



SSVG User's Guide

Solar System Voyager

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What is SSVG?

SSVG (Solar System Voyager) is simulation software that allows us to fly our own spacecrafts in the solar system. Each spacecraft (Probe) has three propulsion systems: a chemical propulsion engine, an electric propulsion engine, and a solar sail.

In SSVG, we send off our Probe to its voyage from one of the space bases maintained in space, so we do not need to launch the Probe from the surface of Earth.

In SSVG, we compose a “Flight Plan” to fly our Probe to its destination with every detail of the flight. The main parts of the Flight Plan are instructions to the Probe; we call them as “Maneuvers.” There are several types of Maneuvers, one to start the Probe, another to fly the Probe, and others to activate and/or deactivate one of the propulsion systems.

Throughout the composition of a Flight Plan, SSVG draws positions and orbits of the Probe on a three dimensional (3D) chart, and we can manipulate (rotate, zoom, etc.) it. SSVG draws positions and orbits of the Target (a celestial body to which the Probe targeting), and positions of planets on it as well.

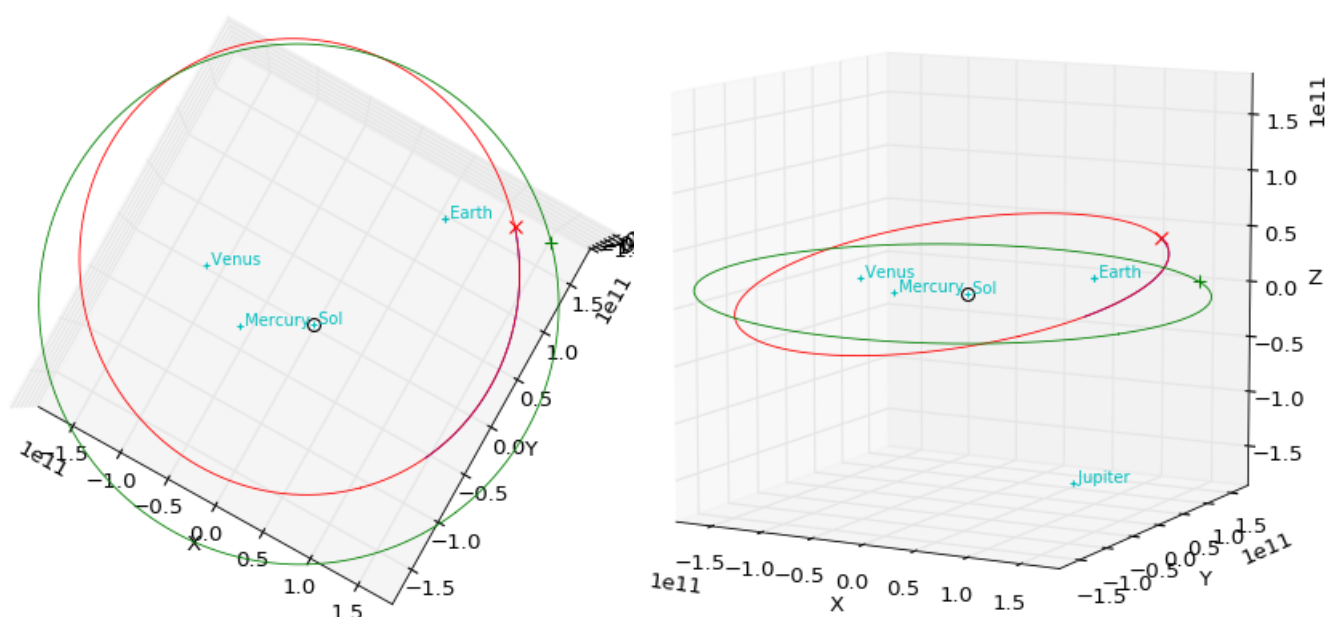


Figure 1 3D charts of SSVG

What Can We Get with SSVG?

What can we get with SSVG? There are some samples.

Change Orbit of the Probe

Do you have any questions for space flight as follows?

- When I accelerate my spacecraft, how does it change its orbit?
- When I accelerate it more violently, what happens?
- When I decelerate it, what happens?
- When I accelerate it laterally, what happens? By the way, which direction is “lateral” in space?

We can look for answers for these questions by ourselves. In SSVG, we can change the velocity of the Probe freely. Resulting orbit is drawn on a 3D chart, then we can manipulate (rotate, zoom, etc.) the chart to grasp shapes and orientations of the orbits in the 3D space.

Unplanned Space Flight

Do you dream of flying in the space freely?

In the actual world, even if we have a spacecraft in outer space, it is a very hard thing to make it arrive to desired celestial body. Because significant orbital transfer requires large amount of propellant, actual spacecraft is usually sent forth in an orbit that is carefully designed in advance and it bring the spacecraft to its destination with small intermediate orbital corrections. Almost all space flights are “planned” ones.

In SSVG, we have entirely different choice for the strategy to perform a space flight. Our Probe can fly its space travel with “unplanned,” or “try and discover” manner.

Gravity Assist

Do you know a gravity assist? Do you want to try it?

When a spacecraft flies by a planet, the gravity of the planet pulls the spacecraft. Using that gravitational pull, we can change orbit of the spacecraft sometimes slightly, sometimes violently. We call it as a “gravity assist” or a “swing-by.”

Because Jupiter is the heaviest and the nearest planet of giant planets of the solar system, gravity assists from it played essential roles on many space flights bound to outer region of the solar system.

For its Probe, SSVG computes realistic trajectories that include gravity assists. In addition, SSVG offers convenient functions for utilizing gravity assists. Let us try some gravity assists of

Jupiter in SSVG.

Replicate Actual Space Flights

Do you have any questions for actual flights of spacecrafts as follows?

- When it left the vicinity of Earth, how fast was it moving relative to Earth?
- When it arrived at the vicinity of the destination body, how fast was it moving relative to the body?
- Why a spacecraft left the vicinity of Earth that day?
- Why a spacecraft arrived at the vicinity of the destination body that day?
- A spacecraft flew toward the destination after getting gravity assist of Jupiter; why didn't it fly directly?

We can replicate space flights of actual spacecrafts as Flight Plans of SSVG. By executing these Flight Plans, we will find answers for previous questions by ourselves.

Two pictures of Figure 2 show a replicated trajectory of Voyager 2, one of the most famous space probes of NASA/JPL. It left the vicinity of Earth in 1977, with a tremendous speed of about 10 kilometers (6.25 miles) per second. It visited all of four giant planets sequentially and completed observations of all of them, and even now, it is continuing its flight to outer space.

The left side picture of Figure 2 shows entire replicated trajectory from 1977 to end of 2020. A small ellipse in green shows the orbit of Neptune, the outermost planet of the solar system, so you can feel the great distance of this trip. At the end of 2020, the space probe is about 20 billion kilometers (12.5 billion miles) away from Sun; this distance is 133 times of the one from Sun to Earth. The right side picture shows a close-up. At several places, the trajectory of the space probe (curved line in blue) bended sharply by getting gravity assists of giant planets.

Note that although we intended to replicate the actual space flight, the trajectory is not so accurate.

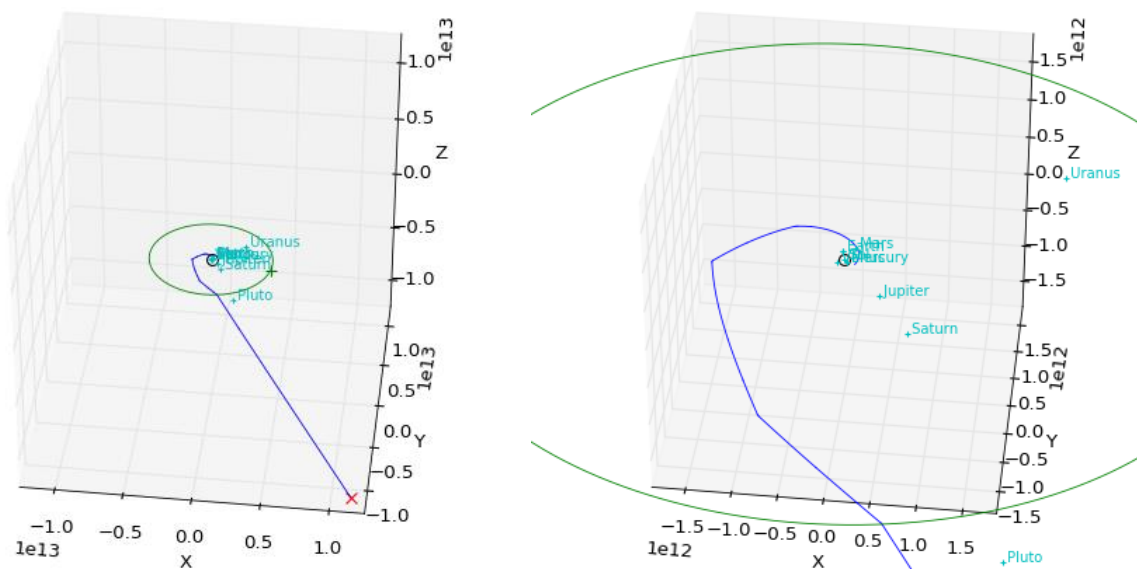


Figure 2 Replicated trajectory of Voyager 2

Compose Feasible Flight Plan

Do you want to compose “feasible” Flight Plans?

Although we can choose any flight path as we like in SSVG, cannot for actual space flights. Because actual space probes are imposed strict limitation of propellant, they cannot choose but very “economical” flight paths.

Feasibility of a space flight may have many aspects as you know, and “economical” (less starting velocity, less orbital maneuvers, etc.) is one of the largest keywords for it. Let us compose economical Flight Plans in SSVG. Achieving this, we have to select two key parameters: date to leave Earth, and flight time. For deciding them, SSVG has convenient functions, powerful and easy to use.

Use Electric Propulsion

Do you want to use electric propulsion?

During recent years, electric propulsion systems (ion thrusters and/or Hall-effect thrusters) were playing essential roles in several space missions exploring asteroids and Ceres, a dwarf planet. They have a large advantage in propellant efficiency over conventional chemical rockets. However, they have a disadvantage in magnitude of the thrust. Typical electric propulsion system accelerates a spacecraft very slowly (from several meters per second to several ten meters per second, by full power operation of 24 hours). Because of this low thrust, it is not a rare case that an orbit transition requires very long time (e.g. 100 days or more), and it makes planning of space flights using electric propulsion systems far more difficult than commonly used chemical propulsion.

Put your heart at ease. A Probe of SSVG has an electric propulsion engine, and that is very easy to use and very powerful. It can be used for low-thrust & long-time orbit transitions, and for high-thrust & short-time orbit transitions either. Let us fly our Probe with the electric propulsion engine.

Use Solar Sail

Do you want to use a solar sail?

Solar sails are large mirrors attached to spacecrafts; they get thrust forces by reflecting the sunlight. Solar sails have a significant advantage in space flight; they need no propellant and no energy for thrusting. However, because pressure of the sunlight is so small, usually we need very light and very large sails (e.g. one hundred square meters or much more) to get effective accelerations. With current technologies, it is very difficult to spread, turn, and hold such large sails in space.

No problem. In SSVG, the Probe spreads its solar sail any time, to any size, and to any orientation following instructions from us. Let us fly our Probe with the solar sail.

How to Use this Document

This document (SSVG_UsersGuide-en.pdf) was reviewed with Adobe Acrobat Reader DC. This software can be downloaded from following URL.

<<https://get.adobe.com/reader/>>

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In this document, links are displayed in colored characters with under line. Links to the internet are in blue (see the third line of this section). Links to the bookmarks of this document are in green (e.g. [License of SSVG](#)).

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The source code of this program can be retrieved from:
<<https://github.com/whiskie14142/SolarSystemVoyager/>>

SSVG uses following programs and modules:

Numpy: <http://www.numpy.org/>
Scipy: <http://scipy.org/>
matplotlib: <http://matplotlib.org/>
PyQt4: <https://www.riverbankcomputing.com/news/>
jplephem: <https://github.com/brandon-rhodes/python-jplephem/>
julian: <https://github.com/dannyzed/julian/>
pytwobodyorbit: <https://github.com/whiskie14142/pytwobodyorbit/>
spktype01: <https://github.com/whiskie14142/spktype01/>
PyInstaller: <http://www.pyinstaller.org/>

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Contact the Author

e-mail: <<mailto:whiskie14142@gmail.com>>

Twitter: Tweet with the hashtag “#SSGV”

Please note that it may take time to reply.

How to Use SSVG

Install and Uninstall SSVG

SSVG is distributed with two formats: an executable of Microsoft Windows, and a set of source programs of Python. You can use any one of them or both.

Windows Executable

Install

You can get a Windows executable of SSVG as a compressed file named “SSVG_x_x_x.zip” (x_x_x is the version number). Open it with your convenient tool, and copy the “SSVG” folder on your PC.

Uninstall

Delete installed “SSVG” folder with its contents.

PC environment

Windows executable of SSVG was tested on Windows 8.1 (64bit) and Windows 10 (64bit).

Recommended display size is 1024 pixel x 1600 pixel or more.

Get SPK file

The program package of SSVG does not contain an essential data file to compute positions and velocities of Sun and planets. Get the data file (a SPK file, named de430.bsp) from following address, and place it in the “data” folder within the “SSVG” folder.

<http://naif.jpl.nasa.gov/pub/naif/generic_kernels/spk/planets/de430.bsp>

Python Source Programs

Install

If you have Python 3.5 with Numpy/Scipy/matplotlib/PyQt4, you may run SSVG on your Python environment. You can retrieve Python source programs of SSVG from GitHub.

<<https://github.com/whiskie14142/SolarSystemVoyager/>>

On the mentioned web page, click “Clone or download.” You will get a ZIP file; open it with your convenient tool, and copy the “source” folder on your PC.

Uninstall

Delete installed “source” folder with its contents.

PC environment

Python 3.5

Recommended display size is 1024 pixel x 1600 pixel or more.

Packages used and their versions

Numpy 1.10.4, Scipy 0.17.0, matplotlib 1.5.1, pyqt 4.11.4,

jplephem 2.6, julian, pytwobodyorbit 0.1.0, spktype01 0.1.0

Last four modules (jplephem, julian, pytwobodyorbit, and spktype01) are registered on the Python Packages Index (PyPI), so you can install them with pip command.

Get SPK file

Installed source programs of SSVG do not contain an essential data file to compute positions and velocities of Sun and planets. Get the data file (a SPK file, named de430.bsp) from following address, and place it in the “data” folder within the “source” folder

<http://naif.jpl.nasa.gov/pub/naif/generic_kernels/spk/planets/de430.bsp>

Run SSVG

Windows Executable

Double click SSVG.exe, which is contained within the “SSVG” folder installed.

Python Source Program

Run SSVG.py from Python. SSVG.py is contained within the “source” folder installed.

Run Flight Plan

Open a Flight Plan

When we run SSVG, we see two windows; those are SSVG window and 3D Orbit window. Because we have no valid Flight Plan yet, those windows do not display any meaningful information.

Click “File” on the menu bar of the SSVG window, and execute “Open.” We can find a folder named “sampleplan” within the installed folder, and it contains several samples of Flight Plan. Select “Mars01.json” among them and open it.

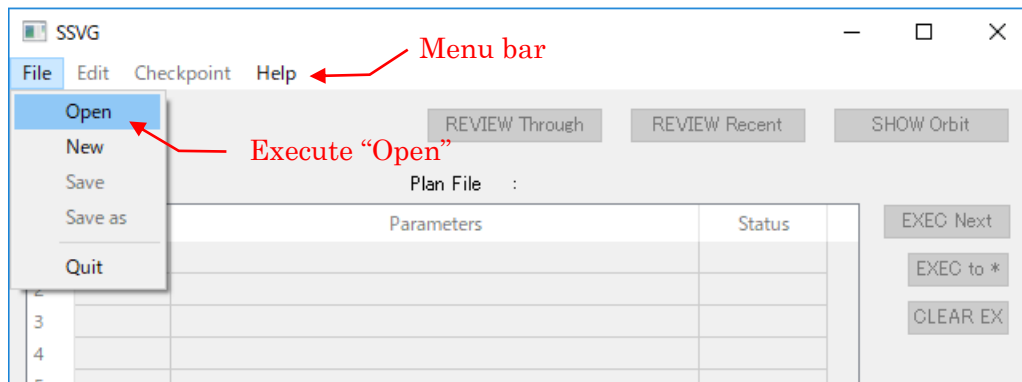


Figure 3 Execute “Open”

In this Flight Plan, a Probe named “Marsexp” starts its flight from a Space Base named “EarthL2”, and flies to Mars. The SSVG window displays the Flight Plan as a table. Each line (row) of the table contains a Maneuver that instructs the Probe to execute an operation. We call the table as “Maneuver Table” (see next figure). As we execute all Maneuvers in the table one by one, from top to bottom, the Probe flies from the Space Base to Mars.

The screenshot shows the SSVG application window with the 'Maneuver Table' displayed. The table has three columns: 'Type', 'Parameters', and 'Status'. The first row (1) is 'START' with 'Next' in the status column. The subsequent rows (2-9) are 'FLYTO' and 'CP' maneuvers with specific dates and parameters. The status column for these rows is empty. The status bar at the bottom shows 'Current Status' and 'Selected Maneuver 1 START'.

	Type	Parameters	Status
1	START	Date=2018-05-05 dv=2533.76 phi=12.64 elv=-32.88	Next
2	FLYTO	Date=2018-06-14 inter=1.00	
3	CP	dv=324.14 phi=-84.61 elv=-0.79	
4	FLYTO	Date=2018-09-07 inter=1.00	
5	CP	dv=27.33 phi=-95.87 elv=-7.88	
6	FLYTO	Date=2018-12-05 inter=1.00	
7	FLYTO	Date=2018-12-05 inter=0.01	
8	CP	dv=1981.38 phi=16.19 elv=-4.43	
9	FLYTO	Date=2018-12-10 inter=0.01	
10			

Figure 4 Maneuver Table

Execute a Maneuver

The Maneuver Table contains three columns; they are labeled as “Type”, “Parameters”, and “Status” respectively. There is one line (row) with “Next” in the Status column. This “Next” indicates that SSVG will execute this line next. We call this line as “Next Line.”

Click [EXEC Next] button of the SSVG window. SSVG executes the Maneuver in the Next Line, and it opens a new window named “Show Orbit” (see next figure).

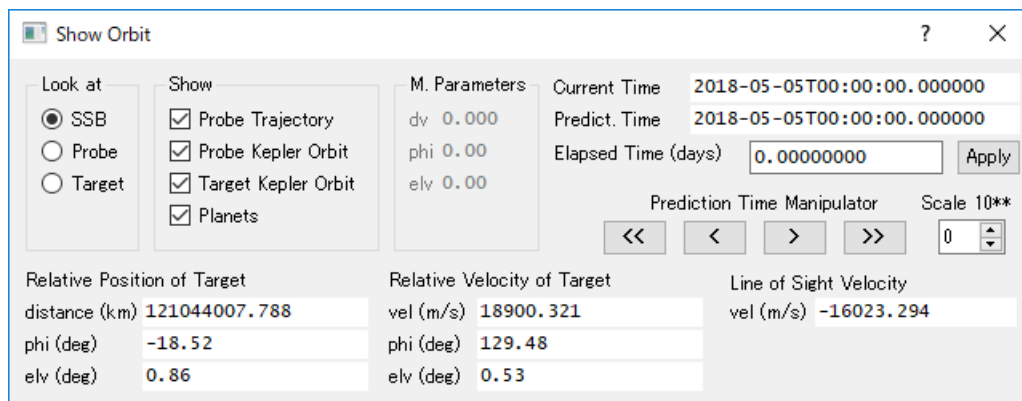


Figure 5 Show Orbit window

As shown in the next figure, the 3D Orbit window displays following information as a three dimensional (3D) chart, after execution of Maneuvers:

- The Probe (an X mark in red)
- Orbit of the Probe (a curved line in red)
- The Target (a + mark in green)
- Orbit of the Target (a curved line in green)
- Sun (a small circle in black)
- Planets (+ marks and names in cyan)

At this point (just after you opened Mars01.json and clicked [EXEC Next] once), the Probe left the space base just now, and started its journey to Mars.

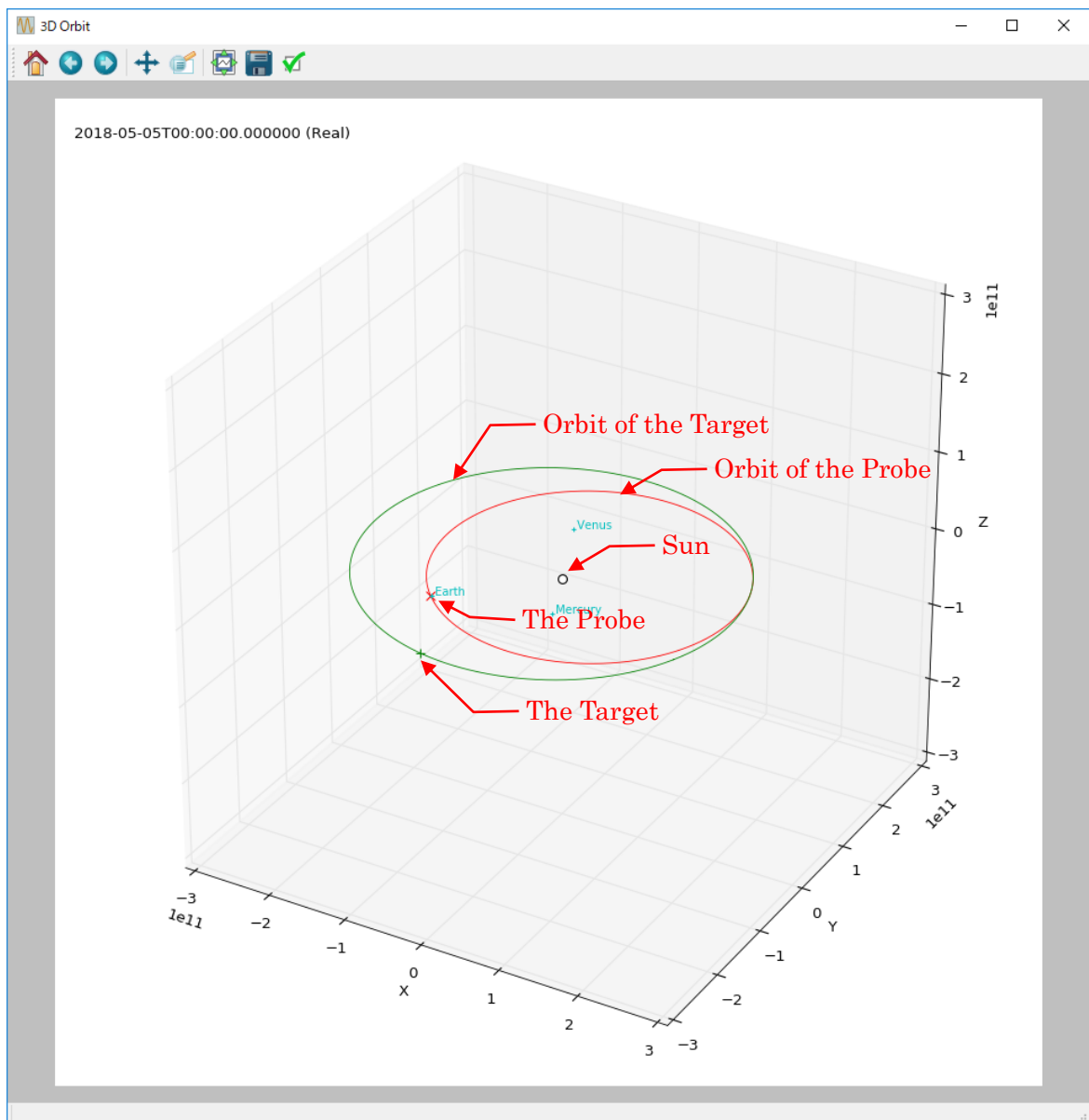


Figure 6 Information displayed on the 3D Orbit window

Let us try manipulating the chart displayed on the 3D Orbit window. Place the mouse cursor on the 3D Orbit window, and move it up/down or right/left with left button held down; it makes the 3D chart rotate. Move the mouse cursor up/down with right button held down; it makes the chart zoom out and zoom in.

Some manipulations of the chart are operated on the Show Orbit window; click [\gg] button in the “Prediction Time Manipulator” (see next figure) several times. The chart shows positions of the Probe, Mars (the Target), and other planets, at moments in the future.

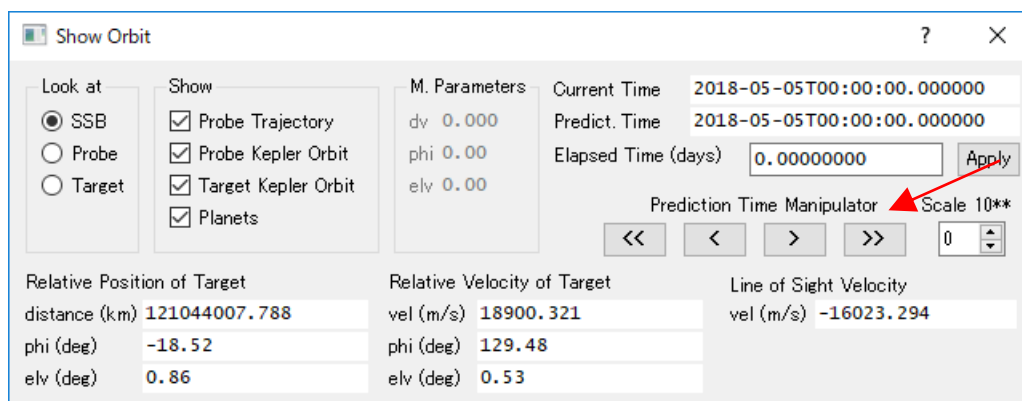


Figure 7 Prediction Time Manipulator

If you wish to know precise manipulation method, see [3D Orbit Window](#) and [Show Orbit Window](#).

Execute Maneuvers

Let us continue executions of Maneuvers. When we click [EXEC Next] button three times more, three Maneuvers next in the table will be executed one by one, toward the bottom: the Maneuvers in the second, third, and fourth line (row).

In SSVG, there are seven types of Maneuvers. This sample uses three types of Maneuvers as follows:

START Maneuver: The Probe starts the space flight with specified velocity.

FLYTO Maneuver: The Probe flies until specified time.

CP Maneuver: The Probe uses Chemical Propulsion Engine and makes an orbit transition.

You can see explanations of all seven types of Maneuvers in [Maneuver](#).

Review Recent Flight

Immediately after an execution of a FLYTO Maneuver, you can review the flight. At this point, because we just executed FLYTO Maneuver in the fourth line (row), we can review it. Click [REVIEW Recent] button of the SSVG window. The Flight Review window replaces the Show Orbit window. With clicking buttons of its Review Manipulator (see next figure), you can see progresses of that flight on the 3D Orbit window. As you click [>] button repeatedly, you see the Probe (the X mark in red) flies on its orbit toward Mars (the Target: the + mark in green).

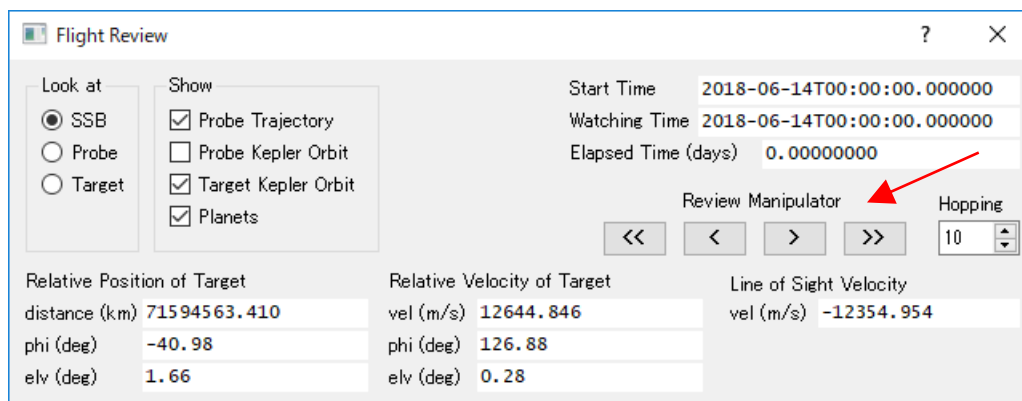


Figure 8 Flight Review window

Let us review the last FLYTO Maneuver of this Flight Plan. Click [EXEC Next] button several times on the SSVG window, and let the tenth line (a blank line) of the Maneuver Table shows the “Next” in the Status column. Then click [REVIEW Recent] button on the SSVG window to review the last Maneuver.

At this point, the Probe is very close to the Target (Mars); distance to the Target is less than 9000 kilometers (5625 miles). Because this distance is very short in the scale of the solar system, the chart on the 3D Orbit window displays the Probe and Target at almost the same position. We need to get a close-up view of the Target and the Probe to make detailed observations.

Let us place the Target at the central point of the chart, get a close-up view, and review the flight. There are hints for operations as follows:

- How can we place the Target at the central point of the chart?
Select [Target] radio button in the “Look at” group on the Flight Review window.
- How can we get a close-up view of the chart?
Place the mouse cursor on the 3D Orbit window, and move it downward with right button held down.
- How can we rotate the chart?
Place the mouse cursor on the 3D Orbit window, and move it up/down or right/left with left button held down.
- How can we follow the flight?
Click buttons in the “Review Manipulator” on the Flight Review window.

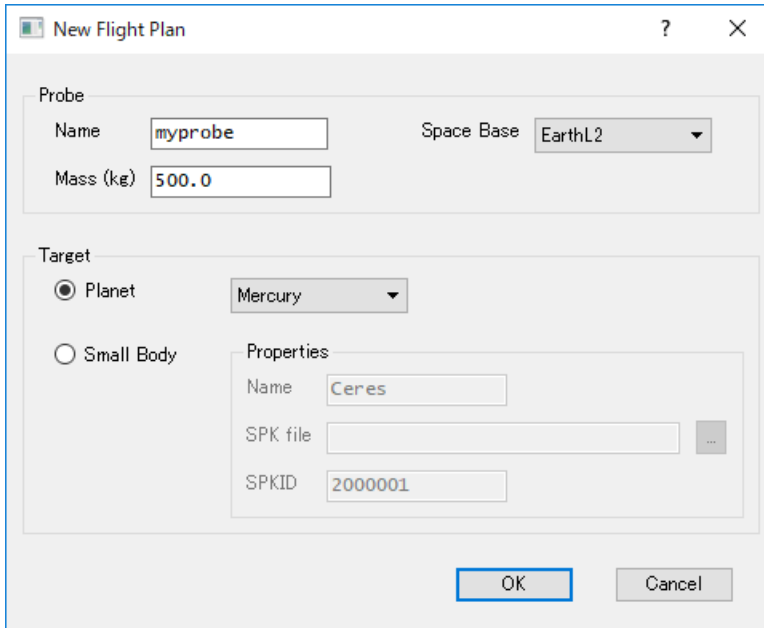
If you want to know precise manipulation method, see [3D Orbit Window](#) and [Flight Review Window](#).

Fly New Probe

Let us compose a Flight Plan of a new Probe.

Generate New Flight Plan

To generate new Flight Plan, click “File” on the menu bar of the SSVG window, and execute “New”. The New Flight Plan window appears.



The image shows a "New Flight Plan" dialog box with the following fields and values:

- Probe**
 - Name: myprobe
 - Mass (kg): 500.0
 - Space Base: EarthL2 (dropdown)
- Target**
 - ☒ Planet: Mercury (dropdown)
 - ☐ Small Body
 - Properties
 - Name: Ceres
 - SPK file: (empty)
 - SPKID: 2000001

Buttons: OK, Cancel

Figure 9 New Flight Plan window

On the “Probe” group, we can specify name and mass of the Probe, but in this case let us use the default value. We can select one of a Space Base in the drop-down list, but let us use the default “EarthL2” now. This Space Base is orbiting Sun with Earth. Its position is approximately 1.5 million kilometers (940 thousand miles) away and opposite to Sun, from the center of Earth.

On the “Target” group, let us select Mars as a Target in the drop-down list.

When you clicked [OK] button, SSVG generate a new Flight Plan and displays it. Because it has not any Maneuvers yet, the Maneuver Table is empty but one blank line that indicates “Next”.

It is a good custom to save an editing Flight Plan at adequate timings. Let us click “File” of the menu bar, and execute “Save as” and save the Flight Plan with an appropriate name.

Start the Flight

Let us add the first Maneuver to the Flight Plan. It starts the flight of the Probe. The

Maneuver Table is empty now, but the first line indicating “Next” in the “Status” column. Click [EDIT Next] button to edit the line. The Maneuver Editor window appears.

Figure 10 Maneuver Editor window

The first Maneuver of a Flight Plan should be a START Maneuver, which starts the flight of the Probe. Select “START” in the drop-down list for Maneuver type, and click adjacent [Apply] button. The Maneuver Editor window becomes the one for a START Maneuver, the Show Orbit window appears below the Maneuver Editor window, and the 3D Orbit window shows current position and orbit of the Probe and other things. On the Maneuver Editor window, the time of zero o’clock of current date (midnight on the day you are operating SSVG) is assigned to the Start Time as the initial value. In addition, three zeros are assigned to three parameters of “dv”, “phi”, and “elv” respectively, in a table named “Parameters”. Those parameters (“dv”, “phi”, and “elv”) are specifying the start velocity (magnitude and direction) of the Probe, and they are editable now.

Now, let us modify the value of the parameter “dv” from 0.000 to 2500. Double-click the “0.000” in the first line (row) of the Parameters Table (see next figure), and rewrite the value from 0.000 to 2500. Leave other parameters (“phi” and “elv”) unchanged. This modification changes magnitude of the start velocity of the Probe from zero to 2500 (in meters per second). Start direction is the same to the velocity of the Space Base (*).

(*) Because the Space Base (EarthL2) is orbiting Sun with Earth, the velocity of the Space Base relative to Earth is a small one (the magnitude is roughly 300 meters per second). On the other hand, it is orbiting Sun with a large velocity (the magnitude is roughly 30 kilometers per second). In this case, “the moving velocity of the Space Base” means the one relative to Sun.

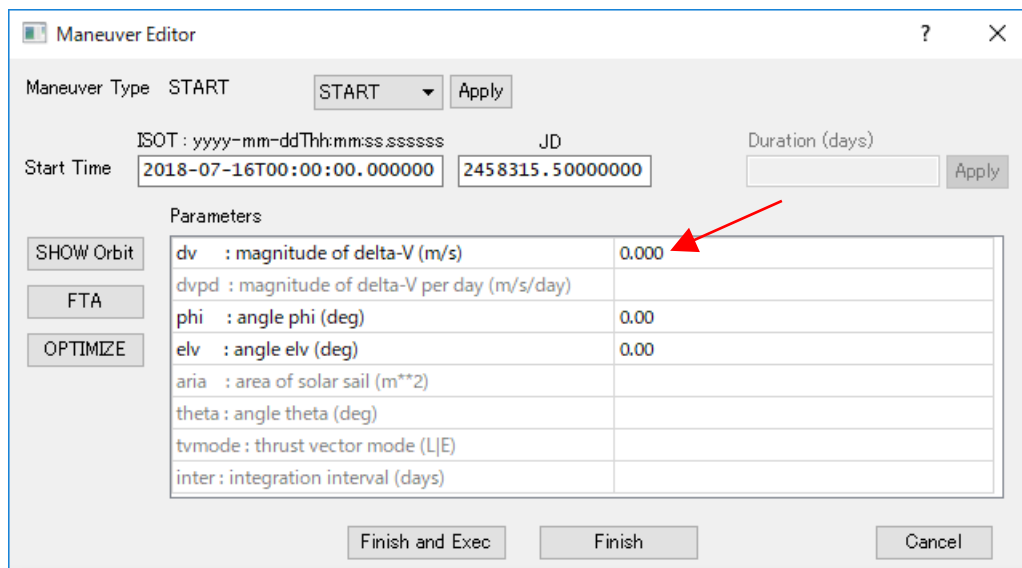


Figure 11 Maneuver Editor window (editing a START Maneuver)

Click [SHOW Orbit] button on the Maneuver Editor window. Modified parameter is applied temporarily to the Show Orbit window and the 3D Orbit window.

Click [Finish and Exec] button on the Maneuver Editor window. SSVG stores the START Maneuver into the Maneuver Table and execute it. Now, the Probe is on its journey. At this point, SSVG sets its “Current Time” to Start Time of the START Maneuver.

Fly Away from the Space Base

Our Probe started its flight, but it has not moved yet. Let the Probe fly away from the Space Base. We use a FLYTO Maneuver to fly the Probe; add it to the Maneuver Table.

Confirm that the second line of the Maneuver Table is a blank line but indicating “Next” on the “Status” column, and click [EDIT Next] button of the SSVG window. The Maneuver Editor window appears again. Select “FLYTO” for the Maneuver Type, and click adjacent [Apply] button. The Maneuver Editor window becomes the one for a FLYTO Maneuver, and the Show Orbit window appears again.

In this case, let us make a FLYTO Maneuver that flies the Probe for 50 days. On the Show Orbit window, click [>>] button five times, in the Prediction Time Manipulator (see next figure). Clicking this button changes prediction time; at the same time, it changes “End Time” and “Duration” of the Maneuver Editor window. As you click it, the “End Time” of the Maneuver Editor window (both ISOT and JD) goes ahead by ten days and the “Duration” (flight time) changes to a value consistent with the “End Time” of this Maneuver and current time of SSVG.

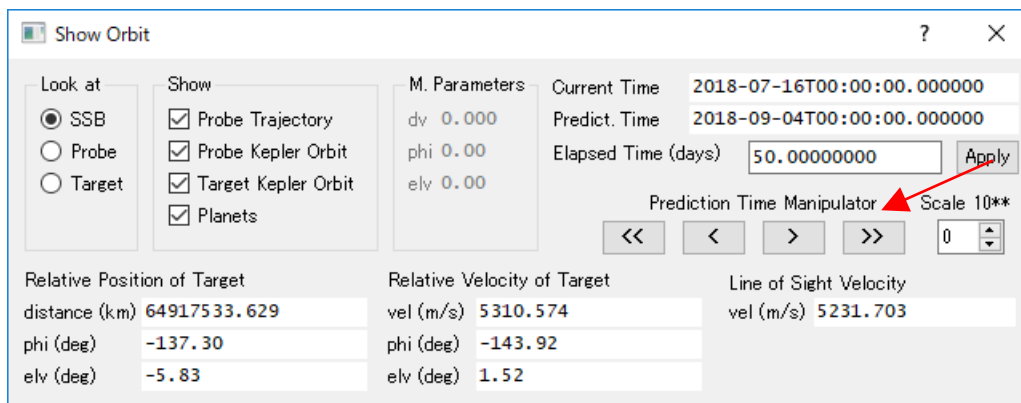


Figure 12 Set the End Time ahead

Confirm that the “Duration” on the Maneuver Editor window indicates 50 (days), and click [Finish and Exec] button. SSVG stores the FLYTO Maneuver into the Maneuver Table, and executes it. When the computation of the flight trajectory completes, the results are applied to the chart on the 3D Orbit window and to the “Current status” of the SSVG window. At this point, SSVG sets its “Current Time” forward, to End Time of the FLYTO Maneuver.

Accelerate the Probe

Now, let us accelerate the Probe to find out what happens to orbit of the Probe. For this, we use a CP Maneuver that utilizes Chemical Propulsion Engine of the Probe.

Confirm that the third line of the Maneuver Table is a blank line but indicating “Next” on the “Status” column, and click [EDIT Next] button on the SSVG window. The Maneuver Editor window appears. Select “CP” for the Maneuver Type of this window.

For a CP Maneuver, there are three parameters to be specified, “dv”, “phi”, and “elv”. The parameter “dv” defines magnitude of delta-V, which is the velocity vector to be added to the Probe by this Maneuver, velocity increment in other word. The pair of “phi” and “elv” defines direction of delta-V.

Let us change the value for “dv” from 0.000 to 3000. Double-click the cell with 0.000 (see next figure), and modify the value to 3000. Leave the values for “phi” and “elv” unchanged, respectively. With these parameters, this CP Maneuver accelerates the Probe by 3000 meters per second (e.g., this Maneuver adds 3000 meters per second to the magnitude of velocity of the Probe, and does not change the direction of velocity).

Now, click [SHOW Orbit] button of the Maneuver Editor window. Parameters on this window are applied to the Show Orbit window and the 3D Orbit window immediately, so you can find out what consequences will be produced by this Maneuver. Note that this is a temporary appliance, and to make it permanent, need you to finish the editing and execute the Maneuver.

If you wish, try other values for the parameter “dv”. Edit the value and click [SHOW Orbit] button. Every time you try another value, SSVG shows you another orbit.

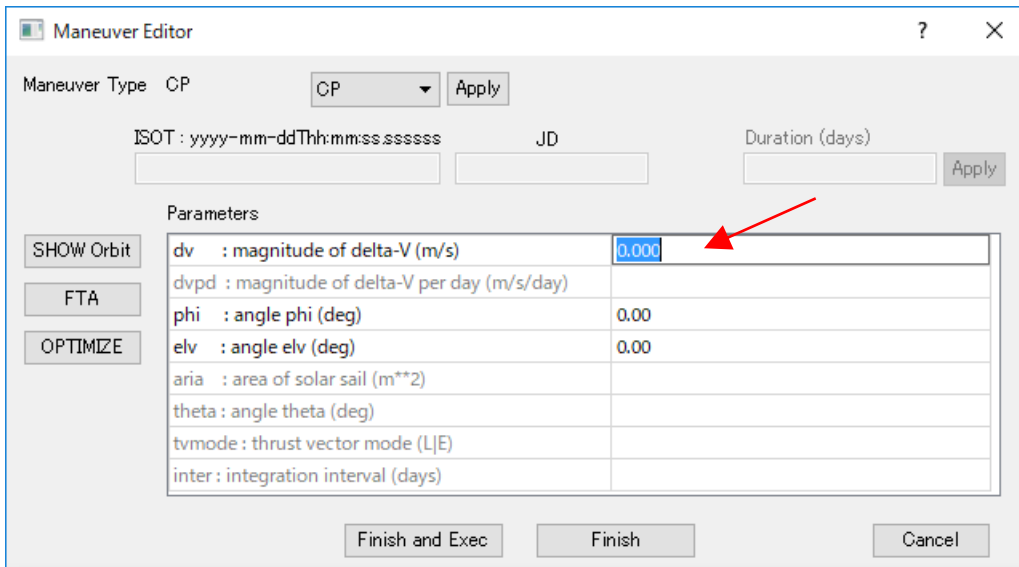


Figure 13 Maneuver Editor window for CP

Decelerate the Probe

When we do not accelerate but decelerate the Probe, what happens for its orbit? When we accelerate the Probe not in the direction of the velocity vector but in other directions, what happens for its orbit?

Looking for answers of these questions, we need to assign appropriate values for parameters “phi” and “elv”. See next figure. On this figure, ΔV indicates delta-V, which is the velocity vector to be added to the Probe by CP Maneuver.

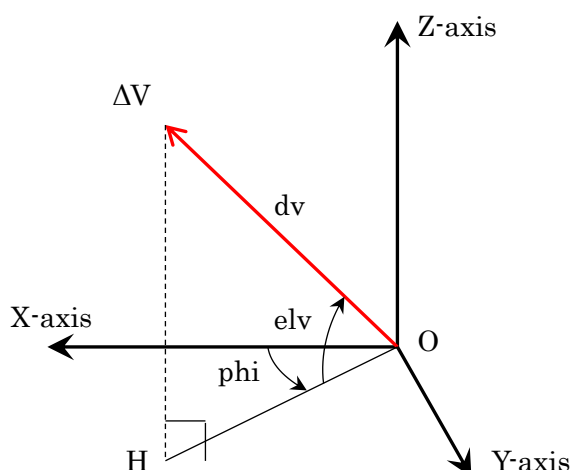


Figure 14 Defining parameters for delta-V

The origin (point O) of the axes is a Probe. The orbital plane of Probe about Sun defines X-Y plane, and the velocity vector of Probe defines the X-axis. The Z-axis is normal to the orbital

plane. The direction of Y-axis is to approach Sun, it is perpendicular to both X- and Z-axes, and it completes the right-handed Cartesian frame. In SSVG, we call this coordinate system as “Orbit Local Coordinate System.”

Drop a perpendicular line from the point of ΔV to the X-Y plane, and name the foot point as “H”. The parameter “phi” is the angle from X-axis to line segment OH. The parameter “elv” is the angle from line segment OH to ΔV .

You know it already, the parameter “dv” is magnitude of ΔV . The parameter “dv” is measured in meters per second, and “phi” and “elv” are measured in degrees.

Let us study parameters to decelerate the Probe. For deceleration, ΔV should have opposite direction for current velocity of the Probe. In the coordinate system of Figure 14, the velocity vector of the Probe has the same direction to the X-axis. Therefore, the ΔV should be a vector opposite to the X-axis, so parameter “phi” should be 180.0 (degrees) and parameter “elv” should be 0.0 (degree). For several values of “dv”, try decelerating the Probe and observe the orbits.

Accelerate the Probe Laterally

Let us accelerate the Probe laterally, precisely speaking, accelerate the Probe to a direction that is perpendicular to the velocity vector of the Probe. See [Figure 14](#) again on the previous page.

Because the direction of the velocity vector of the Probe is the same to the X-axis, any direction perpendicular to it lies on the Y-Z plane. Let us use following four directions as major examples.

- Direction of the Y-axis
- Direction opposite to the Y-axis
- Direction of the Z-axis
- Direction opposite to the Z-axis

The following table shows the values of parameters “phi” and “elv” for previous four directions, in addition to the two directions described in previous two subsections.

Table 1 Parameters for Accelerating Directions

Parameters	Accelerating Directions					
	X-axis (acceleration)	Opposite to X-axis (deceleration)	Y-axis	Opposite to Y-axis	Z-axis	Opposite to Z-axis
phi	0	180	90	270 or -90	(any value)	(any value)
elv	0	0	0	0	90	-90

Let us try these parameters on the Maneuver Editor window. Enter a set of parameters (“dv”, “phi”, and “elv”) into the “Parameters” table on the Maneuver Editor window, and click [SHOW Orbit] button to observe the orbit of the Probe. Then, try other sets, repeatedly.

When these “trys and observes” satisfied you, click [Finish and Exec] button on the Maneuver Editor window to stop the editing of the CP Maneuver.

IMPORTANT

For observing orbits, it is very important to rotate the chart on the 3D Orbit window. In some cases, acceleration of the Probe results in the change of orbital inclination.

Fly the Probe Freely

In previous subsections, we used following three types of Maneuvers.

- START Maneuver: The Probe starts its flight from a Space Base with specified velocity.
- FLYTO Maneuver: The Probe flies until a specified time.
- CP Maneuver: The Probe uses its Chemical Propulsion Engine, with six sets of angular parameters in [Table 1 Parameters for Accelerating Directions](#).

Only using these three types of Maneuvers, we can fly the Probe freely, to anywhere we like in the solar system. Can you believe it? Try it by yourself.

We can change the orbit of the Probe by CP Maneuver. However, it is not enough to fly the Probe freely. It is important to use FLYTO Maneuver combined with CP Maneuver. For example, once you added a CP Maneuver to change the orbit, in many cases need you a FLYTO Maneuver that flies the Probe, prior to another CP Maneuver.

Let us add Maneuvers one by one, and execute each of them.

As you saw many times, a typical way to add a Maneuver to the Flight Plan is to edit the last line (a blank line, sometimes with “Next”) of the Maneuver Table. When you finish the editing, the Maneuver is stored in that line, and a blank line appears as a next one. However, there are other ways to edit the Maneuver Table.

These are operations to delete a line from the Maneuver Table, or insert a blank line in it:

- Delete a line: select the line and click [DEL *] button
- Insert a blank line: select a line where you want to insert, and click [INS *] button

For editing a line (a Maneuver) in the Maneuver Table, we strongly recommend that you make the line be the “Next Line” prior to start editing.

The Maneuver Table has a line that indicates a “Next” in the “Status” column; we call the line as “Next Line.” When we edit the “Next Line”, we can use all functions of the Maneuver Editor; otherwise, we cannot use some of the key functions.

You can move the “Next” indicator with following operations of buttons on the Maneuver Editor window.

- By clicking [EXEC Next] button, the indicator shifts downward by one line
- By clicking [CLEAR EX] button, the indicator moves to the top line

Fly the Probe toward Mars

Fly the Probe toward Mars, the fourth planet next to Earth, orbiting around Sun. Let us create new Probe, and fly it away from the Space Base by following [Generate New Flight Plan](#), [Start the Flight](#) and [Fly Away from the Space Base](#).

In this Flight Plan, Mars is the Target. The orbit of Mars is drawn as an ellipse in green on the 3D Orbit window; the position of Mars is indicated by the + mark in green. Let us continue composing the Flight Plan. Use CP Maneuvers and FLYTO Maneuvers only. The goal is, mark of the Probe (the X mark in red) have an overlap with mark of the Target on the 3D Orbit window, after execution of the last Maneuver of the Flight Plan.

There are some hints to compose this Flight Plan.

- To predict positions of the Probe and the Target at time points in the future, click [>>] button or [>] button in the “Prediction Time Manipulator” group, on the Show Orbit window.
- To observe orientations of the orbits and relative positions, it is useful to rotate the chart on the 3D Orbit window.
- To zoom-up the vicinity of the Target,
 - Place the Target at the central point of the chart by selecting [Target] radio button in the “Look at” group on the Show Orbit window,
 - Place the mouse cursor on the 3D Orbit window, and move it downward with right button held down.

How did it go? I am afraid you experienced many troubles. When you flied the Probe, the Target moved in that time. When you accelerated the Probe, the size of the orbit changed also. The orbit plane of the Probe did not coincide with the one of the Target; you required accelerations to the direction of Z-axis (or opposite) sometimes.

Put your heart at ease. SSVG has a powerful tool to assist you bring the Probe to the Target; this tool (named as “FTA”) computes parameters (“dv”, “phi”, and “elv”) of a CP Maneuver for an orbit transition, which guides the Probe to the vicinity of the Target. We will see the usage of FTA in the next subsection.

Gravity Assist of Jupiter

Let us try orbit transitions by gravity assists (swing-bies) of Jupiter.

For this purpose, we have to put the Probe into an orbit that flies by Jupiter. Of course you can try it, but let us use prepared steps now. Those are as follows:

- Create new Flight Plan. Parameters are as follows:
 - Target: Jupiter
 - Space Base: EarthL2

- Add and execute a START Maneuver. Parameters are as follows:
 - Start Time: 2020-03-26T00:00:00.000000
 - dv: 9058.071
 - phi: -4.80
 - elv: -8.15
- Add and execute a FLYTO Maneuver. Duration of the flight is 428 days.
(End Time is 2021-05-28T00:00:00 by ISOT, 2459362.5 by JD)

When you complete previous steps, save the Flight Plan, and do one more operation. Click “Checkpoint” on the menu bar of SSVG window, and execute “Create”. An indication of “checkpoint” appears on the “Status” column of the second line (the Maneuver executed most recently). You will see the usage of the checkpoint later.

At this point, the Probe is on an orbit that brings the Probe near Jupiter in 150 days. By clicking several times [>>] button on the Show Orbit window, you can look see it by yourself.

Note that this orbit (predicted by the Show Orbit window) of the Probe is a two-body orbit. It means that this orbit is computed using gravitational pull of Sun only, not using Jupiter’s.

Now, let us add a CP Maneuver, which makes an orbit correction to adjust how the Probe flies by Jupiter. Click [EDIT Next] button to start editing, and select “CP” for Maneuver Type.

To get parameters for this CP Maneuver, we use FTA function of SSVG. Click [FTA] button on the Maneuver Editor window. The FTA Setting window appears.

On this window, we specifies following conditions for the computation of FTA:

- Time to arrival: a time length the Probe takes to come at the targeting point with a two-body orbit.
- Precise targeting: specify a targeting point where the Probe flies to with a two-body orbit. We can use one of the two sets of coordinates to specify the point, B-plane Coordinates or Orbit Local Coordinates; we use B-plane Coordinates in this subsection.

For the first case of gravity assists, let us operate the FTA Setting window as follows (see next figure):

- In the “Time to Arrival ” group,
 - Select [Specify Time to Arrival] radio button,
 - Enter 150 to the “Time to Arrival (days)” field.
- In the “Precise Targeting” group,
 - Select [Specify B-plane Coordinates] radio button.
- In the “B-plane Coordinates” group, enter following values (*):
 - For the “offset distance (km)” field: 5000000 (five million)
 - For the “beta (deg)” field: 0.0

(*) Two parameters of B-plane coordinates specify position (distance and direction from the target) of the nearest point on the fly-by path. See [B-plane Coordinate System](#).

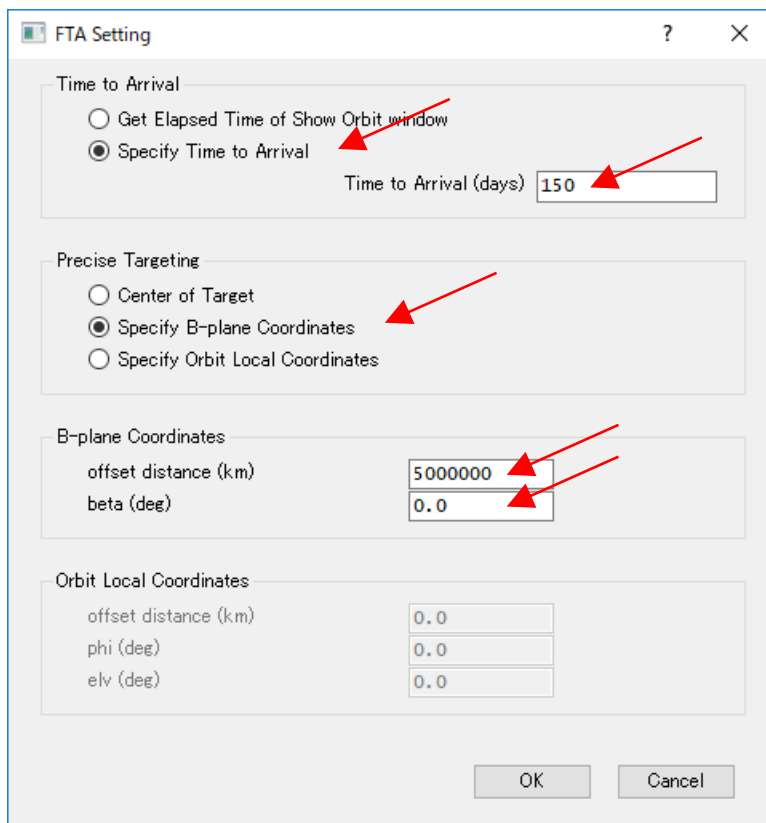


Figure 15 Setting the FTA function

Finish mentioned operations, and click [OK] button. A dialog informs you the results of FTA. Check the results, and click [OK] button. The results (values for parameters “dv”, “phi”, and “elv”) are applied to the Maneuver Editor window.

Click [Finish and Exec] button of the Maneuver Editor window. SSVG stores and executes the CP Maneuver.

Now, the Probe is on an orbit to fly by Jupiter. Let us fly the Probe and make an orbit transition by gravity assist of Jupiter. Add a FLYTO Maneuver into the Flight Plan and execute it. The fly-by occurs in 150 days after current time, so let the duration of the FLYTO Maneuver be 300 days.

Let us look-see how the Probe flied by Jupiter. Click [REVIEW Recent] button on the SSVG window. The Flight Review window replaces the Show Orbit window. By clicking buttons in the “Review Manipulator”, we can follow movements of the Probe and Jupiter. If you set a check mark on the “Probe Kepler Orbit” check box in the “Show” group of the Flight Review window, you see two-body orbit of the Probe for every step of the flight.

When this review satisfied you, let us try other cases of gravity assist. We have a list of parameters for FTA, they guide the Probe to different gravity assists, and result the Probe different orbit transition consequently. See the next table.

Table 2 FTA Parameters for Gravity Assists

Parameters by B-plane Coordinates		Feature of fly-by
offset distance (km)	beta (deg)	
5000000	0	behind Jupiter, moderate distance (*)
3000000	0	behind Jupiter, short distance
2000000	0	behind Jupiter, very short distance
5000000	180	before Jupiter, moderate distance
3000000	180	before Jupiter, short distance
3000000	270	above the north pole, short distance
3000000	90	above the south pole, short distance

* We tried this case already, in the previous part of this subsection

To try these cases, we only need to edit the third line (the CP Maneuver) of the Maneuver Table. To edit this line and use FTA, this line should be the “Next Line”. If the “Next Line” on the Maneuver Table is the fifth line (a blank line), and the second line indicates a “checkpoint”, you can use resuming function. (*) Click “Checkpoint” on the menu bar, and execute “Resume”. The third line (the CP Maneuver) will be the “Next Line”. As long as there is the “checkpoint” on the second line, you can use resuming function as many times as desired.

(*) Otherwise, try following steps:

- Click [CLEAR EX] button on the SSVG window. The first line will be the “Next Line”.
- Click [EXEC Next] button twice. The third line will be the “Next Line”.
- Click “Checkpoint” on the menu bar, and execute “Create”. The indication of “checkpoint” appears on the second line, and you can use the “Resume” function to try other gravity assists.

Then, you can edit the CP Maneuver on the third line by clicking [EDIT Next] button. Try gravity assists repeatedly. For parameters not contained in previous table, see Figure 15.

For more information about FTA and/or B-plane coordinates, see [FTA Setting Window](#) and [B-plane Coordinate System](#).

Flight Plan toward Venus

Let us create a Flight Plan toward Venus, the twin planet of Earth. In this section, we compose a Flight Plan that is “feasible” with current rocket technologies. In this section, a “feasible Flight Plan” means:

- From a Space Base around Earth, the Probe flies directly to Venus,
- With small starting velocity (six kilometers per second or less),
- With few and small intermediate orbital corrections.

If this Flight Plan is an actual one, feasibility includes limitation about the start time of the flight. Let us create a Flight Plan that starts its flight on or after September of 2019.

Generate New Flight Plan

Generate a Flight Plan by executing “New” of “File” on the menu bar of SSVG window. Select Venus for the Target. Next, we select one of the Space Bases, “EarthL1” or “EarthL2”. Which one is better? Both Space Bases lie 1.5 million kilometers from Earth, but opposite direction. “EarthL1” lies in the direction of Sun, but “EarthL2” lies in the opposite.

When you select a Space Base, you should consider initial flight direction of the Probe. If the direction is inward (the direction to approach Sun), it is better to select “EarthL1” to minimize gravity effect from Earth the Probe suffers immediately after the start. If the initial flight direction is outward (the direction to leave Sun), “EarthL2” is better by the same reason.

In fact, there are two feasible paths to reach Venus from Earth. One is a short path that takes roughly 100 days, and the other is a long path that takes roughly 200 days. In this section, we use the short one. Because the Probe leaves Earth inward by this path, the “EarthL1” is better than “EarthL2”.

If you do not have such working knowledge, try both Space Bases and select better one.

START Maneuver

Let us add a START Maneuver as the first Maneuver.

Click [EDIT Next] button of the SSVG window. On the Maneuver Editor window, select “START” for the Maneuver Type.

For a START Maneuver, we specify the Start Time the Probe starts the flight, and the Start Velocity with which the Probe leaves the Space Base. Start Time and Start Velocity determine an orbit (remember that the Start Time determines position and velocity of the Space Base). Because this Flight Plan is a direct flight to Venus, this orbit should bring the Probe to the vicinity of Venus. At the same time, the feasibility requires small Start Velocity.

SSVG has a powerful tool that assists us to find such favorable orbits. That is the “Optimize Assistant”. Let us use it now.

Click [Optimize] button on the Maneuver Editor window. The Start Optimize Assistant window appears (see next figure).

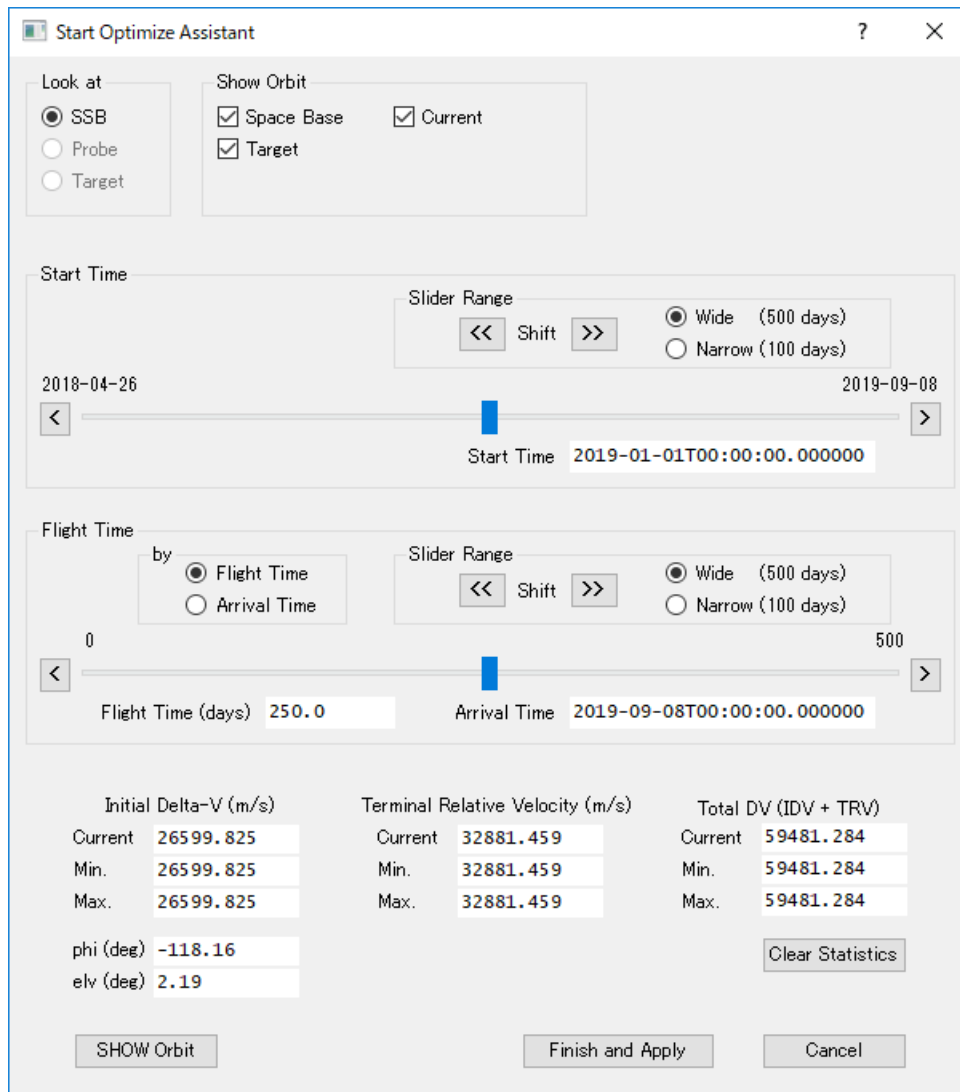


Figure 16 Start Optimize Assistant window

In the middle area of the Start Optimize Assistant window, there are two large groups of items named “Start Time” and “Flight Time”.

We use these two groups to arrange the Start Time of the Probe, and the Flight Time to Venus, respectively. From these Start Time and Flight Time, SSVG computes a two-body orbit and draw it on the 3D Orbit window, at the same time, SSVG computes and displays following values:

- Initial Delta-V: Start Velocity of the Probe (magnitude and direction)
- Terminal Relative Velocity: magnitude of relative velocity of the Target when the Probe arrives
- Total DV: the sum of Initial Delta-V and Terminal Relative Velocity

When you move sliders, Start Time and/or Flight Time change, and mentioned values and the orbit (on the 3D Orbit window, curved line in cyan) change also. With that information, you can

find favorable Start Time and Flight Time.

Note that by clicking [\ll] or [\gg] buttons, you can shift the range of each slider by one-half of it. In addition, see [Start Optimize Assistant Window](#) for more detailed information of the Start Optimize Assistant window.

Let us look for favorable Start Time and Flight Time. Initial values should be as follows:

- Start Time: 2019-09-01T00:00:00.000000 (September 1, 2019)
- Flight Time: 100 (one hundred days)

When you find favorable Start Time and Flight Time, make a note of Flight Time and Arrival Time, and click [Finish and Apply] button. Start Time and Start Velocity are applied to the Maneuver Editor window.

Click [Finish and Exec] button of the Maneuver Editor window. SSVG stores and executes the START Maneuver.

FLYTO Maneuver (1)

Because the orbit, computed by Optimize Assistant, is a two-body orbit that is computed from gravitational pull of Sun only, the trajectory of the Probe will gradually deviate from the orbit with time, particularly during the Probe flies near Earth. Fly the Probe long enough to avoid the gravitational pull of Earth, and then make an orbit correction to ensure precise approach to Venus.

Let us fly the Probe to the mid-point of its journey by time, or around it. Click [EDIT Next] button on the SSVG window. Select “FLYTO” for “Maneuver Type”, edit parameters, and click [Finish and Exec] button on the Maneuver Editor window.

CP Maneuver

Add a CP Maneuver for a mid-course correction of the orbit. Click [EDIT Next] button on the SSVG window, and select “CP” for the Maneuver Type on the Maneuver Editor window.

At this point, we have to decide details of the approach. When and where does the Probe fly-by?

To minimize delta-V, velocity increment of the orbit correction, let us use the time when the Probe comes to the closest point to Venus with current (before correction) orbit, as the time of fly-by. You can evaluate this time by clicking buttons in the “Prediction Time Manipulator” on the Show Orbit window. You can decide the place of fly-by as you like.

Let us use FTA of SSVG. By clicking buttons in the “Prediction Time Manipulator” on the Show Orbit window, set the predicted position of the Probe at the closest point to Venus (*), and click [FTA] button on the Maneuver Editor window. On the FTA Settings window, you will see the input field for “Time to Arrival” contains an appropriate value.

(*) If you wish to minify the time interval by button operations to manipulate the Prediction Time, set the “Scale”

to -1, -2, or less.

In the Precise Targeting group, select the radio button of “Specify B-plane Coordinates”. See [B-plane Coordinate System](#), and set appropriate parameters. Click [OK] button and confirm the results of FTA. The results will be applied to the Maneuver Editor window.

At this point, you can check the results on the 3D Orbit window. Try a close-up view of the Target.

If you satisfied, click [Finish and Exec] button on the Maneuver Editor window.

FLYTO Maneuver (2)

Fly the Probe until five days before the day of fly-by. Add a “FLYTO” maneuver, and execute it.

FLYTO Maneuver (3)

Fly the Probe ten days, until five days after the day of fly-by. Add a “FLYTO” maneuver. In this Maneuver, let us change the parameter “inter” to “0.01”. This parameter defines integration interval of trajectory computation (that is a numerical integration). SSVG computes and saves the points of trajectory at this interval (0.01 day), and we can review the flight at this interval.

After executing this Maneuver, click [REVIEW Recent] button on the SSVG window, and review the flight. You will see how the Probe flies by Venus.

If you wish to insert the Probe into Venus orbit, review the last FLYTO Maneuver to find the time point the Probe being at closest to Venus.

For this time point, you can see the time and relative velocity of the Target (Venus). If you modify the last FLYTO Maneuver to end the flight at this time point, and add a CP Maneuver to reduce relative velocity of the Target to an appropriate value, the Probe will enter Venus orbit. You can confirm it by adding and executing a FLYTO Maneuver, and reviewing it.

Flight Plan toward Celestial Small Body

As a Target of the flight, we can choose one of the celestial small bodies such as asteroids, comets and dwarf planets. Except the Moon of Earth, we cannot choose any moons of planets as a Target.

When we choose a small body for a Target of SSVG, we need a SPK file that provides positions and velocities of the body. We have a SPK file already, that is “de430.bsp” in the “data” folder, but it provides positions and velocities only for eight planets, Sun, Pluto, and the Moon of Earth.

HORIZONS system of NASA/JPL provides us SPK files of celestial small bodies. We can get appropriate SPK file by requesting to HORIZONS system. For more information about HORIZONS system, see <<http://ssd.jpl.nasa.gov/?horizons>>.

Note that HORIZONS system can generate SPK files of several different types, but SSVG can read “Type 1” only. As long as I know (at June 2018), by “telnet” interface can we request to generate “Type 1” SPK files. We have a sample of requesting such a file to HORIZONS system; see [Get SPK File of Celestial Small Body](#).

When we select a small body as a Target, we need the SPKID (SPK object ID) of the body along with name of the SPK file. HORIZONS system will give us SPKID of the body when we request to generate a SPK file.

Once we have SPK file and SPKID for a celestial small body, we can choose it for the Target when we generate a new Flight Plan, or when we edit an existing Flight Plan.

Reference Manual

Basic Terms

Probe

In SSVG, we call a spacecraft as a “Probe”. A Probe starts its flight from a Space Base, uses its propulsion systems, and flies toward a Target (a celestial body the Probe targeting on).

A Probe has three propulsion systems, a Chemical Propulsion Engine, an Electric Propulsion Engine, and a Solar Sail. These propulsion systems are very powerful and very easy-to-use. They are described in other subsections.

In SSVG, a Probe can orbit any planet; it can rendezvous with a celestial small body; but it cannot observe planets or celestial small bodies, because it has no observation systems.

Space Base

In SSVG, a Probe starts its space flight from a Space Base; we do not launch it from the surface of Earth or other planets. We suppose that each Space Base has an installation, something likes a catapult, to send off Probes with specified velocity.

For all eight planets of the solar system, we have two Space Bases for each. For each planet, one Space Base lies at Lagrange point L1 and another lies at L2. Both L1 and L2 are on the line through Sun and the planet (*); L1 is sunward from the planet and L2 is opposite. In a way, L1 (and L2) is a point where two gravitational pulls (one from Sun, one from the planet) make a balance. An object placed here (L1 or L2) orbits Sun, along with the planet at the same orbital period.

(*) L1 and L2 around Earth are on the line through Sun and the barycenter of Earth and its Moon.

Precisely speaking, Lagrange points L1 and L2 can be defined only when the planet has circular orbit around Sun and there are no other planets. Because no orbit is a perfect circle and the solar system has other planets, an object placed at L1 (or L2) gradually drift away with time. In SSVG, we suppose that there are mechanisms to hold Space Bases at prescribed positions.

The distance between a planet and its L1 is almost the same to the one between the planet and its L2, but those distances are different for each planet. For each planet, SSVG computes the distance between the planet and its L1 with multiplying the distance between the planet and Sun, by a “Distance Factor”; for L2, SSVG uses this distance just the same.

The following table is a complete list of Space Bases in SSVG; it also contains Distance Factors, and average distances between the planet and its L1 (and L2) for each planet.

Table 3 Space Bases

Planets	Space Bases at L1	Space Bases at L2	Distance Factors	Average Distances (million kilometers)
Mercury	MercuryL1	MercuryL2	0.00381	0.22
Venus	VenusL1	VenusL2	0.00934	1.0
Earth	EarthL1	EarthL2	0.01008	1.5
Mars	MarsL1	MarsL2	0.00476	1.1
Jupiter	JupiterL1	JupiterL2	0.06828	53
Saturn	SaturnL1	SaturnL2	0.04568	66
Uranus	UranusL1	UranusL2	0.02442	69
Neptune	NeptuneL1	NeptuneL2	0.02580	120

Maneuver

In SSVG, we call every instruction to Probe about space flight as a “Maneuver”. To fly a Probe, we define a sequence of Maneuvers and execute them one by one.

SSVG maintains the sequence of Maneuvers as a table on its main window (SSVG window). We call the table as the “Maneuver Table”. Each line (row) of the Maneuver Table contains a Maneuver; we can edit each line (Maneuver) in it, we can add a line (a Maneuver) to it, and we can delete a line (a Maneuver) from it. As we execute Maneuvers in the Maneuver Table one by one, from top to bottom, the Probe leaves a Space Base and flies toward its destination.

There are seven types of Maneuvers in SSVG. Following table is a complete list of types of Maneuvers. Each type of Maneuver requires different parameters. See [Maneuver Editor Window](#) for precise information for those parameters.

Table 4 Types of Maneuvers

Types	Descriptions
START	<p>This Maneuver starts the Probe from the Space Base.</p> <p>This Maneuver requires a Start Time and a Start Velocity (magnitude and direction) as parameters. The Start Velocity is the one relative to the Space Base. It means that the Probe starts its flight with a vector sum of Start Velocity and the velocity of the Space Base.</p> <p>By executing this, SSVG sets its current time to the Start Time.</p> <p>The first Maneuver in the Maneuver Table should be a START Maneuver; a START Maneuver cannot be used at any other places.</p>
CP	<p>This Maneuver makes orbit transition with Chemical Propulsion Engine of the Probe.</p> <p>This Maneuver requires magnitude and direction of delta-V that makes the orbit transition, as parameters. It means that after executing this, the Probe flies with a vector sum of previous velocity and delta-V.</p> <p>By executing this, SSVG does not change its current time.</p>
EP_ON	<p>This Maneuver switches on the Electric Propulsion Engine of the Probe.</p> <p>This Maneuver requires magnitude and direction of delta-V from one-day operation, and thrust vector mode, as parameters.</p> <p>We can use this for a Probe that has switched on its Electric Propulsion Engine. In this case, SSVG changes parameters of the Electric Propulsion Engine to provided ones.</p> <p>By executing this, SSVG does not change its current time.</p>
EP_OFF	<p>This Maneuver switches off the Electric Propulsion Engine of the Probe.</p> <p>This Maneuver requires no parameters.</p> <p>By executing this, SSVG does not change its current time.</p>
SS_ON	<p>This Maneuver switches on the Solar Sail of the Probe.</p> <p>This Maneuver requires area and orientation of the Solar Sail, and thrust vector mode, as parameters.</p> <p>We can use this for a Probe that has switched on its Solar Sail. In this case, SSVG changes parameters of the Solar Sail to provided ones.</p> <p>By executing this, SSVG does not change its current time.</p>
SS_OFF	<p>This Maneuver switches off the Solar Sail of the Probe.</p> <p>This Maneuver requires no parameters.</p> <p>By executing this, SSVG does not change its current time.</p>
FLYTO	<p>This Maneuver flies the Probe until specified time.</p> <p>This Maneuver requires end time of this flight, and interval of numerical integration, as parameters.</p> <p>SSVG computes trajectory of the Probe by numerical integration, using gravitational pull of Sun, planets, and the Moon of Earth, and accelerations from the Electric Propulsion Engine and the Solar Sail.</p> <p>By executing this, SSVG sets its current time to the end time of this Maneuver.</p>

Flight Plan

In SSVG, a “Flight Plan” is a set of information about Probe and Target, and a sequence of Maneuvers to fly the Probe.

To compose a Flight Plan in SSVG, we create new Flight Plan that has no Maneuver, and we add Maneuvers one by one.

We can save a Flight Plan to a file with appropriate name, with an extension of “json”. After that, we can read the Flight Plan from the file to execute and/or to modify.

When we create new Flight Plan, we define name and mass of the Probe, and select a Space Base to start from, but we can change them later. We choose a celestial body as a Target at the creation of new Flight Plan, but we can change it later. For example, let us consider a Flight Plan in which a Probe flies toward Saturn after a fly-by of Jupiter. On the first phase of the flight (until the fly-by), we would like to choose Jupiter as a Target, and on the second phase, we should choose Saturn as a Target.

Target

In SSVG, Target is a celestial body the Probe targeting on, at the time. SSVG displays position and orbit of the Target on the 3D Orbit window; some tools of SSVG (FTA and Optimize Assistant) compute parameters of Maneuvers that bring the Probe into the vicinity of the Target. For example, if you wish to use FTA to get parameters of a CP Maneuver for an orbit transition that allows the Probe to arrive at a celestial body, the celestial body should be the Target at the time.

On the other hand, which celestial body is chosen for Target does not affect computations of the flight trajectory of the Probe.

Celestial bodies that can be chosen for Target are following two groups:

- Planet: eight Planets, Pluto, and the Moon of Earth. When we choose one of them as a Target, we need no special data files and/or procedures.
- Small body: celestial small bodies (dwarf planets, asteroids, and comets), confined to those for which HORIZONS system of NASA/JPL provides SPK files. When we choose a small body as a Target, we need a SPK file for the body. See [Get SPK File of Celestial Small Body](#).

Except the Moon of Earth, we cannot choose any moons of planets as a Target.

Chemical Propulsion Engine

A Probe of SSVG has a Chemical Propulsion Engine, which is a simplified model of liquid propellant rocket engine that is widely used by actual spacecrafts.

Liquid propellant rocket engines generate large thrust. That is a big advantage of them, and they can change velocity of spacecrafts significantly, in a very short period. A Chemical Propulsion Engine of SSVG enhanced this advantage; it can change velocity of a Probe at an instant, and the delta-V may take any value.

On the other hand, liquid propellant rocket engines have disadvantage of propellant

consumption. They consume very large amount of propellant to change velocity of spacecraft significantly (see [Propulsion Systems and Rocket Equation](#)). This disadvantage is very serious for actual space flights, but in SSVG, we intentionally set aside it. A Chemical Propulsion Engine of SSVG does not consume any propellants.

Simplifications in modeling of a Chemical Propulsion Engine are as follows:

- It can change velocity of a Probe at an instant.
- It does not consume any propellants.
- Its acceleration contains no errors (both magnitude and direction).

Electric Propulsion Engine

A Probe of SSVG has an Electric Propulsion Engine, which is a simplified model of electric propulsion devices, such as ion thrusters and Hall-effect thrusters. Those devices are actually used for some space probes to explore celestial small bodies.

Electric propulsion devices have a common advantage of specific impulses (I_{sp}). Specific impulses of electric propulsion devices are roughly ten times of ordinary liquid propellant rocket engines; it means that an electric propulsion device consumes only one tenth or less of propellant than a liquid propellant rocket engine (see [Propulsion Systems and Rocket Equation](#)) for the same delta-V.

On the other hand, electric propulsion devices have common disadvantage of thrusts. Their thrusts are only one hundredth or less of ordinary liquid propellant engines; it means that significant change of velocity of spacecrafts require very long time of operation, several days, weeks, or months.

An Electric Propulsion Engine of SSVG enhanced mentioned advantage; it does not consume any propellants. About mentioned disadvantage, we made an Electric Propulsion Engine more flexible than electric propulsion devices of current technologies; to accelerate a Probe, an Electric Propulsion Engine of SSVG takes finite (non-zero) time, but there is no limitation of magnitude of the thrust.

As a result, we can use an Electric Propulsion Engine of SSVG in many ways. The first one is a way to use it like actual liquid propulsion rocket engines: very high thrust, and very short operation period. The second one is to use it like actual electric propulsion devices: very low thrust, and very long operation period. In addition, there are many intermediate ways.

Simplifications in modeling of an Electric Propulsion Engine are as follows:

- We can switch on (or off) it at an instant.
- If we have switched on it, we can change its parameters at an instant.
- It does not consume any propellants.
- There is no limitation of thrust (rate of acceleration).
- Its thrust contains no errors (both magnitude and direction).

There are two modes of operation for Electric Propulsion Engine of SSVG. Those are “L” and “E” of “Thrust Vector Mode” or “tvmode”. See [Thrust Vector Mode](#) for details.

Solar Sail

A Probe of SSVG has a Solar Sail, which is idealized light sail (or photon sail) that accelerate the Probe by radiation pressure of sunlight.

The significant advantage of light sails in space flights is that they do not consume any propellants to accelerate spacecrafts. However, because radiation pressure of sunlight is very weak, we need very large sails and very long time, to acquire significant acceleration. For example, IKAROS, a spacecraft of JAXA that demonstrated acceleration by radiation pressure of sunlight in 2010, had a light sail that is square shape, fourteen meters on a side (about two hundred square meters of area). The thrust of the light sail was roughly one-thousandth of a Newton; it means that the light sail accelerate the spacecraft (three hundred kilograms of total mass) by three meters per second, in ten days of operation.

We suppose a Solar Sail in SSVG as a perfect mirror; it forms a perfect plane, and reflects all radiations as a mirror. In this case, the thrust vector of Solar Sail is perpendicular to the plane of sail. Obviously, the thrust vector is not approaching to Sun, but departing from Sun.

A Solar Sail in SSVG has following characteristics:

- It is a double-sided perfect mirror.
- We can switch on (or off) it at an instant.
- When we switch on it, we specify area and orientation of the sail as parameters.
- There is no limitation of area of the sail.
- If we have switched on it, we can change its parameters at an instant.
- Mass of the sail is included in the total mass of Probe.
- Its area and orientation of the sail contains no errors.

There are two modes of operation for Solar Sail of SSVG. Those are “L” and “E” of “Thrust Vector Mode” or “tvmode”. See [Thrust Vector Mode](#) for details.

It is useful to know characteristics of Solar Sail as a thrusting device to achieve orbit transition. Some of them are as follows: (see [Solar Sail Coordinate System](#) about theta and elv)

- Maximum thrust force is achieved when the plane of sail faces directly to Sun (theta = 0.0 and elv = 0.0). Unfortunately, the force in this case has radial component only, no transverse components; radial component is not effective to change orbital energy, orbital angular momentum, and/or orbital inclination, in many situations.
- Transverse components of the thrust force are effective to change orbital energy, orbital angular momentum, and/or orbital inclination, in many situations.
- To get transverse components, we need to incline the plane of sail. Well, how much inclination is?
- A “Magic Angle” maximize transverse component of thrust force of Solar Sail. It is about 35.26 degrees. (*)
- If you wish to make the orbit larger as rapidly as possible, a simple answer is

$\theta = 35.26$ and $\text{elv} = 0.0$ (with “tvmode” = “L”).

- If you wish to incline the orbit as rapidly as possible, a simple answer is $\theta = 0.0$ and $\text{elv} = 35.26$ or -35.26 (with “tvmode” = “L”).

(*) Precise value is: $\sin^{-1}\left(\frac{1}{\sqrt{3}}\right)$

Windows and Operations

SSVG Window

SSVG window is the main window of SSVG. It appears when we execute SSVG, and it remains there until we terminate SSVG.

On the SSVG window, there are following items and groups:

- Menu: we can execute several important functions from the menu.
- Buttons: there are three groups of buttons: REVIEW/SHOW buttons, EXEC buttons, and EDIT buttons.
- Maneuver Table: the list of Maneuvers contained in the current Flight Plan
- Current Status: status of the Probe, immediately after the execution of a Maneuver
- Selected Maneuver: precise information of the Maneuver contained in the selected line of the Maneuver Table
- Other Information: Probe Name, Target, Space Base, Plan File

SSVG

File

Edit

Checkpoint

Help

Probe Name : Marsexp

Target : Mars

Space Base : EarthL2

Plan File : Mars01

REVIEW Through

REVIEW Recent

SHOW Orbit

	Type	Parameters	Status
1	START	Date=2018-05-05 dv=2533.76 phi=12.64 elv=-32.88	
2	FLYTO	Date=2018-06-14 inter=1.00	
3	CP	dv=324.14 phi=-84.61 elv=-0.79	Next
4	FLYTO	Date=2018-09-07 inter=1.00	
5	CP	dv=27.33 phi=-95.87 elv=-7.88	
6	FLYTO	Date=2018-12-05 inter=1.00	
7	FLYTO	Date=2018-12-05 inter=0.01	
8	CP	dv=1981.38 phi=16.19 elv=-4.43	
9	FLYTO	Date=2018-12-10 inter=0.01	
10			

EXEC Next

EXEC to *

CLEAR EX

EDIT Next

EDIT *

INS *

DEL *

Current Status

Executed Last Maneuver	2 FLYTO
Current Time	2018-06-14T00:00:00.000000
Current Time (JD)	2458283.50000000
Distance from Sun (km)	157,500,013
Velocity rel. to Sun (m/s)	30962.781
Semi-major Axis (km)	182,662,783
Semi-major Axis (AU)	1.22102529
Eccentricity	0.16556064
Inclination (deg)	2.387034
Long. of Asc. Node (deg)	43.853327
Arg. of Perihelion (deg)	181.512872
Perihelion Passage	2018-05-06T02:00:57.620099
Perihelion Passage (JD)	2458244.58400023
Mean Anomaly (deg)	28.427933
Orbital Period (days)	492.816697
Accum. DV (m/s) CP, EP, SS	0, 0, 0

Selected Maneuver 3 CP

Date&Time

Parameters

dv (m/s)	324.139
dvpd (m/s/day)	
phi (deg)	-84.61
elv (deg)	-0.79
aria (m**2)	
theta (deg)	
tvmode (L E)	
inter (days)	

Figure 17 SSVG window

Menu

Table 5 Menu of the SSVG window

Menu Items	Sub-items	Functions
File	Open	SSVG reads a Flight Plan from a file.
	New	SSVG creates new Flight Plan. See New Flight Plan Window .
	Save	SSVG saves current Flight Plan into current file.
	Save as	SSVG saves current Flight Plan with specified file name.
	Quit	SSVG terminates.
Edit	Probe	SSVG starts editing of properties of the Probe. SSVG opens the Edit Probe Properties window; for operations of this window, see New Flight Plan Window .
	Target	SSVG starts editing of Target of current Flight Plan. SSVG opens the Select New Target window; for operations of this window, see New Flight Plan Window .
Checkpoint	Create	SSVG creates a checkpoint (*1)
	Resume	SSVG resumes execution from the checkpoint.
Help	about SSVG	SSVG displays information about SSVG.

(*1) SSVG creates a checkpoint with current execution state (*2) of the Flight Plan, and displays a “checkpoint” on the Maneuver Table. When you execute “Resume”, SSVG restores the execution state from the checkpoint. When you clear execution state of the Flight Plan by clicking [CLEAR EX] button or by other means, the checkpoint will be lost.

(*2) An execution state contains sequential number of the line that contains recently executed Maneuver, current time, current position and velocity of the Probe, flight trajectories of the Probe, and so on.

Buttons

Table 6 Buttons on the SSVG window

	Face Name	Function
REVIEW/SHOW Buttons	REVIEW Through	This button opens the Review Throughout window that allows us to review through all executed Maneuvers. When the 3D Orbit window does not exist, SSVG opens it.
	REVIEW Recent	This button opens the Flight Review window that allows us to review the recently executed FLYTO Maneuver. When the 3D Orbit window does not exist, SSVG opens it.
	SHOW Orbit	If not exist, this button opens the Show Orbit window that allows us to observe position and orbit of the Probe. When the 3D Orbit window does not exist, SSVG opens it.
EXEC Buttons	EXEC Next	This button executes the Maneuver on the Next Line of the Maneuver Table.
	EXEC to *	This button executes Maneuvers on the Maneuver Table sequentially, from the Next Line through the selected line.
	CLEAR EX	This button clears the state of execution of the Flight Plan. The first line of the Maneuver Table becomes the Next Line.
EDIT Buttons	EDIT Next	This button opens the Maneuver Editor window to start editing the Next Line of the Maneuver Table.
	EDIT *	This button opens the Maneuver Editor Window to start editing the Maneuver of the selected line. If the line is not a Next Line, we cannot use a part of functions of the Maneuver Editor. If the line is an executed one, execution state of the Flight Plan will be cleared when we finish the editing.
	Insert *	This button inserts a blank line before the selected line of the Maneuver Table. If the selected line is an executed one, execution state of the Flight Plan will be cleared.
	Delete *	This button deletes the selected line of the Maneuver Table. If the selected line is an executed one, execution state of the Flight Plan will be cleared.

Maneuver Table

The Maneuver Table is a sequential list of Maneuvers contained in current Flight Plan. Each line (row) of it contains one Maneuver. Each line of the Maneuver Table has a sequential number and following three columns:

- “Type” column: it shows type of the Maneuver.
- “Parameters” column: it shows shortened values of parameters of the Maneuver.
- “Status” column: it shows “Next”, “checkpoint”, or a blank. If this column is not a blank, it means as follows respectively:
 - “Next”: it means that this line is the “Next Line”.
 - “checkpoint”: it means that SSVG holds a checkpoint that was created

immediately after execution of the Maneuver of this line.

We can manipulate the Maneuver Table as follows:

- Click a line: SSVG selects the line.
- Double click a line: SSVG opens the Maneuver Editor Window to start editing Maneuver of the line. If the line is not a Next Line, we cannot use a part of functions of the Maneuver Editor. If the line is an executed one, execution state of the Flight Plan will be cleared when we finish the editing.

Current Status

SSVG displays following information as the Current Status:

- Executed Last Maneuver: sequential number of the line that contains recently executed Maneuver, and type of the Maneuver
- Current time (ISOT and JD)
- [The Probe's] Distance from Sun
- [The Probe's] Velocity rel(ative) to Sun
- Keplerian orbital elements of the Probe (Semi-major Axis, Eccentricity, Inclination, Long[itude] of Asc[ending] Node, Arg[ument] of Perihelion, Perihelion Passage [Time], Mean Anomaly, and Orbital Period)
- Accum. DV CP, EP, SS (Accumulated Delta-Vs for CP, EP, and SS): SSVG displays on this aria accumulated delta-Vs for each propulsion system; the first is that of Chemical Propulsion Engine, the second is of Electric Propulsion Engine, and the last is of Solar Sail.

Selected Maneuver

SSVG displays following information of the Maneuver contained in the selected line of the Maneuver Table:

- Sequential number of the selected line and type of the Maneuver contained the line
- Date&Time: Start Time for START Maneuver, or End Time for FLYTO Maneuver
- Parameters: other parameters of the Maneuver (see [Maneuver Editor Window](#) for precise information)

Other Information

SSVG displays following information around top of the window:

- Probe Name: name of the Probe
- Target: name of the Target
- Space Base: name of the Space Base
- Plan File: current file name of the Flight Plan

3D Orbit Window

On the 3D Orbit window, SSVG displays a three dimensional (3D) chart that contains position and orbit of the Probe, position and orbit of the Target, positions and names of the planets, and so on.

When SSVG is running, the 3D Orbit window usually exists. We can close it by clicking the “close button”, and it appears again when we click a valid [SHOW orbit] button.

One of the following windows creates and controls information displayed on the 3D chart:

- Show Orbit window: allows us to observe state of the Probe
- Flight Review window: allows us to review recently executed FLYTO Maneuver
- Review Throughout window: allows us to review through executed Maneuvers
- Start Optimize Assistant window: assists us to configure a START Maneuver
- CP Optimize Assistant window: assists us to configure a CP Maneuver

Next figure is an example of 3D Orbit window, which is displaying information from the Show Orbit Window.

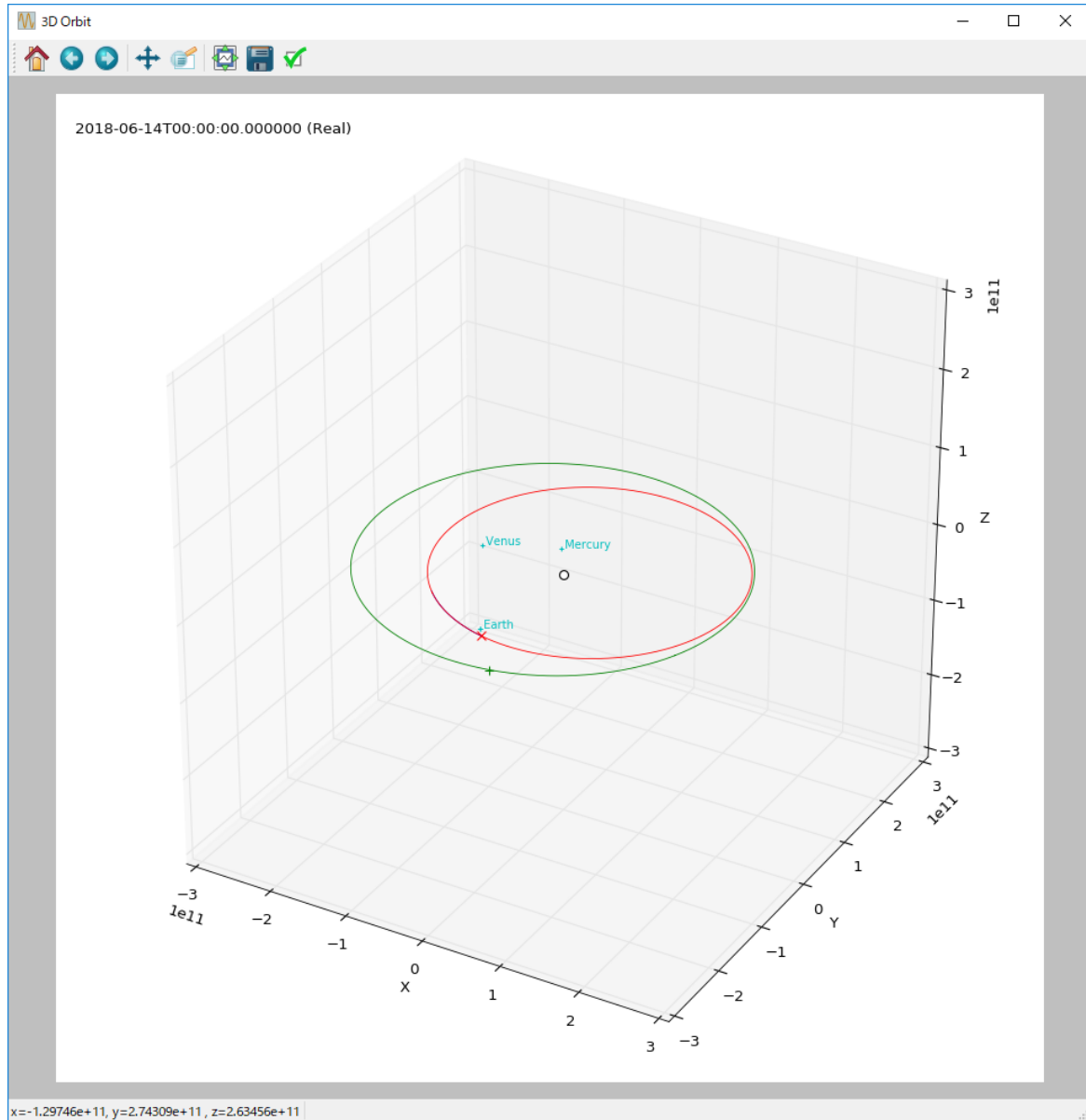


Figure 18 3D Orbit window

The next table is a complete list of items displayed on the 3D orbit window.

Table 7 Items on the 3D Orbit window

Items	What is it?
An X mark in red	The Probe: when reviewing Maneuver(s), state of propulsion systems and information about the Maneuver may be displayed at the right side of the mark
A curved line in red	Two-body orbit (Kepler orbit) of the Probe: when using Start Optimize Assistant, it indicates trajectory of the Space Base; when using CP Optimize Assistant, it indicates current (before execution of the editing Maneuver) orbit of the Probe
A curved line in blue	Actual trajectory of the Probe: the results of FLYTO Maneuvers
A + mark in green	The Target
A curved line in green	Two-body orbit (Kepler orbit) of the Target
An X mark in blue	The place where the Probe arrives at the Target (for Start Optimize Assistant and CP Optimize Assistant)
A curved line in cyan	Considering two-body orbit (Kepler orbit) of the Probe (for Start Optimize Assistant and CP Optimize Assistant)
A small circle in black	Sun
+ marks and names in cyan	Planets and their names; the Moon of Earth is indicated by a + mark without name
Three gridded planes with scales	Each plane is parallel to one of the three planes (X-Y, Y-Z, and Z-X) of the ecliptic coordinate system. Each scale is parallel to one of the three axes (X, Y, and Z) of the ecliptic coordinate system. Each scale has an indication of the length of “1”, and the length is measured by meters. Sometimes, each scale has an indication of offset.
Time information	On the upper left corner of the chart, SSVG displays the time corresponds to the positions of objects, and its attribute (Real or Predicted).
Menu Icons	3D Orbit window has several Menu Icons at the top of the window, but SSVG do not use them.

On the 3D Orbit window, we can manipulate the 3D chart by mouse.

Table 8 Manipulation of 3D Chart

What to do	How to do
Rotate	Place the mouse cursor on the 3D Orbit window, and move it up/down or right/left with left button held down.
Zoom out and zoom in	Place the mouse cursor on the 3D Orbit window, and move it up/down with right button held down.
Place the Probe or the Target at the central point of the chart	We cannot do this manipulation on this window. Try it on the Show Orbit Window , Flight Review Window , or Review Throughout Window .

Show Orbit Window

The Show Orbit window allows us to observe state of the Probe. It displays information as follows:

- Into the 3D Orbit window,
 - the Probe, its orbit, and its trajectory
 - the Target and its orbit
 - positions and names of the planets
- Into the Show Orbit window,
 - relative position and relative velocity (including line of sight velocity) of the Target from the Probe as texts

Note that the time, which corresponds to this information, is a specified time. It can be not only the current time, but also a time in the future or past. We call the specified time as “Prediction Time”. Show Orbit window computes position of the Probe at Prediction Time from two-body motion of the Probe.

The Show Orbit window appears when:

- The user executed a Maneuver.
- The user started editing of a Maneuver on the Next Line. (*)
- The user finished or canceled editing of a Maneuver, and at least one Maneuver has been executed.
- The user clicked valid [SHOW Orbit] button.

(*) While you are editing a START Maneuver, a CP Maneuver, or a FLYTO Maneuver on the Next Line, you can apply the editing parameters temporarily to the Show Orbit window by clicking [SHOW Orbit] button of the Maneuver Editor window.

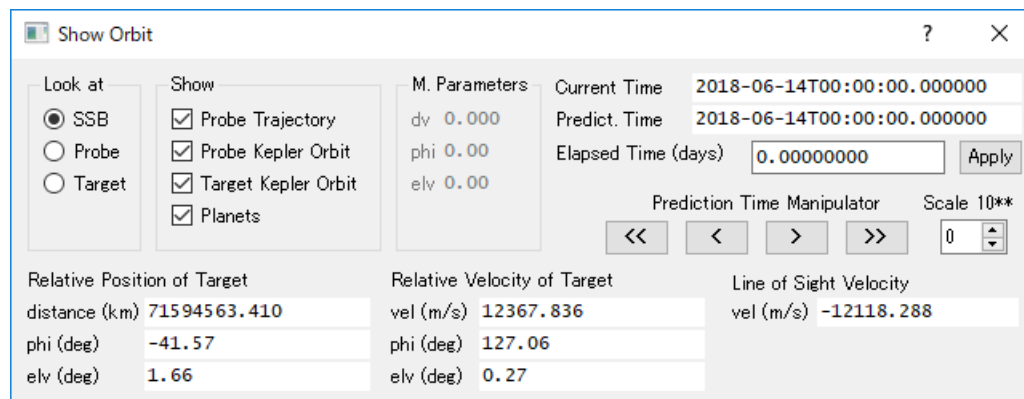


Figure 19 Show Orbit window

There are five item groups as follows on the upper part of the Show Orbit window:

- Look at: three radio buttons to select central point of the 3D chart
- Show: four check boxes to select show/hide of items on the 3D chart
- M. Parameters: Maneuver parameters applied temporarily
- Items about time (three lines on the top-right corner)
- Prediction Time Manipulator: four buttons and a spinner to manipulate Prediction Time

Table 9 Upper part of the Show Orbit window

Group Names	Labels/Names	Explanations
Look at	SSB	When selected, SSB, the Solar System Barycenter, lies at the central point of the 3D chart.
	Probe	When selected, the Probe lies at the central point of the 3D chart.
	Target	When selected, the Target lies at the central point of the 3D chart.
Show	Probe Trajectory	When checked, the trajectory of the Probe is displayed on the 3D Orbit window
	Probe Kepler Orbit	When checked, the two-body orbit (Kepler orbit) of the Probe is displayed on the 3D Orbit window
	Target Kepler Orbit	When checked, the two-body orbit (Kepler orbit) of the Target is displayed on the 3D Orbit window
	Planets	When checked, the marks and names of planets are displayed on the 3D Orbit window
M. Parameters	dv phi elv	Maneuver parameters, applied temporarily by the Maneuver Editor window
(no name) Items about time	Current Time or	Current time of SSVG
	Start Time	Start time, applied temporarily by the Maneuver Editor window (while you are editing a START Maneuver)
	Predict. Time	Prediction Time
	Elapsed Time (days)	Elapsed time, from current time (or start time) to Prediction Time
	and [Apply] button	When you edit this field and click adjacent [Apply] button, the value is applied to the Prediction Time. (*)
Prediction Time Manipulator (*)	[<<] button	Fast backward: when clicked, Prediction Time goes back by ten times of the time interval specified by the scale
	[<] button	Backward: when clicked, Prediction Time goes back by the time interval specified by the scale
	[>] button	Forward: when clicked, Prediction Time goes forward by the time interval specified by the scale
	[>>] button	Fast forward: when clicked, Prediction Time goes forward by ten times of the time interval specified by the scale
	Scale	A spinner that specifies the time interval of one operation of buttons [<] and [>] The value is an exponent of ten. If the value is zero, the time interval is one day; if the value is one, the interval is ten days, and so on.

(*) While you are editing a FLYTO Maneuver on the Next Line, every change of Prediction Time is applied to End Time of the editing FLYTO Maneuver instantaneously.

Lower part of the Show Orbit window contains positions and velocities of the Target relative to the Probe at the Prediction Time, as follows:

Table 10 Lower part of the Show Orbit window

Item groups	labels	Explanations
Relative Position of Target	distance	Distance of the Target from the Probe
	phi elv	Angle phi and elv of the relative position of the Target from the Probe, on the Orbit Local Coordinate System
Relative Velocity of Target	vel	Magnitude of the relative velocity of the Target from the Probe
	phi elv	Angle phi and elv of the relative velocity of the Target from the Probe, on the Orbit Local Coordinate System
Line of Sight Velocity	vel	Line of sight (radial) component of the relative velocity of the Target from the Probe (a positive value indicates that the Target is coming away from the Probe)

Flight Review Window

The Flight Review window allows us to review recent FLYTO Maneuver. For each integration step of the recent Maneuver, it displays information as follows:

- Into the 3D Orbit window,
 - the Probe, its trajectory, and its orbit
 - state of the Electric Propulsion Engine (*1)
 - acceleration from the Solar Sail and its state (*2)
 - the Target and its orbit
 - positions and names of the planets
- Into the Flight Review window,
 - Relative position and relative velocity (including line of sight velocity) of the Target from the Probe as texts

(*1) If the Electric Propulsion Engine has been switched on, a string “EP (m)” appears next to the X mark of the Probe on the 3D Orbit window. Where “m” of “EP (m)” indicates current Thrust Vector Mode (“L” or “E”) of the Electric Propulsion Engine.

(*2) If the Solar Sail has been switched on, a string “SS (m) SSacc=n.nnn” appears next to the X mark of the Probe on the 3D Orbit window. Where “m” of “SS (m)” indicates current Thrust Vector Mode (“L” or “E”) of the Solar Sail, and “n.nnn” of “SSacc=n.nnn” indicates acceleration from the Solar Sail (delta-V from one day operation, meters per second per day), at the instant.

Note that the Flight Review window displays information at the end of an integration step of the Maneuver at a time. We call this integration step as the “current step”.

The Flight Review window appears when the user clicked [REVIEW Recent] button of the SSVG window.

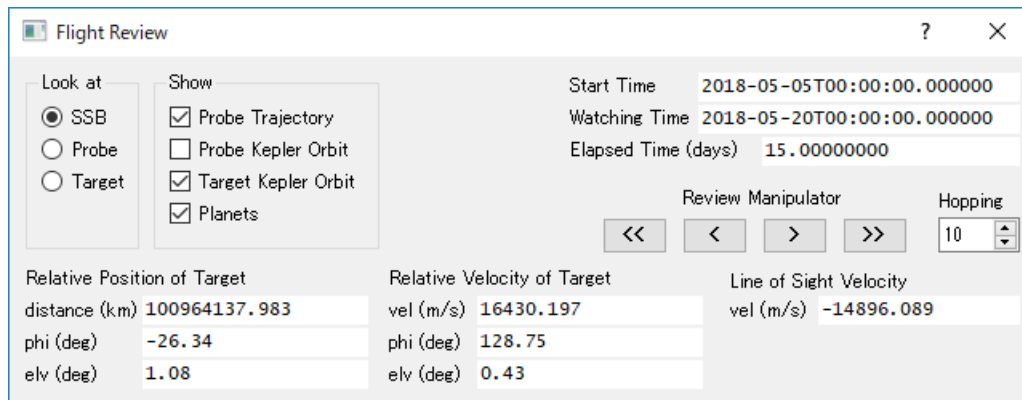


Figure 20 Flight Review window

There are four item groups as follows on the upper part of the Flight Review window:

- Look at: three radio buttons to select central point of the 3D chart
- Show: four check boxes to select show/hide of items on the 3D chart
- Items about time (three lines on the top-right corner)
- Review Manipulator: four buttons and a spinner to manipulate integration steps to watch

Table 11 Upper part of the Flight Review window

Group Names	Labels/Names	Explanations
Look at	SSB	When selected, SSB, the Solar System Barycenter, lies at the central point of the 3D chart.
	Probe	When selected, the Probe lies at the central point of the 3D chart.
	Target	When selected, the Target lies at the central point of the 3D chart.
Show	Probe Trajectory	When checked, the trajectory of the Probe is displayed on the 3D Orbit window
	Probe Kepler Orbit	When checked, the two-body orbit (Kepler orbit) of the Probe is displayed on the 3D Orbit window
	Target Kepler Orbit	When checked, the two-body orbit (Kepler orbit) of the Target is displayed on the 3D Orbit window
	Planets	When checked, the marks and names of planets are displayed on the 3D Orbit window
(no name) Items about time	Start Time	Start time of the reviewing FLYTO Maneuver
	Watching Time	Time of the current step
	Elapsed Time (days)	Elapsed time, from Start Time to Watching Time
Review Manipulator	[<<] button	Fast backward: when clicked, the current step goes back by number of steps that specified by Hopping
	[<] button	Backward: when clicked, the current step goes back by one
	[>] button	Forward: when clicked, the current step goes forward by one
	[>>] button	Fast forward: when clicked, the current step goes forward by the number of steps that specified by Hopping
	Hopping	A spinner that specify the number of integration steps of one operation of buttons [<<] and [>>]

Lower part of the Flight Review window contains positions and velocities of the Target relative to the Probe at the end of the current step. Data items and their meanings are the same to the Show Orbit window. See [Table 10 Lower part of the Show Orbit window](#).

Review Throughout Window

The Review Throughout window allows us review through all executed Maneuvers. For each executed Maneuver, it displays information as follows:

- Into the 3D Orbit window,
 - the Probe with line number and type of the current Maneuver
 - for FLYTO Maneuvers,
 - start and end of a FLYTO Maneuver
 - state of the Electric Propulsion Engine (*1)
 - acceleration from the Solar Sail and its state (*2)
 - trajectory of the Probe, and orbit of the Probe
 - the Target and its orbit
 - positions and names of the planets

- Into the Review Throughout window,
 - relative position and relative velocity (including line of sight velocity) of the Target from the Probe as texts

(*1) If the Electric Propulsion Engine has been switched on, a string “EP (m)” appears next to the type of current Maneuver on the 3D Orbit window. Where “m” of “EP (m)” indicates current Thrust Vector Mode (“L” or “E”) of the Electric Propulsion Engine.

(*2) If the Solar Sail has been switched on, a string “SS (m) SSacc=n.nnn” appears next to the type of current Maneuver on the 3D Orbit window. Where “m” of “SS (m)” indicates current Thrust Vector Mode (“L” or “E”) of the Solar Sail, and “n.nnn” of “SSacc=n.nnn” indicates acceleration from the Solar Sail (delta-V from one day operation, meters per second per day), at the instant.

Note that the Review Throughout window displays information corresponded to one Maneuver at a time. We call this Maneuver as the “current Maneuver”.

Except FLYTO Maneuvers, the Review Throughout window displays information immediately after execution of the current Maneuver. For FLYTO Maneuvers, it displays information of each integration step of the Maneuver.

The Review Throughout window appears when the user clicked [REVIEW Through] button of the SSVG window.

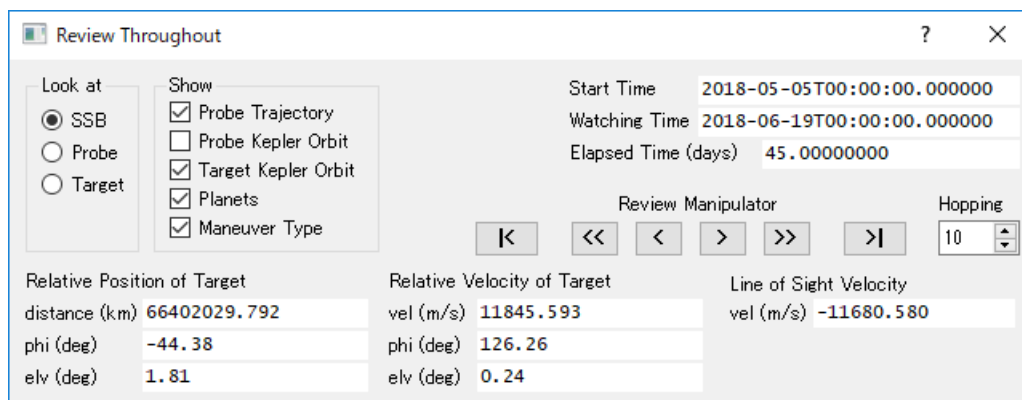


Figure 21 Review Throughout window

There are four item groups as follows on the upper part of the Review Throughout window:

- Look at: three radio buttons to select central point of the 3D chart
- Show: five check boxes to select show/hide of items on the 3D chart
- Items about time (three lines on the top-right corner)
- Review Manipulator: six buttons and a spinner to manipulate current Maneuver and/or integration steps to watch

Table 12 Upper part of the Review Throughout window

Group Names	Labels/Names	Explanations
Look at	SSB	When selected, SSB, the Solar System Barycenter, lies at the central point of the 3D chart.
	Probe	When selected, the Probe lies at the central point of the 3D chart.
	Target	When selected, the Target lies at the central point of the 3D chart.
Show	Probe Trajectory	When checked, the trajectory of the Probe is displayed on the 3D Orbit window
	Probe Kepler Orbit	When checked, the two-body orbit (Kepler orbit) of the Probe is displayed on the 3D Orbit window
	Target Kepler Orbit	When checked, the two-body orbit (Kepler orbit) of the Target is displayed on the 3D Orbit window
	Planets	When checked, the marks and names of planets are displayed on the 3D Orbit window
	Maneuver Type	When checked, Maneuver Type and other information are displayed next to the Probe on the 3D Orbit window
(no name) Items about time	Start Time	Start Time of the Flight Plan
	Watching Time	Time of the current Maneuver For FLYTO Maneuvers, time of the current integration step
	Elapsed Time (days)	Elapsed time, from Start Time to Watching Time
Review Manipulator	[<] button	Go Previous: when clicked, the previous Maneuver becomes current Maneuver (*1)
	[<<] button	(This button can be used to review a FLYTO Maneuver) Fast backward: when clicked, the current step goes back by number of steps that specified by Hopping
	[<] button	(This button can be used to review a FLYTO Maneuver) Backward: when clicked, the current step goes back by one
	[>] button	(This button can be used to review a FLYTO Maneuver) Forward: when clicked, the current step goes forward by one
	[>>] button	(This button can be used to review a FLYTO Maneuver) Fast forward: when clicked, the current step goes forward by the number of steps that specified by Hopping
	[>] button	Go Next: when clicked, the next Maneuver becomes current Maneuver (*2)
	Hopping	(This button can be used to review a FLYTO Maneuver) A spinner that specify the number of integration steps of one operation of buttons [<<] and [>>]

(*1) While you are reviewing a FLYTO Maneuver,

- if the current step is the first one of the Maneuver, the previous Maneuver becomes current Maneuver.
- if the current step is not the first one, the first step of the current Maneuver becomes current step.

(*2) While you are reviewing a FLYTO Maneuver,

- if the current step is the last one of the Maneuver, the next Maneuver becomes current Maneuver.
- if the current step is not the last one, the last step of the Maneuver becomes current step.

Lower part of the Review Throughout window contains positions and velocities of the Target relative to the Probe immediately after the execution of the current Maneuver (or at the end of

current step). Data items and their meanings are the same to the Show Orbit window. See [Table 10 Lower part of the Show Orbit window](#).

Maneuver Editor Window

On the Maneuver Editor window, we edit a Maneuver of the Flight Plan.

The Maneuver Editor window appears when:

- We clicked the [EDIT Next] button of the SSVG window.
- We clicked the [EDIT *] button of the SSVG window.
- We double-clicked a line of the Maneuver Table of the SSVG window.

We strongly recommend that you edit a Maneuver contained in the “Next Line” of the Maneuver Table. Otherwise, you can use only a part of the functions of the Maneuver Editor.

Following explanations in this subsection are for the case you edit a Maneuver that contained in the “Next Line”.

Maneuver Editor

Maneuver Type CP

ISOT : yyyy-mm-ddThh:mm:ss.sssss JD Duration (days)

Parameters

dv : magnitude of delta-V (m/s)	27.330
dvpd : magnitude of delta-V per day (m/s/day)	
phi : angle phi (deg)	-95.87
elv : angle elv (deg)	-7.88
aria : area of solar sail (m**2)	
theta : angle theta (deg)	
tvmode : thrust vector mode (L E)	
inter : integration interval (days)	

Figure 22 Maneuver Editor window

The next table explains groups, a table, and buttons of the Maneuver Editor window.

Table 13 Groups/Table/Buttons of the Maneuver Editor window

Groups/ Table/Buttons	Relating Maneuver type(s)	Explanations
Maneuver Type (a group)	all types	This group displays type of the editing Maneuver. By selecting a type in the drop-down list and clicking adjacent [Apply] button, we can change the type of editing Maneuver.
Start Time (a group)	START	This group displays current Start Time of the Probe in two formats: ISO format (ISOT) and Julian Date (JD). We can modify the Start Time by editing either ISOT or JD.
or End Time (a group)	FLYTO	This group displays current End Time and Duration (*1) of the editing FLYTO Maneuver. End Time is displayed in two formats: ISO format (ISOT) and Julian Date (JD). We can modify the End Time by editing either ISOT, JD, or Duration. When you modified the Duration, you need to click adjacent [Apply] button to validate the modification. (*2) We can also modify the End Time from the Show Orbit window. When we manipulate the Prediction Time on the Show Orbit window, the Prediction Time is applied to the End Time of this window
Parameters (a table)	all types	This table displays current parameters other than Time of the editing Maneuver. Left column contains names and short explanations of parameters. Right column contains values of parameters. See next table. We can modify each value of parameters by double-clicking of appropriate cell.
[SHOW Orbit] button	all types	When clicked, SSVG applies editing parameters (including Time) temporarily to the Show Orbit window.
[FTA] button	START CP	When clicked, SSVG invokes FTA function (*3) to assist user to configure the editing Maneuver. See FTA Setting Window .
[Optimize] button	START CP	When clicked, SSVG invokes Optimize Assistant to assist user to configure the editing Maneuver. See Start Optimize Assistant Window or CP Optimize Assistant Window .
[Finish and Exec] button	all types	When clicked, SSVG stores the editing Maneuver into the Maneuver Table, closes this window, and executes the Maneuver.
[Finish] button	all types	When clicked, SSVG stores the editing Maneuver into the Maneuver Table, and closes this window.
[Cancel] button	all types	When clicked, SSVG cancels the editing.

(*1) "Duration" is the flight time of editing FLYTO Maneuver. It is computed from current time of SSVG and End Time of the editing FLYTO Maneuver.

(*2) When you modify the Duration and click the adjacent [Apply] button, Maneuver Editor computes the End

Time from the value of Duration and current time of SSVG.

(*3) At that time, SSVG gets the “Elapsed time” from the Show Orbit window, and passes it to the FTA Setting window. FTA Setting window uses it as “Time to Arrival”.

The next table explains items in the “Parameters” table.

Table 14 Parameter items on the Maneuver Editor window

Parameter item	Relating Maneuver type(s)	Explanation
dv	START CP	Magnitude of the delta-V, in meters per second
dvpd	EP_ON	Magnitude of acceleration: represented by delta-V from one day operation of the Electric Propulsion Engine, in meters per second per day
phi	START CP EP_ON	Angle “phi” to indicate direction of the delta-V, in degrees See Orbit Local Coordinate System .
elv	START CP EP_ON SS_ON	Angle “elv” to indicate direction of the delta-V or orientation of the solar sail, in degrees See Orbit Local Coordinate System or Solar Sail Coordinate System .
aria	SS_ON	Area of the Solar Sail, in square meters
theta	SS_ON	Angle “theta” to indicate orientation of the Solar Sail, in degrees See Solar Sail Coordinate System .
tvmode	EP_ON SS_ON	Thrust Vector Mode, “L” or “E” See Thrust Vector Mode .
inter	FLYTO	Interval of numerical integration, in days SSVG computes positions and velocities of the Probe at this interval.

New Flight Plan Window

On the New Flight Plan window, we specify properties of the Flight Plan.

The New Flight Plan window appears when we execute “New” of “File” from the menu of the SSVG window.

New Flight Plan

Probe

Name: Space Base:

Mass (kg):

Target

☒ Planet:

☐ Small Body

Properties

Name:

SPK file:

SPKID:

Figure 23 New Flight Plan window

This window has two item groups, “Probe” and “Target”, and the latter contains one sub-group “Properties”. This window has two buttons also. The next table explains all of them.

Table 15 Groups/Items of the New Flight Plan window

Groups	Items		Explanations
Probe	Name (an input field)		Enter name of the Probe into this field.
	Space Base (a drop-down list)		Select one of the Space Bases in the drop-down list. See Space Base .
	Mass (an input field)		Enter total mass of the Probe into this field, in kilograms.
Target	Planet (a radio button with a drop-down list)		When selected, we choose one of the celestial bodies contained in the drop-down list, as the Target. The drop-down list contains eight planets, Moon of Earth, and Pluto.
	Small Body (a radio button with a sub-group)		When selected, we choose a celestial small body as the Target. We need a SPK file for the body, and we should specify properties of the small body in the “Properties” sub-group.
	Properties	Name (an input field)	Enter the name of the celestial small body.
		SPK file (an input field and [...] button)	Enter the name of the SPK file (*1), or enter its full-path (*2).
		SPKID (an input field)	Enter the SPKID (*3) of the celestial small body.
(None)	[OK] button		When clicked, SSVG creates new Flight Plan.
	[Cancel] button		When clicked, SSVG cancels to create new Flight Plan.

(*1) Get the SPK file (see [Get SPK File of Celestial Small Body](#)), and store it into “data” folder within the folder SSVG was installed; enter the file name into this field (recommended).

(*2) Get the SPK file (see [Get SPK File of Celestial Small Body](#)), and store it into a convenient folder. Click adjacent [...] button, and select the SPK file on the “Select SPK file” dialog. When you open the file, SSVG stores full-path of the selected SPK file into this field (not recommended).

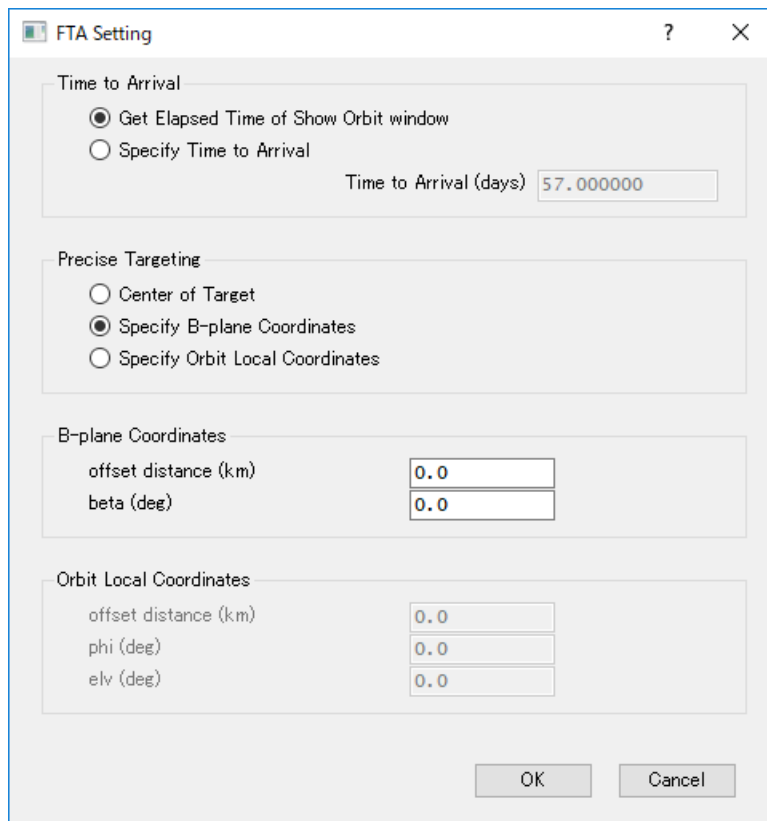
(*3) See [Get SPK File of Celestial Small Body](#).

FTA Setting Window

On the FTA Setting window, we specify parameters for FTA function of SSVG.

“FTA” stands for Fixed Time Arrival guidance. In SSVG, FTA computes parameters for a Maneuver (a START Maneuver or a CP Maneuver) that brings the Probe to a targeting point near the Target, by two-body orbit, at the specified time. To specify the time of arrival, SSVG uses “Time to Arrival”, this is fight time of the Probe, from current time to arrival time.

FTA Setting window appears when the user clicked the [FTA] button on the Maneuver Editor window.



The image shows a software window titled "FTA Setting". It contains four main sections: "Time to Arrival" with two radio buttons and a text field; "Precise Targeting" with three radio buttons; "B-plane Coordinates" with two text fields; and "Orbit Local Coordinates" with three text fields. At the bottom are "OK" and "Cancel" buttons.

Section	Item	Value
Time to Arrival	Get Elapsed Time of Show Orbit window	<input checked="" type="radio"/>
	Specify Time to Arrival	<input type="radio"/>
Precise Targeting	Center of Target	<input type="radio"/>
	Specify B-plane Coordinates	<input checked="" type="radio"/>
	Specify Orbit Local Coordinates	<input type="radio"/>
B-plane Coordinates	offset distance (km)	0.0
	beta (deg)	0.0
Orbit Local Coordinates	offset distance (km)	0.0
	phi (deg)	0.0
	elv (deg)	0.0

Figure 24 FTA Setting window

The FTA Setting window contains four groups of items, along with two buttons.

Table 16 Groups/Items of the FTA Setting window

Groups	Items	Explanations
Time to Arrival	Get Elapsed Time of Show Orbit window (a radio button)	When selected, SSVG get the Elapsed Time of Show Orbit window and use it as time to arrival.
	Specify Time to Arrival (a radio button)	When selected, the user enters the time to arrival into the input field.
	Time to Arrival (an input field)	Enter the time to arrival, in days. This value should be greater than or equal to unity.
Precise Targeting	Center of Target (a radio button)	When selected, center of the Target becomes the targeting point.
	Specify B-plane Coordinates (a radio button)	When selected, the user specifies the targeting point with B-plane Coordinates. See B-plane Coordinate System .
	Specify Orbit Local Coordinates (a radio button)	When selected, the user specifies the targeting point with Orbit Local Coordinates. See Orbit Local Coordinate System .
B-plane Coordinates	offset distance (an input field)	Enter distance of the targeting point from center of the Target, in kilometers.
	beta (an input field)	Enter angle beta of the targeting point, in degrees.
Orbit Local Coordinates	offset distance (an input field)	Enter distance of the targeting point from center of the Target, in kilometers.
	phi (an input field)	Enter angle phi of the targeting point, in degrees.
	elv (an input field)	Enter angle elv of the targeting point, in degrees.
(None)	[OK] button	When clicked, SSVG executes FTA function and applies its results into the Maneuver Editor window (*).
	[Cancel] button	When clicked, SSVG cancels FTA function.

(*) The results are dv, phi, and elv; SSVG stores them into “Parameters” table of the Maneuver Editor window. At this point, SSVG rounds the results as follows:

- dv: rounded to three decimal places
- phi and elv: rounded to two decimal places

Start Optimize Assistant Window

The Start Optimize Assistant window assists us to configure a START Maneuver that sends off a Probe into an orbit, which brings the Probe directly to the Target.

For the economy of the space flight, there are two important issues, the time when we start the flight of the Probe, and flight time of the Probe (from start to arrival). The Start Optimize Assistant window allows us to try various Start Times and various Flight Times. For each case, using current Start Time and current Flight Time, SSVG computes two-body orbit of the Probe;

SSVG shows start velocity of the Probe and relative velocity of the Target at the arrival of the Probe, along with 3D chart of two-body orbit of the Probe.

Note that the words “current *something*” in this sub-section means “*something* currently being tried in this window”, except otherwise mentioned.

The Start Optimize Assistant window appears when the user clicked the [OPTIMIZE] button of the Maneuver Editor window that was editing a START Maneuver.

Start Optimize Assistant

Look at: ☒ SSB, ☐ Probe, ☐ Target

Show Orbit: ☒ Space Base, ☒ Target, ☒ Current

Start Time: 2018-12-25 to 2020-05-08. Slider Range: ☒ Wide (500 days), ☐ Narrow (100 days). Start Time: 2019-09-01T00:00:00.000000

Flight Time: by ☒ Flight Time, ☐ Arrival Time. Slider Range: ☒ Wide (500 days), ☐ Narrow (100 days). Flight Time (days): 100.0. Arrival Time: 2019-12-10T00:00:00.000000

Initial Delta-V (m/s)		Terminal Relative Velocity (m/s)		Total DV (IDV + TRV)	
Current	23695.352	Current	36917.732	Current	60613.083
Min.	7615.478	Min.	5150.900	Min.	12766.377
Max.	35750.680	Max.	46288.712	Max.	81153.300

phi (deg): -170.85
elv (deg): 5.35

Clear Statistics

SHOW Orbit, Finish and Apply, Cancel

Figure 25 Start Optimize Assistant window

At the top of this window, there are two groups of items for options as follows:

Table 17 Options of the Start Optimize Assistant window

Groups	Items	Explanations
Look at	SSB (a radio button)	When selected, SSB, the Solar System Barycenter, lies at the central point of the 3D chart.
	Probe (not selectable)	N/A
	Target (not selectable)	N/A
Show Orbit	Space Base (a check box)	When checked, the trajectory of the Space Base is displayed on the 3D Orbit window. (a curved line in red)
	Target (a check box)	When checked, the two-body orbit (Kepler orbit) of the Target is displayed on the 3D Orbit window. (a curved line in green)
	Current (a check box)	When checked, current two-body orbit (Kepler orbit) of the Probe is displayed on the 3D Orbit window. (a curved line in cyan)

In the middle of the window, there are two groups of items to arrange Start Time and Flight Time as follows:

Table 18 Arrange Start Time and Flight Time

Groups	Items		Explanations
Start Time	Slider Range	[<<] button	Clicking of this button shifts range of the slider backward in time by one-half of the range.
		[>>] button	Clicking of this button shifts range of the slider forward in time by one-half of the range.
		Wide (a radio button)	When selected, the range of the slider is 500 days
		Narrow (a radio button)	When selected, the range of the slider is 100 days
	(a slider)		Dragging of this slider changes current Start Time.
	[<] button		This button moves the slider left by one pixel.
	[>] button		This button moves the slider right by one pixel.
	Start Time (a text)		SSVG shows current Start Time.
Flight Time	by	Flight Time (a radio button)	When selected, the slider of this group sets the Flight Time. If you change current Start Time, the Flight Time remains unchanged, but the Arrival Time changes.
		Arrival Time (a radio button)	When selected, the slider of this group sets the Arrival Time; the Flight Time is computed from it. If you change current Start Time, the Arrival Time remains unchanged, but the Flight Time changes.
	Slider Range	[<<] button	Clicking of this button shifts range of the slider shorter (or backward in time) by one-half of the range.
		[>>] button	Clicking of this button shifts range of the slider longer (or forward in time) by one-half of the range.
		Wide (a radio button)	When selected, the range of the slider is 500 days
		Narrow (a radio button)	When selected, the range of the slider is 100 days
	(a slider)		Dragging of this slider changes current Flight Time and current Arrival Time.
	[<] button		This button moves the slider left by one pixel.
	[>] button		This button moves the slider right by one pixel.
	Flight Time (a text)		SSVG shows current Flight Time in days.
	Arrival Time (a text)		SSVG shows current Arrival Time.

At the bottom of this window, there are three groups of items and four buttons as follows:

Table 19 Groups and Buttons at the bottom of the Start Optimize Assistant window

Groups	Items	Explanations
Initial Delta-V	Current	SSVG shows magnitude of current start velocity of the Probe, in meters per second.
	Min.	SSVG shows minimum value of “Current” of this group up to this point.
	Max.	SSVG shows maximum value of “Current” of this group up to this point.
	phi	SSVG shows angle phi of current start velocity of the Probe, in degrees. See Orbit Local Coordinate System .
	elv	SSVG shows angle elv of current start velocity of the Probe, in degrees. See Orbit Local Coordinate System .
Terminal Relative Velocity	Current	SSVG shows magnitude of relative velocity of the Target at the arrival of the Probe by current two-body orbit, in meters per second.
	Min.	SSVG shows minimum value of “Current” of this group up to this point.
	Max.	SSVG shows maximum value of “Current” of this group up to this point.
Total DV (IDV + TRV)	Current	SSVG shows the sum of values, “Current” of “Initial Delta-V” group and “Current” of “Terminal Relative Velocity” group.
	Min.	SSVG shows minimum value of “Current” of this group up to this point.
	Max.	SSVG shows maximum value of “Current” of this group up to this point.
(None)	[Clear Statistics] button	When clicked, SSVG clears all minimums and maximums.
	[SHOW Orbit] button	When clicked, SSVG shows the 3D Orbit window, if not exist.
	[Finish and Apply] button	When clicked, SSVG applies current Start Time and current start velocity to the Maneuver Editor window.
	[Cancel] button	When clicked, SSVG closes this window.

CP Optimize Assistant Window

The CP Optimize Assistant window assists us to configure a CP Maneuver that performs orbit transition of a Probe into an orbit, which brings the Probe directly to the Target.

For the economy of the space flight, Flight Time of the Probe (from the orbit transition to arrival at the Target) is very important, as well as the Maneuver Time, which is time of the orbit transition. The CP Optimize Assistant window allows us to try various Flight Times and

various Maneuver Times. For each case, using current Maneuver Time and current Flight Time, SSVG computes two-body orbit of the Probe; SSVG shows delta-V of the orbit transition and relative velocity of the Target at the arrival of the Probe, along with 3D chart of two-body orbit of the Probe.

Note that the words “current *something*” in this sub-section means “*something* currently being tried in this window”, except otherwise mentioned.

The CP Optimize Assistant window appears when the user clicked the [OPTIMIZE] button of the Maneuver Editor window that was editing a CP Maneuver.

CP Optimize Assistant

Look at
☒ SSB
☐ Probe
☐ Target

Show Orbit
☒ Previous
☒ Current
☒ Target
☐ Trajectory

Maneuver Time
☒ Fix to SSVG's Time
 Slider Range: ☒ Wide (500 days) ☐ Narrow (100 days)
 2019-09-18 2021-01-30
 Maneuver Time: 2020-05-25T00:00:00.000000

Flight Time
 by: ☒ Flight Time ☐ Arrival Time
 Slider Range: ☒ Wide (500 days) ☐ Narrow (100 days)
 0 500
 Flight Time (days): 55.0
 Arrival Time: 2020-07-19T00:00:00.000000

Initial Delta-V (m/s)		Terminal Relative Velocity (m/s)		Total DV (IDV + TRV)	
Current	217.900	Current	4527.797	Current	4745.697
Min.	202.134	Min.	3778.522	Min.	4473.903
Max.	46865.461	Max.	50513.335	Max.	97378.796

phi (deg): 67.15
 elv (deg): -5.58

Clear Statistics

SHOW Orbit Finish and Apply Cancel

Figure 26 CP Optimize Assistant window

At the top of this window, there are two groups of items for options as follows:

Table 20 Options of the CP Optimize Assistant window

Groups	Items	Explanations
Look at	SSB (a radio button)	When selected, SSB, the Solar System Barycenter, lies at the central point of the 3D chart.
	Probe (not selectable)	N/A
	Target (not selectable)	N/A
Show Orbit	Previous (a check box)	When checked, previous two-body orbit (Kepler orbit) of the Probe is displayed on the 3D Orbit window. (a curved line in red)
	Target (a check box)	When checked, the two-body orbit (Kepler orbit) of the Target is displayed on the 3D Orbit window. (a curved line in green)
	Current (a check box)	When checked, current two-body orbit (Kepler orbit) of the Probe is displayed on the 3D Orbit window. (a curved line in cyan)
	Trajectory (a check box)	When checked, the trajectory of the Probe in the past is displayed on the 3D Orbit window. (a curved line in blue)

In the middle of the window, there are two groups of items to arrange Maneuver Time and Flight Time as follows:

Table 21 Arrange Maneuver Time and Flight Time

Groups	Items		Explanations
Maneuver Time	Fix to SSVG's Time (a check box)		When checked, SSVG uses its time as Maneuver Time. The user cannot modify the Maneuver Time.
	Slider Range	[<<] button	Clicking of this button shifts range of the slider backward in time by one-half of the range.
		[>>] button	Clicking of this button shifts range of the slider forward in time by one-half of the range.
		Wide (a radio button)	When selected, the range of the slider is 500 days
		Narrow (a radio button)	When selected, the range of the slider is 100 days
	(a slider)		Dragging of this slider changes current Maneuver Time.
	[<] button		This button moves the slider left by one pixel.
	[>] button		This button moves the slider right by one pixel.
	Maneuver Time (a text)		SSVG shows current Maneuver Time.
Flight Time	by	Flight Time (a radio button)	When selected, the slider of this group sets the Flight Time. If you change current Maneuver Time, the Flight Time remains unchanged, but the Arrival Time changes.
		Arrival Time (a radio button)	When selected, the slider of this group sets the Arrival Time; the Flight Time is computed from it. If you change current Maneuver Time, the Arrival Time remains unchanged, but the Flight Time changes.
	Slider Range	[<<] button	Clicking of this button shifts range of the slider shorter (or backward in time) by one-half of the range.
		[>>] button	Clicking of this button shifts range of the slider longer (or forward in time) by one-half of the range.
		Wide (a radio button)	When selected, the range of the slider is 500 days
		Narrow (a radio button)	When selected, the range of the slider is 100 days
	(a slider)		Dragging of this slider changes current Flight Time and current Arrival Time.
	[<] button		This button moves the slider left by one pixel.
	[>] button		This button moves the slider right by one pixel.
	Flight Time (a text)		SSVG shows current Flight Time in days.
	Arrival Time (a text)		SSVG shows current Arrival Time.

At the bottom of this window, there are three groups of items and four buttons as follows:

Table 22 Groups and Buttons at the bottom of the CP Optimize Assistant window

Groups	Items	Explanations
Initial Delta-V	Current	SSVG shows magnitude of current delta-V of the orbit transition, in meters per second.
	Min.	SSVG shows minimum value of “Current” of this group up to this point.
	Max.	SSVG shows maximum value of “Current” of this group up to this point.
	phi	SSVG shows angle phi of current delta-V of the orbit transition, in degrees. See Orbit Local Coordinate System .
	elv	SSVG shows angle elv of current delta-V of the orbit transition, in degrees. See Orbit Local Coordinate System .
Terminal Relative Velocity	Current	SSVG shows magnitude of relative velocity of the Target at the arrival of the Probe by current two-body orbit, in meters per second.
	Min.	SSVG shows minimum value of “Current” of this group up to this point.
	Max.	SSVG shows maximum value of “Current” of this group up to this point.
Total DV (IDV + TRV)	Current	SSVG shows the sum of values, “Current” of “Initial Delta-V” group and “Current” of “Terminal Relative Velocity” group.
	Min.	SSVG shows minimum value of “Current” of this group up to this point.
	Max.	SSVG shows maximum value of “Current” of this group up to this point.
(None)	[Clear Statistics] button	When clicked, SSVG clears all minimums and maximums.
	[SHOW Orbit] button	When clicked, SSVG shows the 3D Orbit window, if not exist.
	[Finish and Apply] button	When clicked, SSVG applies current delta-V to the Maneuver Editor window, and close this window. (*)
	[Cancel] button	When clicked, SSVG closes this window.

(*) NOTE THAT EVEN IF YOU MODIFIED MANEUVER TIME, SSVG APPLIES CURRENT MANEUVER TIME *NEITHER* TO THE EDITING MANEUVER *NOR* TO ANY OTHER MANEUVERS. IF YOU WANT TO USE THE MANEUVER TIME, YOU *SHOULD MODIFY* PRECEDING MANEUVER(S) SO THAT SSVG EXECUTE THE EDITING MANEUVER AT THE APPROPRIATE TIME.

Coordinate systems

Ecliptic Coordinate System

The ecliptic coordinate system of SSVG is an inertial Cartesian system fixed to the solar system. The origin of the axes (X, Y, and Z) is at the SSB, the solar system barycenter. The X-Y plane is parallel to the ecliptic plane, the orbital plane of Earth about Sun. The direction of the X-axis is the vernal equinox direction. The Z-axis is perpendicular to the ecliptic plane and its direction is northward, and completes right-handed Cartesian frame. SSVG uses J2000 system for the ecliptic plane and the vernal equinox.

Orbit Local Coordinate System

The orbit local coordinate system of SSVG is defined for objects, which orbit about Sun. Objects include Probes, Space Bases, and Targets. The orbit local coordinate system is a Cartesian system fixed to an object.

The origin of the axes (X, Y, and Z) is at the center of the object. The orbital plane of the object defines the X-Y plane, the velocity vector of the object (relative to Sun) defines X-axis, Y-axis is on the orbital plane and its direction is to approach Sun, and Z-axis is perpendicular to the orbital plane and completes right-handed Cartesian frame.

It is useful to remember that the X-axis is parallel to the tangential line of the two-body orbit of the object, at the current position.

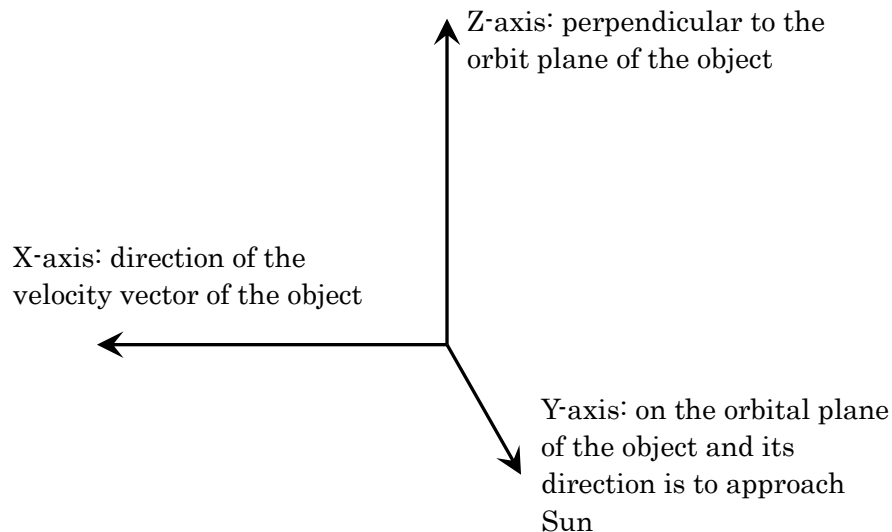


Figure 27 Orbit Local Coordinate System

Next figure shows polar coordinates (r , ϕ , elv) on the orbit local coordinate system.

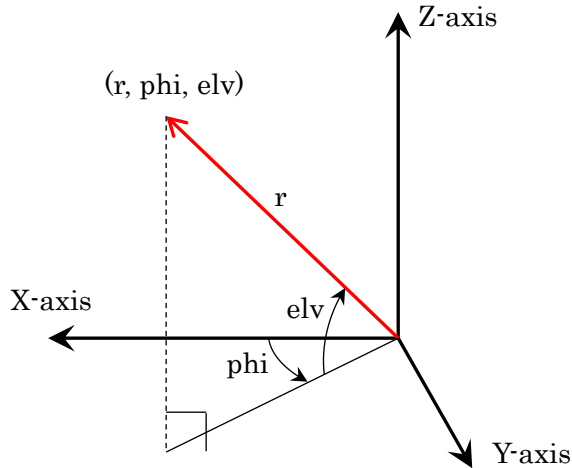


Figure 28 Polar Coordinates on Orbit Local Coordinate System

Solar Sail Coordinate System

The solar sail coordinate system of SSVG is defined for Probes, which orbit about Sun. The solar sail coordinate system is a Cartesian system fixed to a Probe.

The origin of the axes (X, Y, and Z) is at the center of the Probe. The orbital plane of the Probe defines the X-Y plane, the position vector of the Probe from Sun defines X-axis, Y-axis is on the orbital plane and its direction is forward of the orbit, and Z-axis is perpendicular to the orbital plane and completes right-handed Cartesian frame.

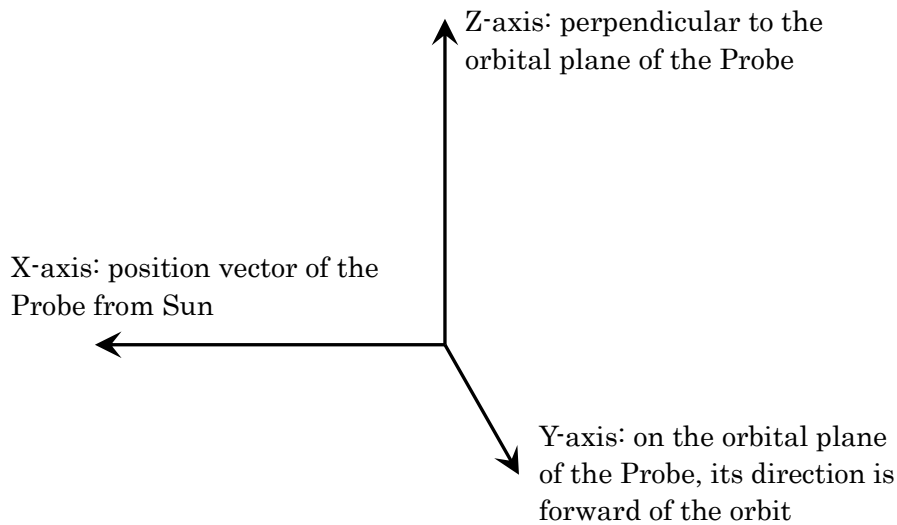


Figure 29 Solar Sail Coordinate System

In SSVG, we use a unit vector that is normal to the plane of sail to represent the orientation of the Solar Sail. The unit vector can be one of the two directions. Because Solar Sail of SSVG is a double-sided mirror, we have no preference. Usually, we use the one in a direction away from Sun.

The Next figure shows polar coordinates of the unit vector on the solar sail coordinate system.

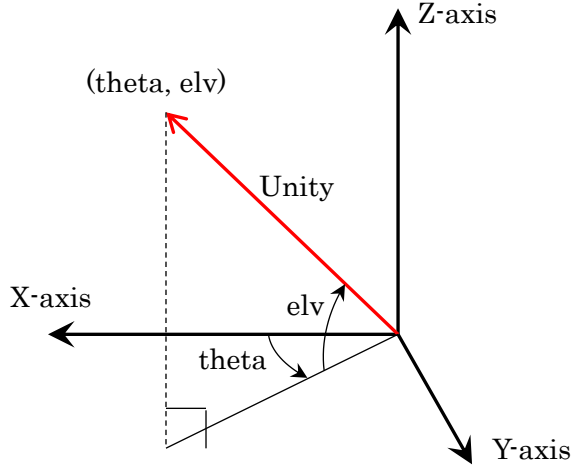


Figure 30 Polar Coordinates on Solar Sail Coordinate System

B-plane Coordinate System

The B-plane coordinate system of SSVG is defined for a Target that orbits about Sun, and a Probe that flies by the Target. The B-plane coordinate system is a Cartesian system fixed to the Target.

We consider the two-body motion of the Probe about Sun, and define:

- B-point: the nearest point of the two-body orbit from the Target
- Relative Velocity: a velocity vector of the two-body motion relative to the Target, at the B-point

The origin of the axes (R, S, and T) is at the center of the Target. The Relative Velocity defines S-axis, the T-R plane is perpendicular to S-axis, and T-axis is on the orbital plane of the Target about Sun. There can be two opposite directions for T-axis; we choose the one represented by following vector cross product.

$$\vec{T} = \vec{S} \times \vec{H}_T$$

where

\vec{T} , \vec{S} : Vectors of T-axis and S-axis, respectively

\vec{H}_T : Angular momentum vector of the Target (an vector perpendicular to the orbital plane of the Target, its direction is northward when the orbit is prograde)

In SSVG, we use the B-plane coordinate system to define the targeting point of FTA (see [FTA Setting Window](#)). For this purpose, we need to specify only two parameters, angle “beta” and offset distance “d”, because the targeting point (that is B-point) is on the T-R plane (we call it as the “B-plane”). Next figure shows B-plane coordinate system and those two parameters.

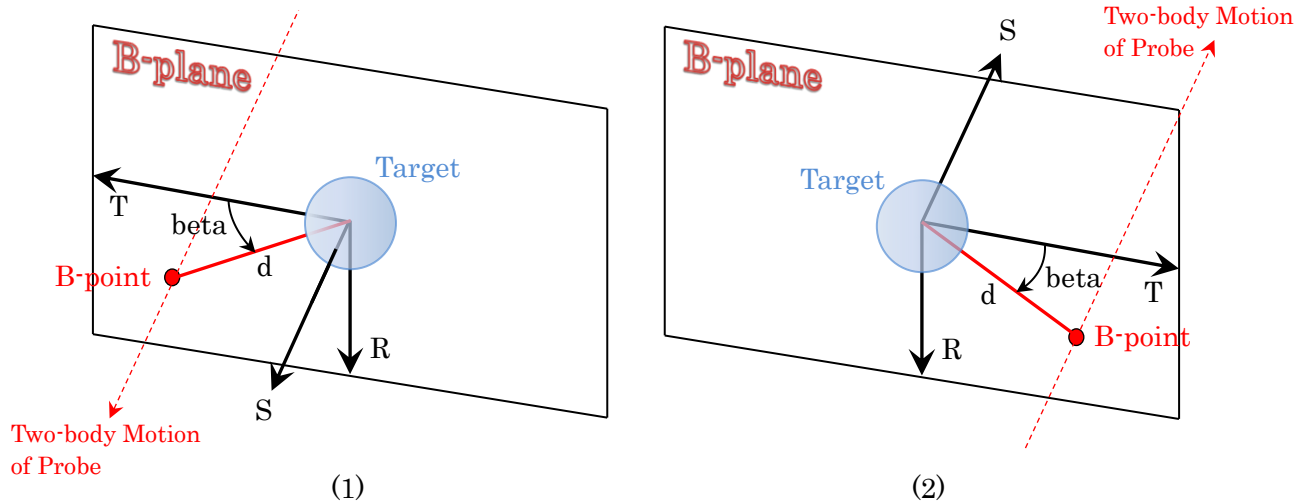


Figure 31 B-plane Coordinate System

Two sub-figures of Figure 31 show different cases of fly-bys respectively. The sub-figure labeled (1) is the case the Target overtakes the Probe; the Probe passes through the B-plane from far side to near side. On the other hand, the sub-figure labeled (2) is the case the Probe overtakes the Target; the Probe passes through the B-plane from near side to far side. For each sub-figure, we are looking at the Target from behind of its orbiting motion; Sun is far left of the Target.

Miscellaneous Information

Time

In SSVG, the time is Barycentric Dynamical Time (TDB).

SSVG uses Julian date (JD) for both internal expression and user interface, also it uses ISO 8601 extended format (ISOT) with no time zone designators for user interface.

For example, 6 o'clock AM on January 1, 2020 is displayed as:

2020-01-01T06:00:00.000000 (ISOT)

2458849.75000000 (JD)

SSVG has a time range, in which we can fly the Probe. That is as follows:

From: 0 o'clock AM on December 31, 1549

To: 0 o'clock AM on January 25, 2650

In addition, a SPK file for celestial small body has its own time range, in which we can use the body as a Target.

Numerical Integration of the Probe Trajectory

When executing a FLYTO maneuver, SSVG computes trajectory (positions and velocities) of the Probe by numerical integration of forces, which affect motion of the Probe. SSVG considers following forces, and neglects others:

- Gravitational attraction of Sun
- Gravitational attractions of the eight planets and the Moon of Earth
- Propulsive forces of the Electric Propulsion Engine and the Solar Sail

Two-body Motion of the Probe

SSVG computes “Real” trajectory of the Probe by numerical integration as mentioned above. However, all other computations about orbits, positions, and velocities of the Probe are performed by two-body motion about Sun. Examples are as follows:

- Positions and orbits of the Probe, displayed on the 3D Orbit window
- Positions and velocities of the Probe, used to compute relative positions and relative velocities of the Target on the Show Orbit window
- FTA function
- Optimize Assistant (Start Optimize Assistant and CP Optimize Assistant)

In addition, orbits of the Target, which are displayed on the 3D Orbit window, are computed by two-body motion about Sun.

Propulsion Systems and Rocket Equation

Although three propulsion systems in SSVG do not consume any propellant, propellant on board and its consumption are one of the focus of attention of actual space flights. We have an equation that governs relation between delta-V, velocity increment of an orbit transition, and total mass of the spacecraft; we often call it as “rocket equation.” That is:

$$\frac{m_0}{m_T} = \exp\left(\frac{\Delta V}{I_{sp} \cdot g}\right)$$

where

m_0 : Total mass of the spacecraft (before orbit transition)

m_T : Total mass of the spacecraft (after orbit transition)

ΔV : Delta-V of orbit transition

I_{sp} : Specific impulse of the propulsion system

g : Earth’s standard gravitational acceleration near sea level

$\exp()$: Exponential function

The subtraction $m_0 - m_T$ yields propellant consumption during the orbit transition.

Next two tables show samples of computation results of the rocket equation for two propulsion systems respectively; the first table is for typical liquid propellant rocket engine, its I_{sp} is 300 seconds; the second table is for typical ion engine, its I_{sp} is 3000 seconds. For these two tables, we assumed that m_T (total mass of the spacecraft, after orbit transition) is 1.000.

Table 23 Computation Results of Rocket Equation (Liquid Propellant Engine)

Delta-V (meters per second)	m_0	Propellant Consumption ($m_0 - m_T$)	m_T
500	1.185	0.185	1.000
1000	1.405	0.405	1.000
2000	1.974	0.974	1.000
4000	3.895	2.895	1.000
8000	15.169	14.169	1.000
16000	230.094	229.094	1.000
32000	52943.095	52942.095	1.000

Table 24 Computation Results of Rocket Equation (Ion Engine)

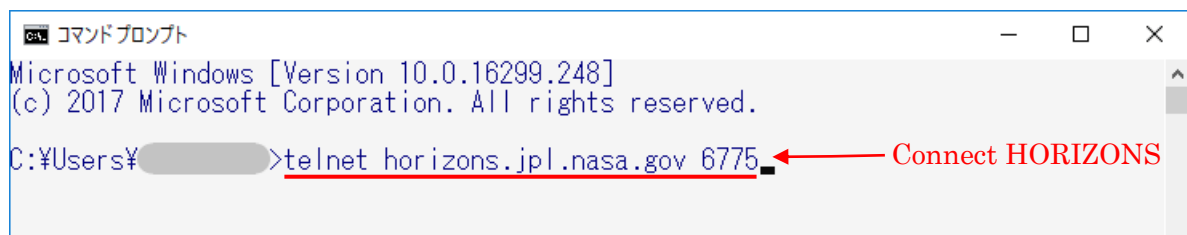
Delta-V (meters per second)	m_0	Propellant Consumption ($m_0 - m_T$)	m_T
500	1.017	0.017	1.000
1000	1.035	0.035	1.000
2000	1.070	0.070	1.000
4000	1.146	0.146	1.000
8000	1.312	0.312	1.000
16000	1.723	0.723	1.000
32000	2.967	1.967	1.000

Get SPK File of Celestial Small Body

This sub-section shows a sample of telnet operation that requests HORIZONS system of NASA/JPL to generate a SPK file of celestial small body. In this sample, we request and get a SPK file of Ryugu, an asteroid.

About HORIZONS system, see <<https://ssd.jpl.nasa.gov/?horizons>>.

On a command prompt of Microsoft Windows or other command line interface, connect HORIZONS with Telnet as follows:

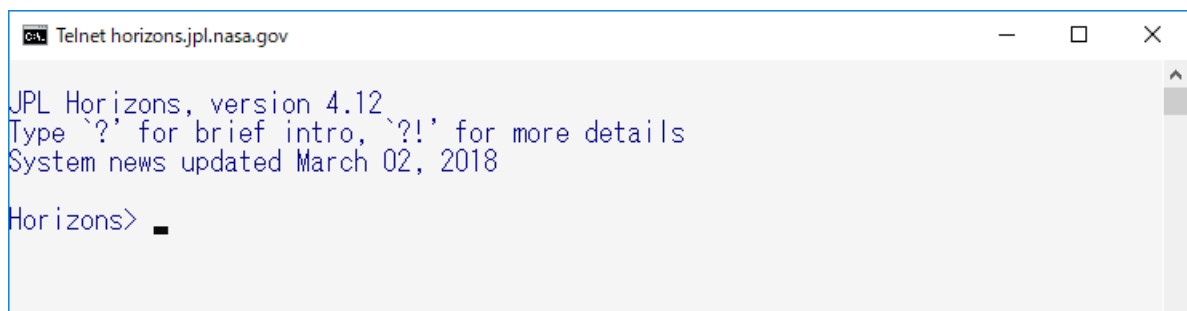


```
コマンドプロンプト
Microsoft Windows [Version 10.0.16299.248]
(c) 2017 Microsoft Corporation. All rights reserved.
C:\Users\%>telnet horizons.jpl.nasa.gov 6775
```

A red arrow points from the text "Connect HORIZONS" to the command `telnet horizons.jpl.nasa.gov 6775`.

Figure 32 Connect HORIZONS

HORIZONS shows prompt as follows:



```
Telnet horizons.jpl.nasa.gov
JPL Horizons, version 4.12
Type '?' for brief intro, '?!' for more details
System news updated March 02, 2018
Horizons>
```

Figure 33 Prompt of HORIZONS

On the prompt of HORIZONS, specify the celestial small body by its name, and type Enter key to confirm; HORIZONS shows precise information about the body, as follows:

```

JPL Horizons, version 4.12
Type '?' for brief intro, '?' for more details
System news updated March 02, 2018

Horizons> name = Ryugu; ← Specify the body by
                               its name

>EXACT< name search [SPACE sensitive]:
NAME = Ryugu;
Continue [ <cr>=yes, n=no, ? ] : ← Type Enter key
*****
JPL/HORIZONS          162173 Ryugu (1999 JU3)          2018-Mar-22 02:24:19
Rec #: 162173 (+COV) Soln.date: 2017-Apr-06_09:26:35   # obs: 725 (1986-2016)

IAU76/J2000 helio. ecliptic osc. elements (au, days, deg., period=Julian yrs):

EPOCH= 2455838.5 ! 2011-Oct-04.00 (TDB)          Residual RMS= .35399
EC= .1902778037787081   QR= .9633112167957903   TP= 2455902.249617131
OM= 251.6202622385231   W= 211.4184829650048     IN= 5.88355604508763
A= 1.18968112927032     MA= 311.5787724308354     ADIST= 1.41605104174485
PER= 1.29764            N= .759553208           ANGMOM= .01841997
DAN= 1.36889            DDN= .98643              L= 102.9042975
B= -3.0630813           MOID= .00081935             TP= 2011-Dec-06.7496171310

Asteroid physical parameters (km, seconds, rotational period in hours):
GM= n.a.                RAD= n.a.                ROTPER= 7.627
H= 19.3                 G= .150                  B-V= n.a.
                        ALBEDO= n.a.             STYP= Cg

ASTEROID comments:
1: soln ref.= JPL#117, PHA OCC=0
2: source=ORB
*****
Select ... [A]pproaches, [E]phemeris, [F]tp,[M]ail,[R]edisplay, [S]PK,?,<cr>:

```

Figure 34 Specify the Celestial Small Body

To request generating a SPK file, type “s” and Enter key, as underlined in the next figure. HORIZONS shows “SPK object ID” (SPKID) of the body at the double underlined portion. You should write it down.

```

ASTEROID comments:
1: soln ref.= JPL#117, PHA OCC=0
2: source=ORB
*****
Select ... [A]pproaches, [E]phemeris, [F]tp,[M]ail,[R]edisplay, [S]PK,?,<cr>: s
Assigned SPK object ID: 2162173 ← SPKID (you should write it down)
Enter your Internet e-mail address [?]:

```

Figure 35 SPK object ID (SPKID)

HORIZONS requests to input your e-mail address; enter it and confirm it; HORIZONS requests

to specify SPK file format as follows.

```
Enter your Internet e-mail address [?]:                     .com
Confirm e-mail address [yes(<cr>),no] : yes
Address stored this login only ... use "email" cmd to change

SPK file format    [Binary, ASCII, 1, ?] :   
```

Figure 36 Enter E-mail Address

Enter “1” (one) for the “SPK file format” as in the next figure. It is very important, because SSVG cannot read SPK files of other formats. Then enter the START time and STOP time to generate the SPK file. During this time span, you can use the body as Target in SSVG. When you answer “no” for the next question, HORIZON generates the requested SPK file and stores it on a FTP server. The file name will be displayed at the double underlined portion of the next figure. You should retrieve it in ten minutes.

By clicking following link, your web browser opens appropriate FTP address.

<<ftp://ssd.jpl.nasa.gov/pub/ssd/>>

```
SPK file format    [Binary, ASCII, 1, ?] : 1
SPK object START   [ t >= 1900-Jan-01, ? ] : 2001-Jan-01
SPK object STOP    [ t <= 2101-Jan-01, ? ] : 2100-Dec-31

Current integration step:
2451921.77869 2001 Jan 12.27869 -2.8070735
Current integration step:
2488401.50441 2100 Nov 29.00441  1.2697332

Binary SPK file created.
Add more objects to file [ YES, NO, ? ] : no

You have 10 minutes to retrieve the following by anonymous FTP:
Machine name:  ssd.jpl.nasa.gov
Directory      :  cd to "/pub/ssd/"
File name      :  wld66875.15
File type      :  BINARY  >* set FTP binary mode *<
Full path      :  ftp://ssd.jpl.nasa.gov/pub/ssd/wld66875.15

Select ... [E]phemeris, [M]ail, [R]edisplay, ?, <cr>:   
```

Figure 37 Generate a SPK file

We got the SPK file. Enter “x” to the prompt to close the Telnet session.

Let us change the file name to something like [object name].bsp (HORIZONS system uses the extension “bsp” for SPK files).

Operational Log

For each execution, SSVG records operations creating and/or editing of flight plan(s) as a text file (log file). SSVG stores log files into the “log” folder within the installed folder of SSVG.

Thrust Vector Mode

Thrust Vector Mode (tvmode) defines the way SSVG controls thrust directions of two propulsion devices of the Probe, the Electric Propulsion Engine and the Solar Sail.

Thrust Vector Mode in parameters of Maneuvers, EP_ON Maneuver and SS_ON Maneuver, has one of the two values, “L” or “E”. “L” stands for “Local”, and “E” stands for “Ecliptic”.

Because electric propulsion and solar sail are low-thrust propulsion systems, usually they take long time to provide significant delta-V. To enable effective control of thrust direction during operating time with small number of Maneuvers, we introduced Thrust Vector Mode. For example, Mode “L” of Electric Propulsion Engine allows us to accelerate the Probe for a long time, in the tangential direction of the orbit, by only one Maneuver.

If the Mode is “L”, thrust directions are fixed to local coordinates, orbit local coordinate system for Electric Propulsion Engine, or solar sail coordinate system for Solar Sail, during an operation of each propulsion system. To perform numerical integration of Probe trajectory, SSVG requires thrust directions in the ecliptic coordinate system. SSVG computes them from local coordinates every time they needed.

If the Mode is “E”, thrust directions are fixed to ecliptic coordinate system during an operation of each propulsion system. At the time an operation is initiated by an EP_ON Maneuver or by a SS_ON Maneuver, SSVG computes thrust vector direction in the ecliptic coordinate system. SSVG uses this direction throughout this operation of the propulsion system.

Note that Mode “E” of the Solar Sail fixes orientation of plane of the sail in the ecliptic coordinate system. It means that, in some cases, the sunny side of plane of the sail changes to other side, during one operation of the Solar Sail. When it happens, the thrust of the Solar Sail will reverse its direction.

Samples of Flight Plans

SSVG has some samples of Flight Plans. They can be retrieved from the “sampleplan” folder within the installed folder of SSVG. Those are as follows:

Mars01.json

This is a Flight Plan for a Mars exploration mission.

The Probe starts its space flight from EarthL2 Space Base. It uses only Chemical Propulsion Engine for orbit transitions. Flight time is 215 days. After arriving near Mars, the Probe enters Mars orbit.

Mars02_SS.json

This is a Flight Plan to Mars with the Solar Sail.

The Probe starts its space flight from EarthL2 Space Base, and its start velocity is 1000 meters per second. It flies to near Mars by using the Solar Sail only, as propulsion systems. This journey takes a little more than five years (1896 days), from the Space Base to Mars. Area of the Solar Sail is ten thousand square meters, and total mass of the Probe is five hundred kilograms. Accumulated delta-V from the Solar Sail is 8511 meters per second.

Mercury01.json

This is a Flight Plan for Mercury exploration mission.

The Probe starts its space flight from EarthL2 Space Base, and it enters Mercury orbit. To minimize total delta-V from Chemical Propulsion Engine, this Flight Plan uses gravity assist of Venus twice and gravity assist of Mercury twice, before Mercury orbit insertion. This journey takes about five and a half year (2050 days), from the Space Base to Mercury orbit insertion.

Venus01.json

This is a Flight Plan that replicates the flight of “AKATSUKI”, a space probe of JAXA.

The Probe started its space flight from EarthL2 Space Base at May 20, 2010. After two hundred days of space trip, it arrived at the vicinity of Venus at December 6, 2010, and entered Venus orbit.

Note that although we intended to replicate the actual space flight, the trajectory is not so accurate.

Voyager2.json

This is a Flight Plan that replicates the flight of “Voyager 2”, one of the most famous space probes of NASA/JPL.

The Probe started its space flight from EarthL2 Space Base at August 20, 1977. It flew by Jupiter, Saturn, Uranus, and Neptune sequentially, and performed valuable observations. The fly-by of Neptune occurred at August 25, 1989; the total flight time until Neptune was about twelve years (4389 days).

Note that although we intended to replicate the actual space flight, the trajectory is not so accurate.

References

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