be considered useful approximations, pending additional analysis, especially in these cases:

> A) objects with several close planetary encounters,
> B) objects with very close planetary encounters (< 0.01 AU),
> C) objects with very short data arcs (days or weeks).

While linearized projections will tend to indicate such cases with obviously rapid uncertainty growth, the specific numbers output can inadequately represent orbit uncertainty knowledge. Possible output quantities are described below. "Nominal" effectively means "highest-probability for the given orbit solution", although there can be other possible orbits of equal probability. If there is no covariance available, no statistical quantities are returned.

Date (CT)
Nominal close-approach date (Coordinate Time). Calendar dates prior to 1582-Oct-15 are in the Julian calendar system. Later calendar dates are in the Gregorian system.

Body
Name or abbreviation of the planetary body or major asteroid beingclosely approached by the selected small-body.

CA Dist
Nominal close-approach distance at the close-approach time. Units: AU

MinDist
Minimum close-approach distance possible (formal 3 standard-deviations with linearized covariance mapping). Units: AU

MaxDist
Maximum close-approach distance possible (formal 3 standard-deviations with linearized covariance mapping). Units: AU

Vrel

    Relative velocity of the object and the body it is approaching at the nominal time of close-approach. Units: KM/S

TCA3Sg

    Close-approach-time 3-standard deviation uncertainty. Units: MINUTES

SMaA

    3-sigma error ellipse semi-major axis projected into the B-plane at nominal time of closest-approach. Units: KM

SMiA

    3-sigma error ellipse semi-minor axis projected into the B-plane at nominal time of closest-approach. Units: KM

Gamma

    Orientation angle of error ellipse in the B-plane. Counter-clockwise angle from the B vector to the semi-major axis of the error ellipse. Units: DEGREES

Nsigs

    The number of standard deviations (sigmas) required for the error ellipse to intersect the body being closely approached. Units: STANDARD DEVIATIONS

P_i/p

    Linearized probability of the object impacting the body. Non-zero values less than approximately 0.001 may not be numerically significant due to the linearization process.

16. UNDERSTANDING RISE, TRANSIT AND SET INDICATORS

There are 2 ways the system can be used to mark rise, transit and set (RTS) conditions: activate the RTS-only print option OR produce a general observer table with step-size less than 30 minutes.

NORMAL-TABLE RTS-MARKER MODE

RTS is indicated automatically during normal observer table generation, when the step-size is less than 30 minutes. Markers are placed to indicate the event occurred at some point in the previous step. Thus, precision of the indicator depends on the step-size selected. For this mode, rise and set are always with respect to the true-visual-horizon reference plane (TVH), described below.

RTS-ONLY PRINT MODE

The advantage of this mode is it allows production of a more compact RTS table over a longer time-span than does the "normal" table generation mode.

When RTS-only print is selected, the program will search for the events at a user-specified resolution, from 1 to 9 minutes. Output will be generated ONLY for these three events. The marker symbols in the table indicate that the event took place sometime in the previous step interval.

This RTS-only mode can be turned on at two different points in the program:
> #1) Preferably, when specifying the ephemeris/search step-size
> #2) ... but also in the "change defaults" prompt structure

Three types of criteria are available for the rise and set conditions, relative to an input elevation angle (nominally 0 degrees). Select by specifying, when prompted at #1 or #2, one of these symbols:

> **TVH** ... True visual horizon plane. The horizon seen by an observer on
> the reference ellipsoid. Allows for horizon dip effect and
> refraction, but not local topography.
> **GEO** ... Geometric horizon plane. The horizon is defined by the plane
> perpendicular to the reference ellipsoid local zenith (no
> horizon dip). Refraction is allowed for.
> **RAD** ... Radar case. Geometric horizon plane, no refraction.

For example, when prompted for the step-size, one could enter "5 min GEO' to search, at five-minute steps, for the refracted rise/set relative to the geometric horizon plane.

BACKGROUND DESCRIPTION

Rise and set elevations are taken to be the maximum of 0 or the input elevation cut-off value [0-90 deg], set in the "change defaults" prompt section. Thus, if there are local hills, one could set the cut-off at 10 degrees and get RTS relative to that elevation.

At low elevations, these rise/set times should be viewed as approximations, realistically good to perhaps only 1-2 minutes at the horizon due to local atmospheric variation and topography.

To speed RTS-only searches, use the largest step-size compatible with the required accuracy. For example, considering the inherent atmospheric instability at the horizon, one should rarely need to identify rise/set to better than 5 minute accuracy. Setting a search-step of 5 minutes will then produce a table 5 times faster than 1 minute searching.

The program computes approximate refraction angles assuming yellow-light observations at 10 deg C sea-

level with pressure of 1010 millibars. Corrected coordinates should be accurate to < 10 arcsec, but errors may be much larger near the horizon (+- 0.3 deg) or fluctuate unpredictably with local weather.

Both Moon and Sun rise/set are based on when the refracted upper limb of the object reaches the specified elevation. Transit is based on the center of the target body.

17. CONSTELLATION IDENTIFICATION

The observed background constellation of a target (corrected for light-time) may be requested for an observer table. The output field will contain a three letter abbreviation of the constellation name, from the list shown below. Constellation boundaries are those delineated by Gould (1877) and Delporte (1930) under the auspices of the International Astronomical Union.

Abbrev.	Constellation Name	Abbrev.	Constellation Name
And	Andromeda	Leo	Leo
Ant	Antila	LMi	Leo Minor
Aps	Apus	Lep	Lepus
Aqr	Aquarius	Lib	Libra
Aql	Aquila	Lup	Lupus
Ara	Ara	Lyn	Lynx
Ari	Aries	Lyr	Lyra
Aur	Auriga	Men	Mensa
Boo	Bootes	Mic	Microscopium
Cae	Caelum	Mon	Monoceros
Cam	Camelopardis	Mus	Musc
Cnc	Cancer	Nor	Norma
CVn	Canes Venatici	Oct	Octans
CMa	Canis Major	Oph	Ophiuchus
CMi	Canis Minor	Ori	Orion
Cap	Capricornus	Pav	Pavo
Car	Carina	Peg	Pegasus
Cas	Cassiopeia	Per	Perseus
Cen	Centaurus	Phe	Phoenix
Cep	Cepheus	Pic	Pictor
Cet	Cetus	Psc	Pisces
Cha	Chamaeleon	PsA	Pisces Austrinus
Cir	Circinus	Pup	Puppis
Col	Columba	Pyx	Pyxis
Com	Coma Berenices	Ret	Reticulum
CrA	Corona Australis	Sge	Sagitta
CrB	Corona Borealis	Sgr	Sagittarius
Crv	Corvus	Sco	Scorpius
Crt	Crater	Scl	Sculptor
Cru	Crux	Sct	Scutum
Cyg	Cygnus	Ser	Serpens
Del	Delphinus	Sex	Sextans
Dor	Dorado	Tau	Taurus
Dra	Draco	Tel	Telescopium
Equ	Equuleus	Tri	Triangulum
Eri	Eridanus	TrA	Triangulum Australe
For	Fornax	Tuc	Tucana
Gem	Gemini	UMa	Ursa Major
Gru	Grus	UMi	Ursa Minor
Her	Hercules	Vel	Vela
Hor	Horologium	Vir	Virgo
Hya	Hydra	Vol	Volans
Hyi	Hydrus	Vul	Vulpecula
Ind	Indus		
Lac	Lacerta		

18. SPK FILE PRODUCTION

Introduction:

An SPK file is a binary file which may be smoothly interpolated to retrieve an object's position and velocity at any instant within the file time-span. Such files may be used as input to visualization and mission design programs, allowing them to quickly retrieve accurate target body observation and data analysis ephemerides without having to repeatedly integrate equations of motion.   An SPK file could be considered a "recording" of the integrator.

SPK stands for "Spacecraft and Planet Kernel". It is a file element of the SPICE system devised and maintained by the NAIF (Navigation and Ancillary Information Facility) team at JPL. SPK files may hold ephemerides for any kind of spacecraft or solar system body, but Horizons produces SPK files only for comets and asteroids.

Potential users are advised that programming and science/math skills at an advanced college level are needed to utilize these files. Users must have a computer with 25-50 Mbytes of disk space, 8 Mbytes of available RAM and a FORTRAN or C compiler. The user's own code must be capable of calling FORTRAN or C modules. Internet FTP capability is needed to obtain the necessary SPICE components as well as the SPK files generated by Horizons.

For information on SPK files in general, contact

Charles.H.Acton-Jr@jpl.nasa.gov (NAIF team leader)

or see web site "http://pds-naif.jpl.nasa.gov/".

Horizons Implementation:

SPK files can be produced on demand using the Horizons telnet interface.Horizons allows a maximum of 20 small-bodies per SPK file. To construct an SPK for a comet or asteroid, Horizons retrieves the latest orbit solution and numerically integrates the object's trajectory over a user-specified time span less than 200 years. Internal data from the integrator is written directly to the SPK file as this occurs. When a users' application program reads the SPK file, that data can be used to reconstruct the integrator state to within machine precision limits.

SPK files are capable of storing trajectory data with a fidelity greater than 1 millimeter (more accurately than should ever be required). Summary information is stored in the SPK file comment area. It can be read using the "spacit" or "commnt" utility in the SPICE Toolkit distribution.

Files produced autonomously by Horizons users are considered informal file releases and should not be used for purposes affecting the safety and success of spacecraft hardware or missions without first contacting the JPL Solar System Dynamics Group:

Donald.K.Yeomans@jpl.nasa.gov (Supervisor, 818-354-2127)
Jon.D.Giorgini@jpl.nasa.gov   (SSDG analyst).

This is because an object's orbit solution may be insufficiently determined over the chosen time-span to be suitable for some high-precision purposes, due to the quantity of measurements available for an object, the time-span they cover, and the object's dynamical path.

Although not stored in an SPK file, the statistical uncertainty of the trajectory as a function of time may be available from the JPL Horizons system.This can help interpret the accuracy of the trajectory.

The orbit solutions used to produce SPK files on demand are updated inHorizons as new measurements are made. Therefore, a trajectory in an SPK file may be superceded by more recent solutions. Check the orbit solution number for an object (given as "source" in the SPK file comments area) against the latest Horizons entry to determine if an updated orbit solution is available.

19. STATEMENT OF EPHEMERIS LIMITATIONS

To produce an ephemeris, observational data (optical, VLBI, radar & spacecraft) containing measurement errors are combined with dynamical models containing modeling imprecisions. A best fit is developed to statistically minimize those errors. The resulting ephemeris has an associated uncertainty that fluctuates.

For example, only a limited percentage of **asteroid orbits** are known to better than 1 arcsec in the plane-of-sky over significant periods of time. While 1991 JX center-of-mass was known to within 30 meters along the line-of-sight during the 1995 Goldstone radar experiment, errors increase outside that time-span. Uncertainties in major planet ephemerides range from 10cm to 100+ km in the state-of-the-art JPL/DE-405 ephemeris, used as the basis for spacecraft navigation, mission planning and radar astronomy.

Cartesian state vectors are output in all their 16 decimal-place glory. This does not mean all digits are physically meaningful. The full-precision may be of interest to those studying the ephemerides or as a source of initial conditions for subsequent integrations. For **osculating element output**, GM is rarely known to better than 5 significant figures. For **observer angular outpu**t tables, purely local atmospheric conditions will affect "refraction-corrected" apparent places by several arcseconds, more at the horizon.

Small-body elements are reported in the optical FK5/J2000.0 frame currently thought to differ by less than 0.01 arcseconds from the ICRF of the planetary ephemeris DE-405. Until a generally agreed upon transformation from one frame to the other is defined and implemented, they will be treated by this program as equivalent.

The Earth is assumed to be a rigid body and solid Earth tides affecting station location are not included. Of course, precession and nutation effects are included, as is polar motion. CT-TAI terms less than 20 usec are omitted. These and other Earth-model approximations result in topocentric station location errors, with respect to the reference ellipsoid, of less than 20 meters. However, many optical site positions (latitude and longitude) are known far less accurately and can be many kilometers off.

Relativistic effects are included in all planet, lunar and small-body dynamics, but not for satellites. Relativity is included in observables via 2nd order terms in stellar aberration and the deflection of light due to gravity fields of the Sun (and Earth, for topocentric observers).

Deflections due to other gravity fields can potentially have an effect at the 10^{-4} arcsec level but are not currently included here. Satellites of other planets, such as Jupiter could experience deflections at the 10^{-3} arcsec level as well. Light time iterations are Newtonian. This affects light-time convergence at the millisecond level, position at ~10^{-6} arcsec level.

For many small natural satellites, the orbit orientation is well known, but the position of the body along the ellipse is not. Errors may be significant, especially for the lesser satellites of outer planets. Satellite osculating elements output by Horizons should NOT be used to initialize a separate integration or extrapolation. Such elements assume Keplerian motion (two point masses, etc.) which does not match, for example, kinematic models such as a precessing ellipse, used for some satellites. One would do better extrapolating mean orbital elements at http://ssd.jpl.nasa.gov/sat_elem.html

Spacecraft in low Earth orbit (such as ISS, HST, Swift, GALEX) need frequent updates to maintain high accuracy. LEO predicts more than a few days into the future can have 10s or 100's of km of error. If accurate predicts are needed, and the last update was more than a few days ago, an update can be done on request. For interplanetary spacecraft, users having high-precision applications (such as mission data reduction) should contact JPL Solar System Dynamics to verify the status of the specific trajectory in Horizons.

 IF YOUR CAREER OR SPACECRAFT DEPENDS ON A NON-LUNAR NATURAL SATELLITE OR SMALL-BODY EPHEMERIS, CONTACT JPL BEFORE USING IT. YOU >MUST< HAVE ADDITIONAL INFORMATION TO CORRECTLY UNDERSTAND EPHEMERIS LIMITATIONS AND UNCERTAINTIES.

20. LONG-TERM EPHEMERIS

SOLAR SYSTEM MODEL:

The JPL DE-406/LE-406 extended ephemeris covers the interval from 3000 B.C. to A.D. 3000. This ephemeris is identical to the shorter DE-405 in the sense it is the same data-fit (solution) and the same numerical integration as DE-405. However, it has been stored with slightly less accuracy to reduce its size.

For the Moon, DE-406 recovers the original integrator state to within 1 meter, other bodies within 25 meters (maximum error). This difference can be less than the uncertainty associated with the trajectory solution itself, thus is insignificant for all but the most specialized circumstances. The short-span version, DE-405, recovers the integrator state to the millimeter level.

Horizons uses the long-term DE-406/LE-406 for the following objects:

Objects	ID code #
All planet barycenters	0,1,2,3,4,5,6,7,8,9
Sun	10
Moon	301
Mercury	199
Venus	299
Earth	399
Mars	499

Satellites and outer solar-system planet-centers each have various shorter intervals, as warranted by their observational data arc. Comets and asteroids are available only over the A.D. 1599 to A.D. 2200 interval of the DE-405 ephemeris they are integrated against. (Only a few dozen small-bodies have sufficiently well-known orbits to justify rigorous integration over time-spans of hundreds of years.)

PRECESSION MODEL:

For the time-span of 1799-Jan-1 to 2202-Jan-1, the official IAU precession model [16] of Lieske is used. As published, this model is valid for only ~200 years on either side of the J2000.0 epoch. This is due to round-off error in the published coefficients and truncation to a cubic polynomial in the expressions for the Euler rotation angles.

Therefore, outside this interval, the long-term precession and obliquity model [17] of Owen is used to maintain accuracy in the calculation of apparent ("of-date") quantities. This model is a rigorous numerical integration of the equations of motion of the celestial pole using Kinoshita's model for the speed of luni-solar precession.

NUTATION MODEL:

The IAU (1980) model [18] of Wahr is used. This is the same table printed in the 1992 Explanatory Supplement to the Astronomical Almanac. Note there is an error in the Explanatory Supplement for the Node term, given on p. 114 as:

$$\Omega = 135deg\ 2'40.280'' + ...$$

This system uses the correct formulation:

$$\Omega = 125deg\ 2'40.280'' + ...$$

UNIVERSAL TIME (CT to UT Conversion):

This program internally uses the CT time-scale of the ephemerides (the independent variable in the equations of motion). To produce the more familiar Universal Time (UT) output tied to the Earth's rotation, it is necessary to use

historical reconstructions of old or ancient observations of constrained events, such as eclipses, to derive a CT-UT difference. This program currently uses the analyses of [12-15] as follows:

Span	CT-UT offset ("delta-t")	Type	Argument (T=...)
3000 BCto 500 BC	(31*T*T) - 20	UT1	cent. since JD1820
500 BC to AD 1620	Stephenson cubic spline fit		
AD 1620 to AD 1962	Smoothed table	UT1	
AD 1962 to Present	EOP file	UTC	

Values prior to 1962 above are adjusted for compatibility with the Horizons planetary ephemeris lunar tidal acceleration (n_dot) of -25.7 "/century^2 as follows:

$$\Delta(CT\text{-}UTC) = -0.911*(n\_dot + 26)*T*T, \text{ where } T = (\text{year} - 1955.5) / 100$$

For epochs after 1962, the calculation is as follows:

$$CT - UTC = (CT - TAI) + (TAI - UTC)$$

... where

$$CT - TAI = 32.184 + 1.657E\text{-}3 * SIN(M + 0.01671*SIN(M))$$
$$M = 6.239996 + T * 1.99096871E\text{-}7$$
$$T = CT \text{ or } TAI \text{ seconds past J2000.0 epoch}$$
$$TAI - UTC = \text{interpolated from current EOP file.}$$

... dropping terms less than about 20 υsec in CT-TAI.

As one progresses to earlier times, particularly those prior to the 1620 telescopic data span, uncertainties in UT determination generally (though not always and not uniformly) increase due to less precise observations and sparser records. At A.D. 948, uncertainty (not necessarily error) can be a few minutes. At 3000 B.C., the uncertainty in UT is about 4 hours. The TT time scale, being uniform, does not have this uncertainty, but is not directly related to Earth's rotation (local time) either.

GREENWICH MEAN SIDEREAL TIME:

GMST, used for topocentric ephemerides, is related to UT1 using an expression consistent with the IAU 1976 system of constants, as shown on p. 50 of the Explanatory Supplement (1992), along with the new, more accurate 1997 IAU equinox equation.

HIGH PRECISION EARTH ORIENTATION PARAMETER (EOP) MODEL:

The EOP file is currently updated twice a week based on GPS and other Earth-monitoring measurements. Horizons uses it to obtain calibrations for UT1-UTC, polar motion and nutation correction parameters necessary to determine the rotation from the Earth-fixed reference frame to an inertial reference frame. The EOP file provides data from 1962 to the present, with predictions about 78 days into the future from the date of file release. For times outside the available interval, Horizons uses the last value available in the file as constants. For CT-UT calculations, it switches to the different models described above.

Because EOP values are fit to data, it is possible an ephemeris may differ slightly from one produced days or weeks or months later, especially, if the original ephemeris extended into the predicted region of the EOP file. The most recent ephemeris will be more accurate, but if it is necessary to reproduce results exactly, contact JPL. EOP files are archived and the one used in your initial run (indicated in your output) can be retrieved.

BODY ROTATIONS:

The current IAU rotation models for planets and satellites are simply extended in time as necessary.

21. BACKGROUND

A)   Comet and asteroid orbits are INTEGRATED from initial conditions stored in the JPL-maintained DASTCOM database.

B)   Planet and satellite ephemerides are INTERPOLATED from files previously generated by JPL, such as the DE-405 planetary ephemeris.

C)   SMALL BODY DATA SCREENS are from the JPL DASTCOM database. These display constants ARE ACTUALLY USED to produce the ephemeris.

D)   MAJOR BODY DATA SCREEN CONSTANTS are from "Astrometric and Geometric Properties of Earth and the Solar System", Charles Yoder (JPL), published in "Global Earth Physics: A Handbook of Physical Constants", AGU Reference Shelf 1.

E)   MAJOR BODY DATA SCREEN CONSTANTS are presented for your information (FYI) only and ARE NOT USED to generate the ephemeris output (see below). While an effort has been made to insure their accuracy, suitability of these DISPLAY constants for any given purpose must be determined by individual users.   Users should be aware there is often more than one determination in the literature for many of these constants and that they are subject to revision as more data are accumulated.

F)   Horizons uses the current planetary ephemeris solved-for GM values when calculating osculating elements. For DE-405/DE-406, they are as follows (units are KM^3/SEC^2):

Sun	1.3271244001798698E+11
Mercury	2.2032080486417923E+04
Venus	3.2485859882645978E+05
Earth	3.9860043289693922E+05
Moon	4.9028005821477636E+03
Mars System	4.2828314258067119E+04
Jupiter System	1.2671276785779600E+08
Saturn System	3.7940626061137281E+07
Uranus System	5.7945490070718741E+06
Neptune System	6.8365340638792608E+06
Pluto System	9.8160088770700440E+02

22. SOURCES AND REFERENCES FOR PRIMARY EPHEMERIS DATA

Planets

Standish, E.M., XX Newhall, J.G. Williams, and W.M. Folkner. JPL Planetary and Lunar Ephemerides, DE403/ LE403. JPL Interoffice Memorandum 314.10-127 dated May 22, 1995.

Natural Satellites

Satellite	Ephemeris Theory	References
Phobos & Deimos	MARSAT (Analytic)	Jacobson et al. (1989)
Galileans	GALSAT(E5, Analytic)	Lieske (1995)
Minor Jovians	Precessing ellipse	Jacobson (1994)
Outer Jovians	Numerical Integration	Jacobson (1991)
Major Saturnians	Numerical Integration	Jacobson (1996a)
Phoebe	Numerical Integration	Jacobson (1996c)
Inner Saturnians	Precessing ellipse	Jacobson (1995)
Saturn co-orbiters	Numerical Integration	Jacobson (1995)
Saturn librators	Numerical Integration	Jacobson (1995)
Major Uranians	GUST (Analytic)	Laskar & Jacobson (1987)
Minor Uranians	Precessing ellipse	Jacobson (1996b)
Triton	Numerical Integration	Jacobson et al. (1991)
Nereid	Numerical Integration	Jacobson et al. (1991)
Inner Neptunians	Precessing ellipse	Owen et al. (1991)
Charon	Dynamic conic	Tholen (1990)

References For Natural Satellite Ephemerides:

Jacobson, R.A., 1991. Outer Jovian Satellite Ephemerides for the Galileo Project. JPL Interoffice Memorandum 314.6-1261 (JPL internal document).

Jacobson, R.A., 1994. Revised Ephemerides for the Inner Jovian Satellites. JPL Interoffice Memorandum 314.10-101 (JPL internal document).

Jacobson, R.A., 1995. The Orbits of the Minor Saturnian Satellites. Bulletin, American Astronomical Society, vol. 27, No.3, p. 1202-1203.

Jacobson, R.A., 1996a. Update of the Major Saturnian Satellite Ephemerides. JPL Interoffice Memorandum 312.1-96-012 (JPL internal document).

Jacobson, R.A., 1996b. Updated Ephemerides for the Minor Uranian Satellites. JPL Interoffice Memorandum 312.1-96-014 (JPL internal document).

Jacobson, R.A., 1996c. Update of the Ephemeris for Phoebe. JPL Interoffice Memorandum 312.1-96-024 (JPL internal document).

Jacobson, R.A., Synnott, S.P., and Campbell, J.K., 1989. The Orbits of the Satellites of Mars from Spacecraft and

Earthbased Observations. Astronomy and Astrophysics, 225, 548.

Jacobson, R.A., Riedel, J.E. and Taylor, A.H., 1991. The Orbits of Triton and Nereid from Spacecraft and Earthbased Observations. Astronomy and Astrophysics, 247, 565.

Laskar, J. and Jacobson, R.A., 1987. GUST86. An Analytic Ephemeris of the Uranian Satellites. Astronomy and Astrophysics, 188, 212.

Lieske, J.H., 1995. Galilean Satellite Ephemerides E5. JPL Engineering Memorandum 312-583 (JPL internal document).

Owen, W.M., Vaughan, R.M., and Synnott, S.P., 1991. Orbits of the Six New Satellites of Neptune. Astronomical Journal, 101, 1511.

Tholen, D. and Buie, M.W., 1990. Further Analysis of Pluto-Charon Mutual Event Observations - 1990. Bulletin, American Astronomical Society, vol. 22, No.3, p. 1129.

COMETS AND ASTEROIDS

Sources of Orbital Elements for Comets and Asteroids

1. Minor Planet Circulars (MPC) published by the Minor Planet Center,   60 Garden St., Cambridge, Massachusetts 02138,   http://cfa-www.harvard.edu/cfa/ps/mpc.html

2. Solar System Dynamics Group/Jet Propulsion Laboratory (JPL) , D.K. Yeomans, Supervisor

Cometary Magnitude Parameters

1. International Comet Quarterly (D.W.E. Green, editor), 60 Garden St.,   Cambridge, Massachusetts, 02138

2. Charles Morris, Jet Propulsion Laboratory, Pasadena, California 91109   http://encke.jpl.nasa.gov

Asteroid Physical Parameters

Radius and Albedo:

1. Tedesco, E.F. (1995) "IMPS Diameters and Albedos V1.0" Planetary Data System - Small Bodies Node (PDSSBN) (M. A'Hearn, University of Maryland, College Park, Maryland) http://pdssbn.astro.umd.edu

2. McFadden, L.A. et al. (1989) In Asteroids II, p. 456.

3. Williams, J.G. (1990) Private Communication.

Taxonomic Type ("Spectral Type"):

1. Tholen, D.J. (1989) "Asteroid Taxonomy V1.0" Planetary Data System - Small Bodies Node (PDSSBN) (M. A'Hearn, University of Maryland, College Park, Maryland) http://pdssbn.astro.umd.edu

2. Binzel, R.P. and Xu, S. (1993) Science 216:186-191.

Rotation Period:

     1. Harris, A.W. (1996) "Asteroid Lightcurve Derived Data V2.0" Planetary Data System - Small Bodies Node (PDSSBN) (M. A'Hearn, University of Maryland, College Park, Maryland) http://pdssbn.astro.umd.edu

Magnitude Parameters:

     1. Minor Planet Circulars (MPC) published by the Minor Planet Center, 60 Garden St., Cambridge, Massachusetts 02138 http://cfa-www.harvard.edu/cfa/ps/mpc.html

Constants and Model References

     Major body (planet/satellite) GM and AU definitions ACTUALLY USED (as opposed to the FYI data screens) are from the DE-405 ephemeris, a major improvement over the earlier DE-200. Other planet and satellite constants used by this software, such as radii, rotation and orientation, are based on the following sources:

1. 'Report of the IAU/IAG Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites: 2000', Celestial Mechanics and Dynamical Astronomy 82: 82-110, 2002.

2. 'The Astronomical Almanac', 1993.

3. 'Planetary Geodetic Control Using Satellite Imaging', Journal of Geophysical Research, Vol. 84, No. B3, March 10, 1979, by Thomas C. Duxbury.

4. Letter from Thomas C. Duxbury to Dr. Ephraim Lazeryevich Akim, Keldish Institute of Applied Mathematics, USSR Academy of Sciences, Moscow, USSR.

     Most values are from the 'IAU/IAG Working Group on Cartographic Coordinates and Rotational Elements of the Planets and Satellites: 2000'. The exceptions are:

-- Radii for the Sun are from the above reference [2].

  -- The second nutation precession angle (M2) for Mars is represented by a quadratic polynomial in the 1997 IAU report. Current software cannot handle this term (which is extremely small), so the polynomial is truncated to a linear one.

  -- The expressions for the pole and prime meridian of Neptune given in the IAU report include trigonometric terms which current software doesn't yet handle. These terms are omitted.

  -- For several satellites, the IAU2000 report either gives a single radius value or a polar radius and a single equatorial radius. Current software uses a triaxial ellipsoid model that requires three radii. In the cases listed below, additional values have been supplied in order to allow the software to function.

     The affected satellites are:

Body	ID code	
Thebe	514	
Metis	516	
Helene	612	
Caliban	716	(no IAU value)
Sycorax	717	(no IAU value)
Larissa	807	

Airmass computation is based on [5]:

5. Kasten, F., Young, A., "Revised Optical Air Mass Tables and Approximation Formula", Applied Optics, vol 28, no. 22, p. 4735-4738, Nov. 15, 1989.

Refraction computation is based on [6-7]:

6. Saemundsson, T., Sky & Telescope, July, 1986, p.70.
7. Meeus, J., "Astronomical Algorithms", 1991, p. 101-102

Constellation identification based on [8-9,(10-11)]:

8. Roman, N.G. ,1987, "Identification of a Constellation from a Position", Publ. Astro. Soc. of Pac., 99,695-699
9. Warren, Wayne H., Jr., (1997, GSFC) private communication.
10. Delporte, E. 1930, "Delimitation Scientifique des Constellations", Cambridge, Cambridge University Press.
11. Gould, B.A., 1877, "Uranometria Argentina, mapas" (Buenos Aires, Argentina: Observatorio Nacional)

Long-term CT-UT offset calculations based on [12-15]:

12. priv. comm. Morrison (1980).
13. Stephenson, F.R., Houlden, M.A., "Atlas of Historical Eclipse Maps", Cambridge Univ. Press, p X, (1986).
14. Stephenson, F.R, Morrison, L.V., "Long-term Changes in the Rotation of the Earth: 700 B.C. to A.D. 1980", Phil. Trans. R. Soc. London, 313, 47-70 (1984)
15. Stephenson, F.R., Morrison, L.V., "Long-term Fluctuations in the Earth's Rotation: 700 BC to AD 1990", Phil. Trans. R. Soc. London, 351, p. 165-202 (1995)

Precession (IAU), [1799-Jan-1 to 2202-Jan-1]:

16. Lieske, J., "Precession Matrix Based on IAU (1976) System of Astronomical Constants", Astron. Astrophys. 73, 282-284, 1979.

Precession (long-term) before 1799-Jan-1 and after 2202-Jan-1:

17. Owen, William M., Jr., (JPL) "A Theory of the Earth's Precession Relative to the Invariable Plane of the Solar System", Ph.D. Dissertation, University of Florida, 1990.

Nutation:

18. Table 1, 'Proposal to the IAU Working Group on Nutation', John M. Wahr and Martin L. Smith 1979. Adopted 1980.

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Design/implementation :	Jon Giorgini	
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	Alan Chamberlin	(web interface, database)
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	Ray Wimberly	(database maintenance)
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Appendix A

(Submitting job requests using e-mail)

Appendix B

(Automating a session using Expect scripting language)