

Solar System Ephemeris and Target Visibility Processing for HST

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Abstract

The "Percy" computer program provides ephemeris and geometrical event information about solar system objects. Percy is the primary component of the Moving Object Support System (MOSS) at the Space Telescope Science Institute. Percy was designed specifically for Hubble Space Telescope observation planning, though it should be a useful planning tool for any ground or space based observatory. An overview of the features and capabilities of Percy is presented.

Introduction

The Hubble Space Telescope Moving Object Support System consists of just one primary computer program called "Percy". Percy is an interactive program which provides ephemeris and geometrical event information about solar system objects. These objects include the Sun, major planets and their natural satellites, comets, and asteroids.

Percy performs four primary functions :

- Locates time spans during which complex geometric constraints are satisfied.
- Graphically displays a field of view from any vantage point.
- Generates text reports of solar system phenomena
- Generates ephemeris files.

This paper presents a very brief introduction to the Percy computer program. The major features are discussed through example Percy commands.

Percy, named after Percival Lowell, and a companion program, Clyde, named after Clyde Tombaugh, were originally developed by the Jet Propulsion Laboratory (JPL) under contract to NASA Goddard Spaceflight Center and the Space Telescope Science Institute (STScI). STScI took over the development and maintenance of Percy and Clyde in 1992. Since then, extensive modifications and improvements have been made including a port from

VAX/VMS to SPARC Solaris. The functionality of Clyde was merged into Percy, so Clyde is no longer supported.

Percy was originally developed specifically for Hubble Space Telescope (HST) observation planning. While it contains some HST specific features, Percy should be useful for almost any ground or spacecraft based observing system.

Internally, Percy uses the SPICELIB software library supplied by JPL's Navigation and Ancillary Information Facility (NAIF). SPICELIB provides many lower level services, calculations, and ephemeris file utilities.

A Percy configuration is a small set of data files which defines ephemerides and other solar system data. The details of these files are hidden from most Percy users. Advanced users may need to modify the configuration for some observation planning sessions. Configuration data files include :

- NAIF supplied solar system body ephemeris files (.bsp files).
- Spacecraft ephemeris data files.
- Files that contain body size, shape, prime meridian, and rotational information.
- Leap Second data.
- Star Catalogs for graphical displays. This includes the SAO and HST Guide Star Catalogs.
- Telescope aperture data for graphical display.

Percy is a command line system with a custom built-in scripting language. Commands can be entered interactively or through the execution of nested procedure files. The language is free formatted and semi-colon terminated. It also supports symbol definition and substitution.

The Percy language allows for the flexible entry of dates and times in many common time formats. By default all input times are assumed to be in UTC. Numerical values can be entered using many common units. However, the

default units are kilometers, seconds (time), and arc-seconds (angular measure).

Program output can be directed to the computer screen or to data files. Graphics output can be directed to color PostScript files or to X/Motif devices.

Before discussing the major features of Percy, a few key concepts must be presented. The next section presents basic information about time and window manipulation concepts. A later section describes solar system body conventions.

Time, Windows, and Intervals

Every Percy session has a set of default time bounds. These bounds represent the default time limits of all commands. The SET BOUNDS command is used to set the default time bounds until the end of the Percy session. For example, to set the session bounds to the entire year of 1997, enter :

```
SET BOUNDS FROM 1 JAN 1997
TO 1 JAN 1998;
```

A key Percy idea is the concept of a "window". A window is a finite collection of disjoint (non-overlapping) time intervals. For example, the following set of three time intervals forms a window :

```
From 1 JAN 1997 12:00:00
To 2 JAN 1997 03:00:00
```

```
From 4 JAN 1997 01:00:00
To 5 JAN 1997 11:00:00
```

```
From 9 JAN 1997 01:00:00
To 9 JAN 1997 01:02:00
```

Percy contains an extensive set of commands to create and manipulate named windows. To create a window named TEST1 with just one interval matching the default session bounds, enter :

```
CREATE TEST1;
```

To create windows with specific time intervals, additional arguments are needed. To create a window with one interval from 12/1/97 to the end of the default bounds enter:

```
CREATE TEST2 FROM DEC 1 1997;
```

To create a window with a single interval from the default start boundary to 11/1/97 enter :

```
CREATE TEST3 TO 1 NOV 1997;
```

Finally, to create a window with a single interval from 10/15/1997 until noon on 12/15/1997, enter :

```
CREATE TEST4 FROM 10/15/1997 00:00:00
TO 12/15/1997 12:00:00;
```

Note that in the above examples several different date formats were used. Percy understands many unambiguous date representations. By default, all date-time expressions are entered and displayed in calendar format, UTC.

Percy supports several primitive window operations. Among these are the basic set operations INTERSECT, COMPLEMENT, and UNION. The union of two windows is analogous to the union of two sets. The resulting window contains every point in either of the original windows. Two windows may be unioned with the UNION command. For example, to create a new window named TEST5 which is the union of TEST1 and TEST2, enter:

```
UNION TEST1 TEST2 TEST5;
```

Two windows may be intersected with the INTERSECT command. For example, to create a new window named TEST6 which is the intersection of TEST1 and TEST2, enter:

```
INTERSECT TEST1 TEST2 TEST6;
```

The COMPLEMENT command is useful for finding intervals when some condition is not fulfilled. For example, complementing TEST2 produces the intervals within the default bounds of the planning session that are not in TEST2. The following command creates a new window TESTC2:

```
COMPLEMENT TEST2 TESTC2;
```

Many other window manipulation commands are supported. The following table briefly lists each command:

COPY	Copies one window to a new window.
CREATE	Creates a new window.
DROP	Deletes a window.
RESTORE	Loads a window from a file.
STORE	Stores a window in a file.
COMPLEMENT	Complements a window.
CONTRACT	Reduces intervals by some time x.
EXPAND	Increases intervals by some time x.
FILL	Merges adjacent intervals.
FILTER	Deletes intervals less than time x.
SHIFT	Moves intervals +/- by some time x.
DIFFERENCE	Forms intervals by diff. two windows.
INTERSECT	Intersect two windows into a third.
UNION	Union two windows into a third.
SHOW WINDOW	Display intervals in a window.
SHOW BOUNDS	Display the current session bounds.

Bodies

Percy supports three types of bodies: ephemeris bodies, designated objects, and stars. An ephemeris body is any body for which ephemerides are available. Ephemeris files for the planets and their major satellites are supplied by the NAIF group at JPL.

Ephemerides for minor satellites, asteroids, and comets may be numerically integrated from user supplied orbital elements. HST and other artificial satellites for which ephemeris data exists are also considered to be ephemeris bodies.

Ephemeris bodies for which physical size/shape data is known are drawn graphically as tri-axial ellipsoids. The physical data is also needed for some geometrical event calculations (e.g. occultation calculations).

A designated object is a temporary object, created by one of the DESIGNATE commands. Each designated object is specified by a set of coordinates in a particular Target Reference Frame (TRF) centered at a particular ephemeris body. Each TRF is associated with a separate DESIGNATE command.

Stars are only displayed by the graphics subsystem. No geometrical event calculations can reference a star. For example, Percy does not currently support operations involving star occultation events.

Percy uses integer codes instead of names to refer to ephemeris bodies for two reasons. The names of some satellites conflict with the names of some asteroids and comets. Also, some satellites are commonly referred to by names other than those approved by the IAU.

The type of a body (barycenter, planet, satellite, comet, asteroid, or spacecraft) and the system to which it belongs (Earth, Mars, Jupiter, Saturn, Uranus, Neptune, or Pluto) can be recovered algorithmically from the integer code assigned to a body.

In practice, names are defined as symbols using the Percy DEFINE command. For example, to define symbols for the body codes for Phobos and Deimos (natural satellites of Mars):

```
DEFINE PHOBOS 401;  
DEFINE DEIMOS 402;
```

Following the above commands, references to these bodies can be made using either the integers or the symbolic names.

Negative codes are reserved for man-made objects such as the Hubble Space Telescope, the Galileo spacecraft, etc. The body code for HST is -1.

The smallest positive codes are reserved for the Sun and the planet barycenters:

```
0 Solar system  
1 Mercury  
2 Venus  
3 Earth  
4 Mars  
5 Jupiter  
6 Saturn  
7 Uranus  
8 Neptune  
9 Pluto  
10 Sun
```

The code for a natural satellite is normally computed by adding its IAU designation to 100 times the code for its barycenter. For example, Ananke, the 12th satellite of Jupiter (JXII), is body number 512. Some examples are listed below:

```
301 Moon  
401 Phobos  
402 Deimos  
501 Io  
502 Europa  
503 Ganymede  
504 Callisto  
801 Triton  
802 Nereid  
901 Charon
```

A planet is always considered to be the 99th satellite of its own barycenter. For example, Jupiter is body number 599.

```
199 Mercury  
299 Venus  
399 Earth  
499 Mars  
599 Jupiter  
699 Saturn  
799 Uranus  
899 Neptune  
999 Pluto
```

Numbers between 1001 and 1099 are assigned to designated objects as the objects are created. These numbers may not be used for ephemeris bodies.

Comets are numbered in the range [1000000, 2000000). Asteroids are numbered in the range [2000000, 3000000).

FIND Commands

Percy supports several FIND commands that find windows where some geometric constraint is satisfied. For example, a single FIND command can find the intervals when the Jovian satellite Io is occulted by Jupiter as viewed from Earth. The actual Percy command to do this over the session bounds could be :

```
FIND OCC OCCULTATION OF IO BY JUPITER
FROM EARTH;
```

Where OCC is the name of a window containing the intervals requested. IO, JUPITER, and EARTH are Percy symbols. The integer body codes could be used instead.

Eclipses and transits can also be found similarly :

```
FIND ECL ECLIPSE OF IO BY JUPITER FROM
EARTH;
```

```
FIND TRN TRANSIT OF JUPITER BY IO FROM
EARTH;
```

Window manipulation commands can be used to create a window named NOT_OBSCURED where Io is not "obscured" by Jupiter :

```
UNION      OCC      ECL OBSCURED;
UNION      OBSCURED TRN OBSCURED;
COMPLEMENT OBSCURED - NOT_OBSCURED;
```

Another FIND command could be used to find a window named PLAN_WIND within window NOT_OBSCURED when Io is at least 50 degrees from the Sun as viewed from the Earth :

```
FIND PLAN_WIND SEPARATION OF IO SUN
FROM EARTH GREATER THAN 50 DEGREES
WITHIN NOT_OBSCURED;
```

To summarize, the sequence of commands listed above in this section can be used to find time intervals under specific constraints. In this case, the constraints are that Io is not occulted by Jupiter, transiting Jupiter, eclipsed by Jupiter, and is greater than 50 degrees from the Sun. The time intervals for these conditions are in window PLAN_WIND.

Note that the WITHIN clause can often provide a significant performance improvement because it limits the time span of the FIND calculation to intervals previously calculated.

Note also the keyword DEGREES. The default for all angular quantities is ARCSECONDS.

Finally note that, other constraints in addition to GREATER THAN 50 DEGREES could have been specified such as LESS THAN 75 DEGREES.

Windows under the following constraints may be found using the FIND command:

ANGULAR RATE	The angular rate of a target body across the sky satisfies a numeric constraint.
APPARENT DIAMETER	The apparent angular diameter of a target body satisfies a numeric constraint.
CENTRAL MERIDIAN	The longitude of the sub-observer point on a target body is confined to a particular arc.
DISTANCE	The apparent distance between a pair of bodies satisfies a numeric constraint.
ECLIPSE	One target body is eclipsed by another.
ELONGATION	The angular separation of a target body from the Sun satisfies a numeric constraint.
MOONLIGHT	The Moon is visible from an Earth orbiting spacecraft.
OCCULTATION	One target body is at least partially occulted by another.
ORBITAL LONGITUDE	The orbital longitude of a target body is confined to a particular arc.
PHASE	The phase angle of a target body satisfies a numeric constraint.
QUADRATURE	The elongation of a target body is 90 degrees.
RANGE RATE	The range rate between a pair of target bodies satisfies a numeric constraint.
SAA	An Earth orbiting spacecraft is inside the South Atlantic Anomaly.
SEPARATION	The angular separation of a target body from the Sun satisfies a numeric constraint.

TRANSIT	One target body is in transit across another (full disc).
UMBRA	An Earth orbiting spacecraft is inside the (umbral) shadow of Earth.

Reports

A report is a tabular collection of function values over time. The values within a row all correspond to the same epoch. The values within a column all correspond to the same function. The functions are not necessarily numeric functions. (For example, a "Boolean" function that states whether or not an object is visible as a function of time.)

The following example illustrates how to create a report that gives the right ascension and declination of the Moon as seen from Earth as a function of time.

```
NEW ENTRY MOON_RA DESCRIPTION J2000
RIGHT ASCENSION OF 301 FROM 399
UNITS DEGREES      FORMAT X.XXXXXXX
HEADING "R.A.";
```

```
NEW ENTRY MOON_DEC DESCRIPTION J2000
DECLINATION OF 301 FROM 399
UNITS DEGREES      FORMAT X.XXXXXXX
HEADING "Dec.";
```

```
NEW ENTRY TIME DESCRIPTION TIME FORMAT
UTC HEADING "Time" NO LEGEND;
```

```
NEW REPORT MOON_POSITION ENTRIES
      TIME MOON_RA MOON_DEC;
```

```
GENERATE SMART REPORT MOON_POSITION
      FROM 15 MAR 1991
      TO 25 MAR 1991
      EVERY 1 DAY
      HEADER LEGEND;
```

The NEW ENTRY commands define the columns in the report. The NEW REPORT command defines the columns to put into the next report. The GENERATE SMART REPORT command specifies the time range, header, and report columns for the printed report. The output from these commands is:

```
R.A. --- J2000 RIGHT ASCENSION OF 301
      FROM 399 UNITS DEGREES
      FORMAT X.XXXXXXX
Dec. --- J2000 DECLINATION OF 301
      FROM 399 UNITS DEGREES
      FORMAT X.XXXXXXX
```

Corrections for stellar aberration are enabled.

Time (utc)	R.A. (degrees)	Dec. (degrees)
1991 MAR 15	3.380E+02	-5.6302818
1991 MAR 16	3.499E+02	0.1388443
1991 MAR 17	2.0758449<*	6.0211735
1991 MAR 18	14.7290874	11.7237596
1991 MAR 19	28.0758534	16.9129390
1991 MAR 20	42.2451251	21.2271872
1991 MAR 21	57.2206409	24.3105445
1991 MAR 22	72.7833123	25.8708325
1991 MAR 23	88.5284585	25.7492790<
1991 MAR 24	1.040E+02 *	23.9659817
1991 MAR 25	1.188E+02	20.7099431

The "*" is used to mark changes of magnitude. The ">" is used to mark points where a quantity begins increasing. The "<" is used to mark points where a quantity begins decreasing.

Satellites, Comets, and Asteroids

Percy can generate NAIF formatted ephemeris files (.BSP files) for satellites, comets, and asteroids using two body numerical integration. These ephemeris files can then be used in FIND commands, reports, or other Percy commands.

Ephemeris files are created using the MAKE SATELLITE, MAKE ASTEROID, or MAKE COMET commands. These commands accept an epoch and a set of orbital elements in various formats. The ephemeris file is generated relative to a user specified time span.

The following example creates an asteroid for the month of March 1990 using body number 10001. The file is SAMPLE.BSP.

```
MAKE ASTEROID 10001 USING ELEMENTS
SEMI-MAJOR AXIS      294123638.3 KM
ECCENTRICITY         0.51376
INCLINATION          21.289 DEGREES
LONGITUDE OF NODE   173.213 DEGREES
ARGUMENT OF PERIAPSE 11.59 DEGREES
MEAN ANOMALY AT EPOCH 49.10 DEGREES
EPOCH OF ELEMENTS   21 AUG 1989
BEGINNING            1 MAR 1990
ENDING               1 APR 1990
FRAME                EQUATORIAL
EQUINOX              J2000
MAXIMUM ABSOLUTE ERROR 500 KM
INSERT INTO NEW      SAMPLE.BSP;
```

The following example creates a comet for the months of June, July, and August 1989 using body number 10001. The file is RACKNE.BSP.

```

MAKE COMET 10001 USING ELEMENTS
DISTANCE OF PERIAPSE      294123638.3 KM
ECCENTRICITY              0.51376
INCLINATION               21.289 DEGREES
LONGITUDE OF NODE        173.213 DEGREES
ARGUMENT OF PERIAPSE     11.598 DEGREES
TIME OF PASSAGE          1 JUN 1989
EPOCH OF ELEMENTS        1 SEP 1989
BEGINNING                 1 JUN 1989
ENDING                    1 SEP 1989
FRAME                     EQUATORIAL
EQUINOX                   J2000
MAXIMUM ABSOLUTE ERROR   500 KM
RADIAL NONGRAV            7.01E-10
TANGENTIAL NONGRAV       1.549E-10
INSERT INTO NEW          RACKNE.BSP;

```

The following example creates a satellite of Venus for the months of June, July, and August 1989 using body number 201. The file is SAT.BSP.

```

MAKE SATELLITE 201 ORBITTING VENUS
USING ELEMENTS
SEMI MAJOR AXIS           29438.3 KM
MEAN LONGITUDE AT EPOCH  219.31 DEGREES
MEAN MOTION               419 DEGREES/DAY
EPOCH OF ELEMENTS        21 AUG 1994
INCLINATION               31 DEGREES
BEGINNING                 1 JUN 1989
ENDING                    1 SEP 1989
INSERT INTO NEW          SAT.BSP;

```

User Ephemeris File Generation

NAIF formatted ephemeris files are often not in an ideal form for use by other software systems. Percy supports the generation of two types of ephemeris files. The first file is human readable and in the traditional form where state vectors are written one per line. Each line contains the time followed by the Cartesian position and velocity vectors. The ephemeris for a body can be generated relative to any other body with or without light-time correction. The Percy TRACK command generates these files.

The second form of ephemeris file contains a piecewise Chebychev polynomial representation. This representation is limited to ephemeris data that is relative to the Earth and light-time corrected. These files are not human readable, but they are portable to any computer platform. The Percy CHEBY command generates these files. Applications using CHEBY generated files must call Percy C++ software to determine state vectors for the body.

The following TRACK command generates a file relative to Earth for Io. The ephemeris is generated over the window named A_WIND. The output filename is A_FILE.TRH. The data (not light-time corrected) is generated every 5 minutes.

```

TRACK IO RELATIVE EARTH OVER A_WIND
EVERY 5 MINUTES INTO A_FILE;

```

The following command adds light time correction. The command also generates points such that linear interpolation between the points yields an accuracy of 0.1 arcseconds.

```

TRACK IO RELATIVE EARTH OVER A_WIND TO
0.1 ARCSECONDS INTO A_FILE CORRECT FOR
LIGHT TIME;

```

The following CHEBY command generates a Chebychev polynomial ephemeris file. This example generates a file named A_FILE.CBY which essentially contains the same information as that generated in the last TRACK command.

```

CHEBY IO FROM 1 JAN 1990 TO 1 FEB 1990
INTO A_FILE ANGULAR_ERROR 0.1;

```

Graphics

Percy can generate instantaneous wireframe graphical displays of the solar system. Currently, Percy supports graphical display to X/Motif devices and color PostScript files. At a minimum, given a time, a pointing, a vantage point, and a field of view, Percy can draw the scene that would be visible from a telescope. For example, a scene of Jupiter, its satellites, and background stars can be plotted as viewed from HST. HST apertures can also be included in the field of view.

The image plane of the telescope is centered at the optic axis. Points in the image plane are specified by their coordinates along axes labeled V2 and V3. Percy normally draws scenes as you would see them in images returned from the telescope. V2 is normally positive to the right, V3 is positive up, and V1 is positive toward you. V2V3 values are normally measured in arc seconds. The V1 axis lies along the boresight of the telescope.

The contents of a scene depend primarily on the current time, location (vantage), and orientation (pointing) of the telescope. The term "roll angle" denotes the spherical angle, measured at the telescope +V1 axis, between the reference axis vector and the +V3 telescope axis. For example; with celestial north as the reference vector, roll angle is the north position angle, at +V1, of the +V3 axis. By convention, roll angle is measured counterclockwise, through east.

By default, the telescope assumes a "nominal" roll. This means that the +V3 axis is placed such that the sun lies in the V1/+V3 half-plane. The roll angle can be changed by the SET ROLL command.

The term "orientation" denotes the celestial orientation of the sky with respect to the graphics device. For example; a

North-up orientation is one in which celestial north lies in the "up" direction on the screen. By default, the sky is presented in a North-up orientation. The orientation can be changed by the SET ORIENTATION command.

The term "instrument" denotes the position (in V2/V3 coordinates) of the telescope field-of-view which overlays the pointing position. This will determine the apparent positions of the overlays with respect to the sky. By default, the instrument position is the +V1 axis; i.e. the center of the field-of-view ($V2 = V3 = 0$). However, an arbitrary field-of-view location can be placed over the object of interest via the SET INSTRUMENT command.

The term "center" denotes that location on the sky, in celestial coordinates (e.g. right ascension, declination) which corresponds to the center of the graphic device. By default, the position specified by the SET POINTING command becomes the center of the plot. However, the center position may be changed by use of the SET CENTER command.

The Percy commands to generate graphical images are listed below :

SET MOTIF	All commands that follow are to generate graphics to an X/Motif window.
SET POSTSCRIPT	All commands that follow are to generate graphics to a PostScript file.
SET TIME	Set the time for the next image.
SET POINTING	Set the direction to "look". Could be a body.
SET VANTAGE	Set the position to view from. Could be a body.
SET FIELD OF VIEW	Sets the field of view angle.
SET ROLL	Sets the roll angle of a spacecraft.
SET ORIENTATION	Sets the orientation of a spacecraft.
SET INSTRUMENT	Sets the instrument or position within the field of view to place target.

SET CENTER	Defines the center of a plot relative to the graphics device.
SET ATTRIBUTE	Sets specific colors or other characteristics for a graphics object.
SET PICTURE	If more than one image is to be plotted, this command identifies the next image to be updated.
SET MAGNITUDE LIMITS	Sets the magnitude range for the display of stars.
SET OVERLAYS	Identifies one or more graphics overlays to be displayed. Overlays can be used to indicate grid lines or telescope apertures.
DRAW	Executes the drawing operation for the currently defined scene.

The following sequence of commands illustrates the typical sequence of commands. Four pictures are created. The first centers a wide field of view on Jupiter. The others center a much narrower field of view on Io, Europa, and Ganymede.

```

SET MOTIF;
SET TIME 1 JAN 1997;
SET FIELD OF VIEW 4 ARCMINUTES;
SET POINTING AT JUPITER
SET PICTURE 1 OF 4 ;
DRAW;

SET FIELD OF VIEW 2 ARCSECONDS;
SET POINTING AT IO;
SET PICTURE 2 OF 4 ;
DRAW;

SET POINTING AT EUROPA;
SET PICTURE 3 OF 4 ;
DRAW;

SET POINTING AT GANYMEDE;
SET PICTURE 4 OF 4 ;
DRAW;

```

Remarks

Percy is a robust tool for the planning of ground or space based observations of solar system objects. Percy was originally developed specifically for HST observation planning. While it contains some HST specific features, Percy should be useful for almost any ground or spacecraft based observing system. Percy is planned to be used for the Far Ultraviolet Spectrographic Explorer (FUSE) spacecraft.

This paper has presented a very brief introduction to the Percy program. Percy supports many features, commands, and command options that were not mentioned here. See the reference below for more information.

Reference

Complete documentation for Percy can be found on the World Wide Web in:

http://www.pst.stsci.edu/moss/percy_main.shtml