SSVG User's Guide

Solar System Voyager

Contents

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 the Sun on it as well.
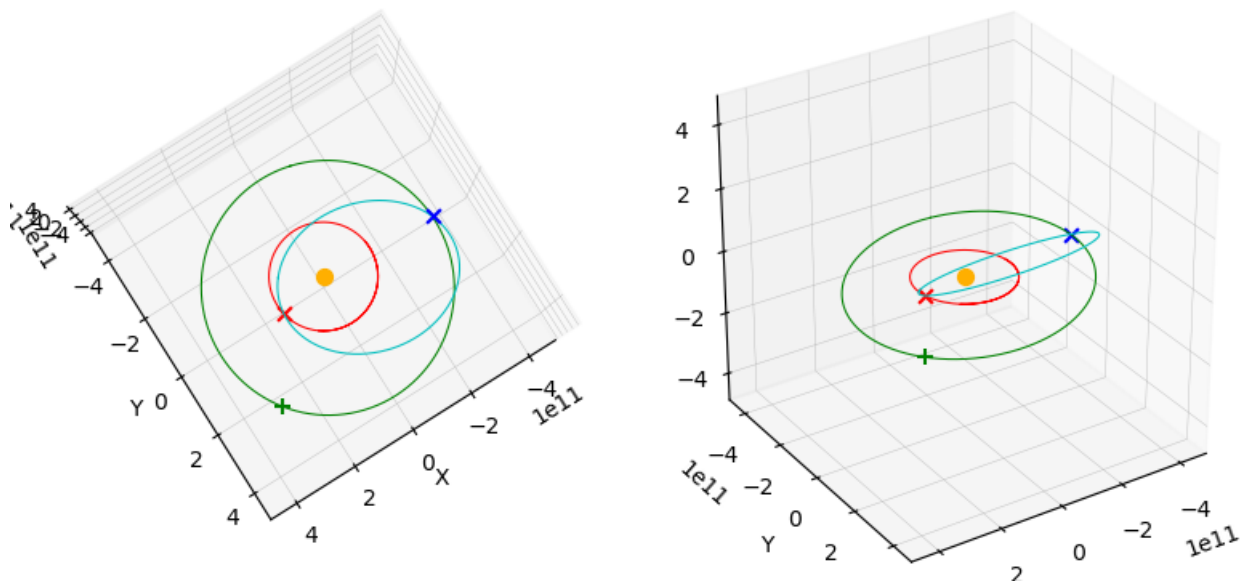
Figure 1   3D charts of SSVG

What's new in recent Versions

Version 1.3

Internationalized

User interface of SSVG was internationalized.   In Japanese environment, user interface of SSVG uses Japanese; otherwise, it uses English.

In addition, SSVG became extensible to other languages without modification of Python scrips.

Improved User Interface

User interface of SSVG was improved to achieve more understandable system.

Version 1.2

Adapted to new format of SPK files

SSVG was adapted to new format of SPK files for celestial small bodies of solar system. It means that you can use more convenient tool to get SPK files.

Renewal of Development Environment

Renewal of development environment was carried out to ensure long-term maintainability 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 the orbit bring the spacecraft to its destination with small intermediate orbital corrections. Almost all space flights are "preplanned" ones.

In SSVG, we have entirely different choice for the strategy to perform a space flight. Our Probe can fly its space travel with "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 the gravitational pull, we can change orbit of the spacecraft sometimes slightly, sometimes violently. We call it as "gravity assist" or "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 tools 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 a spacecraft 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 did not it fly directly?

We can replicate space flights of actual spacecrafts as Flight Plans of SSVG. By composing 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 large 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 the Sun; this distance is 133 times of the one from the Sun to the 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 each giant planet.

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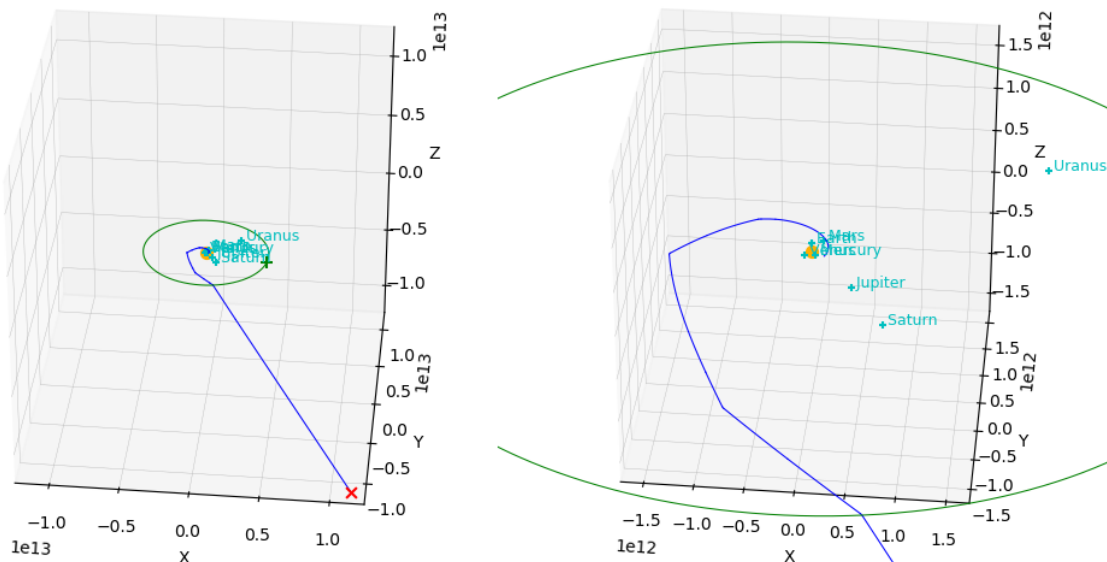

Figure 2 Replicated trajectory of Voyager 2

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: the date to leave Earth, and the flight time. For choosing them, SSVG has convenient tools, 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 twenty-four hours). Because of this low thrust, it is not a rare case that an orbit transition requires very long time (e.g. one hundred 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 generate thrust force 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 is able to spread its solar sail at any time, to any size, and to any orientation under instructions from us. Let us fly our Probe with the solar sail.

How to Use this Document

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

This document (a PDF document) has bookmarks of each chapter, section, etc.   For convenience, it is recommended that you turn ON the "Show Bookmarks" function (or equivalents) of the PDF reader in use.

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 each bookmark of this document are in green (e.g. License of SSVG).

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

SSVG uses following programs and modules:

    Python: https://www.python.org/
    Numpy: http://www.numpy.org/
    Scipy: http://scipy.org/
    matplotlib: http://matplotlib.org/
    PyQt: https://riverbankcomputing.com/software/pyqt/intro
    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/
    spktype21: https://github.com/whiskie14142/spktype21/
    PyInstaller: http://www.pyinstaller.org/

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Please note that it may take time to reply.

How to Use SSVG

Install and Uninstall SSVG

SSVG is distributed in two formats: one is an executable of Microsoft Windows with related modules and files, and another is a set of scripts (source programs) of Python with related files. You can use any one of them or both.

Windows Executable
Install
You can get a Windows executable of SSVG from following web pages.
http://whsk.sakura.ne.jp/ssvg/index-en.html
https://www.freewarefiles.com/Solar-System-Voyager-SSVG-_program_112419.html
You can download a compressed file named "SSVG_x_x_x.zip" (x_x_x is version number).   Open it with your convenient tool, and copy the "SSVG_x_x_x" folder (x_x_x is version number) on your PC with its contents.   The zip file also contains PDF files including this document.

Uninstall
Delete installed "SSVG_x_x_x" folder (x_x_x is version number) 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 1280 pixel or more.
SSVG consumes roughly one giga byte of disk space.

Get SPK file
The program package of SSVG does not contain an essential data file to compute positions and velocities of the Sun and planets. Get the data file (an SPK file, named de430.bsp) from following address, and place it in the "SSVG_data" folder within the folder of SSVG.
<http://naif.jpl.nasa.gov/pub/naif/generic_kernels/spk/planets/de430.bsp>

Create Shortcut
The folder of SSVG contains executable of SSVG; you can find it as "SSVG.exe" or "SSVG" with following icon.   We recommend you to create a shortcut of it on your Windows desktop.

 (Icon of SSVG executable)

Upgrade install from older versions
Previous procedures install new version of SSVG into a new folder.   Copy following files from older installation to newer installation.
- SPK files (including de430.bsp) you have downloaded: copy them into "SSVG_data" folder of newer installation
- Flight Plan files you have created: copy them into "SSVG_plan" folder of newer installation

If you are satisfied by newer installation, you may uninstall older version.

Python Scrips (Source Programs)

Install

If you have Python 3.7 with Numpy/Scipy/matplotlib/PyQt5, you may run SSVG on your Python environment.　You can retrieve Python scripts (source programs) of SSVG from GitHub. <https://github.com/whiskie14142/SolarSystemVoyager/>

On the mentioned web page of GitHub, click "Clone or download."　You will get a ZIP file; open it with your convenient tool, and copy the "source" folder on your PC with its contents. We recommend you to rename the folder to "SSVG_x_x_x" (x_x_x should be version number).

Uninstall

Delete installed folder with its contents.

PC environment

Python 3.7
Recommended display size is 1024 pixel x 1280 pixel or more.

Packages used and their versions

Numpy　1.15.1
Scipy　1.1.0
matplotlib　2.2.3
PyQt　5.9.2
jplephem　2.8
julian　0.14
pytwobodyorbit　1.0.0
spktype01　1.0.0
spktype21　0.1.0

Last five modules (jplephem, julian, pytwobodyorbit, spktype01, and spktype21) are registered on the Python Packages Index (PyPI), so you can install them with pip commands.

The pytwobodyorbit module was updated.　If you have older version, you need to perform upgrade install of it.

Setup Japanese Font

If you are using Japanese environment, you need to setup Japanese font for the matplotlib module.　Go along with following instructions.

- Copy a font file into the font folder of matplotlib
  - The ZIP file of SSVG downloaded from GitHub contains the font file.　Name of the font file is `ipaexg.ttf`, and the path of the file within the ZIP file is: `font¥ipaexg00301¥ipaexg.ttf`
  - The font folder of matplotlib is in your Python environment.　The path is something like: `[Python root]¥Lib¥site-packages¥matplotlib¥mpl-data¥fonts¥ttf`
- Erase font cache file of matplotlib.　The path of the file is something like: `[User root]¥.matplotlib¥fontList.json`

Get SPK file

Installed scripts of SSVG do not contain an essential data file to compute positions and velocities of the Sun and planets.　Get the data file (an SPK file, named `de430.bsp`) from following

address, and place it in the "SSVG_data" folder within the folder of SSVG.
<http://naif.jpl.nasa.gov/pub/naif/generic_kernels/spk/planets/de430.bsp>

Upgrade install from older versions

Previous procedures install new version of SSVG into a new folder.　Copy following files from older installation to newer installation.

- SPK files (including de430.bsp) you have downloaded: copy them into "SSVG_data" folder of newer installation
- Flight Plan files you have created: copy them into "SSVG_plan" folder of newer installation

If you are satisfied by newer installation, you may uninstall older version.

Run SSVG

Windows Executable

Double click the shortcut of SSVG.exe on your Windows desktop.　Otherwise, double click SSVG.exe itself within the folder in which SSVG is installed.　A command prompt window appears, and then SSVG starts its execution.

Python Scripts

Run SSVG.py from Python.　SSVG.py is contained within the folder in which SSVG is installed.

Run Flight Plan

Open a Flight Plan

On executing 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 see files within "SSVG_plan" folder; we can find several samples of Flight Plan.　Select "sample_Mars" (or "sample_Mars.json" in some environments) among them and open it.
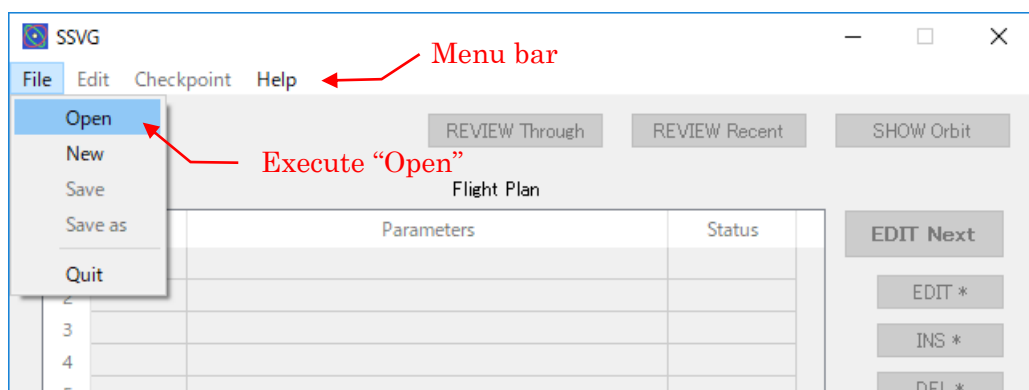
Figure 3　Execute "Open"

In this Flight Plan, a Probe named "Marsexp" starts its flight from a Space Base named "Earth L2", 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 Maneuvers in the table one by one, from top to bottom, the Probe flies from the Space Base to Mars.
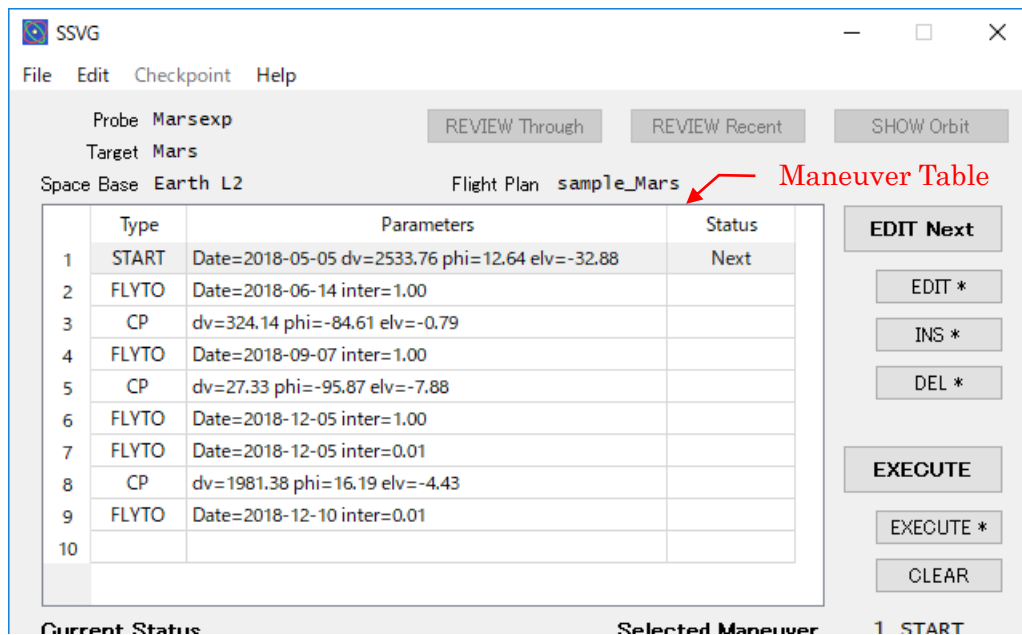
Figure 4　Maneuver Table

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 [EXECUTE] 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).
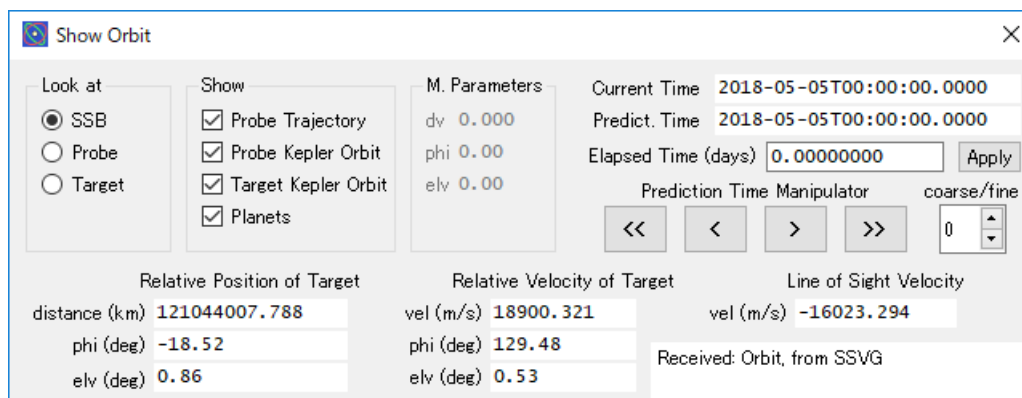
Figure 5　Show Orbit window

At the same time, the 3D Orbit window appears. As shown in the next figure, the window displays following information as a three dimensional (3D) chart:

    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)
    The Sun (a small disk in orange)
    Planets (+ marks and names in cyan)

At this point (just after you opened sample_Mars and clicked [EXECUTE] once), the Probe left the space base just now, and started its journey to Mars.
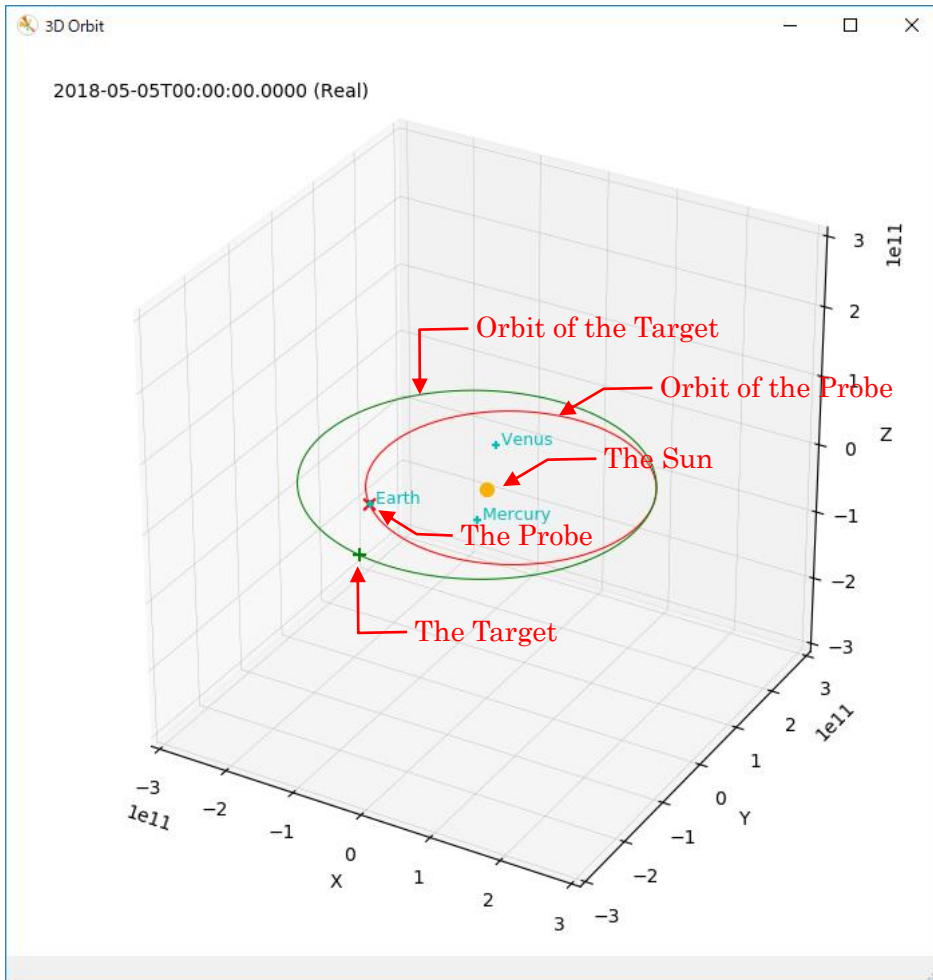
Figure 6   Information displayed on the 3D Orbit window

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. In addition, you can resize the 3D Orbit window by dragging each side or corner of the window.

Some manipulations of the chart are performed on the Show Orbit window; click [>>] button in the "Prediction Time Manipulator" (see next figure) several times. The 3D chart shows positions of the Probe, Mars (the Target), and other planets in the future.
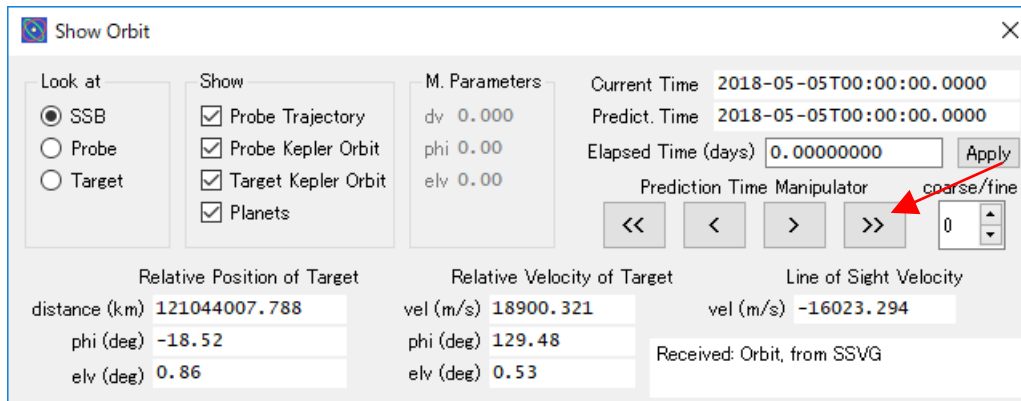
Figure 7   Prediction Time Manipulator

If you wish to know precise manipulation method, see 3D Orbit Window and Show Orbit Window subsections.

Execute Maneuvers

Let us execute next three Maneuvers.   Click [EXECUTE] button three times; three Maneuvers next in the table will be executed one by one, toward the bottom of the table: 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 subsection.

Review Recent Flight

Immediately after an execution of a FLYTO Maneuver, you can review the fight.   At this point, we can review a FLYTO Maneuver because we just executed the one in the fourth line (row) of the Maneuver Table.   Click [REVIEW Recent] button of the SSVG window.   A 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).
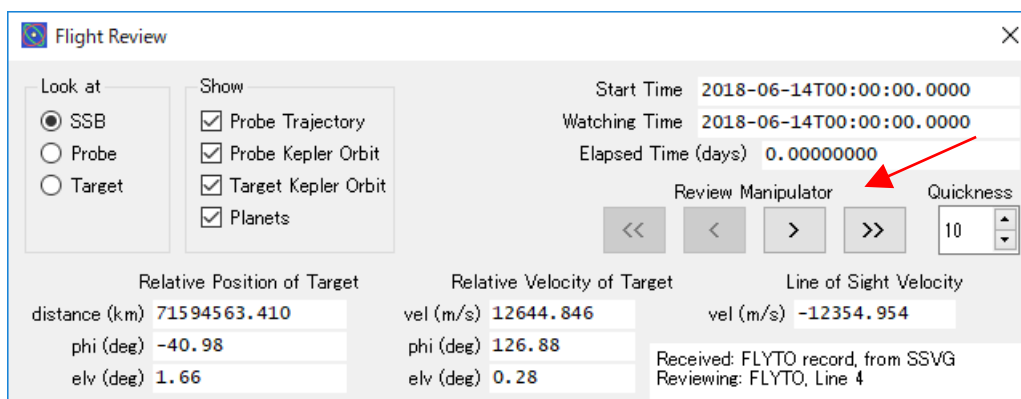
Figure 8   Flight Review window

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Let us review the last FLYTO Maneuver of this Flight Plan. Click [EXECUTE] 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 the 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 center of the chart, get a close-up view, and review the flight. Hints for these operations are as follows:

- How can we place the Target at the center 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 subsections.

Fly New Probe

Let us compose a Flight Plan of a new Probe.

Create New Flight Plan

To create new Flight Plan, click "File" on the menu bar of the SSVG window, and execute "New". A New Flight Plan window appears.

Figure 9　New Flight Plan window

With the "Probe" group, we can specify name and mass of the Probe, but in this case let us use the default values.　We can select one of the Space Bases in the drop-down list, but let us use the default "Earth L2" now.　This Space Base is orbiting the Sun with Earth.　Its position is approximately 1.5 million kilometers (940 thousand miles) away and opposite to the 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 create a new Flight Plan and displays it on the Maneuver Table.　Because the Flight Plan 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.　A Maneuver Editor window appears.

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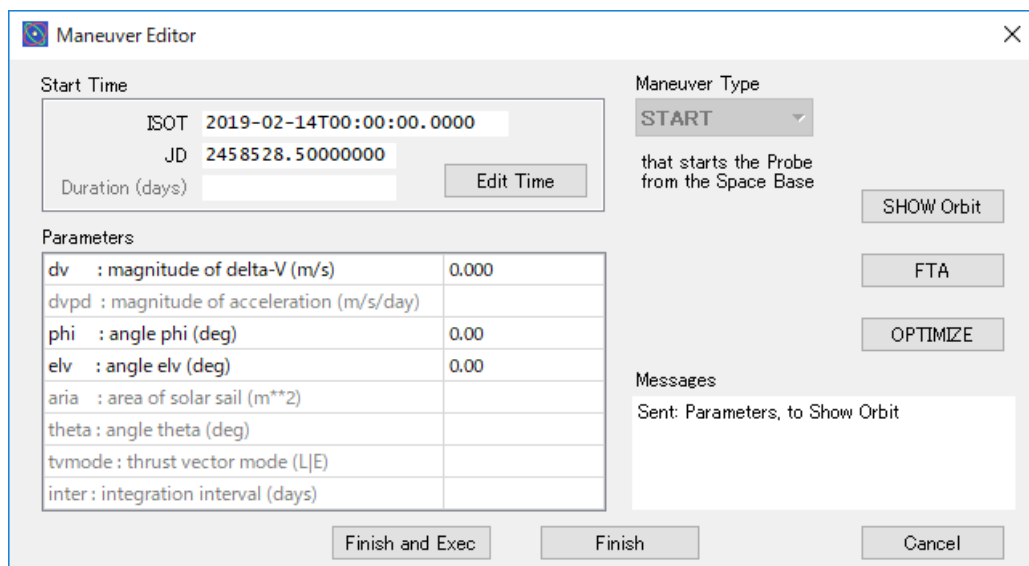
Figure 10　Maneuver Editor window

In this case, the Maneuver Editor is editing a START Maneuver. A Show Orbit window also appears below the Maneuver Editor window, and the 3D Orbit window shows current position and orbit of the Probe and other objects. 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, and rewrite the value from `0.000` to `2500` (see next figure). 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 (*).

(*) In this case, "the velocity of the Space Base" means the one relative to the Sun.
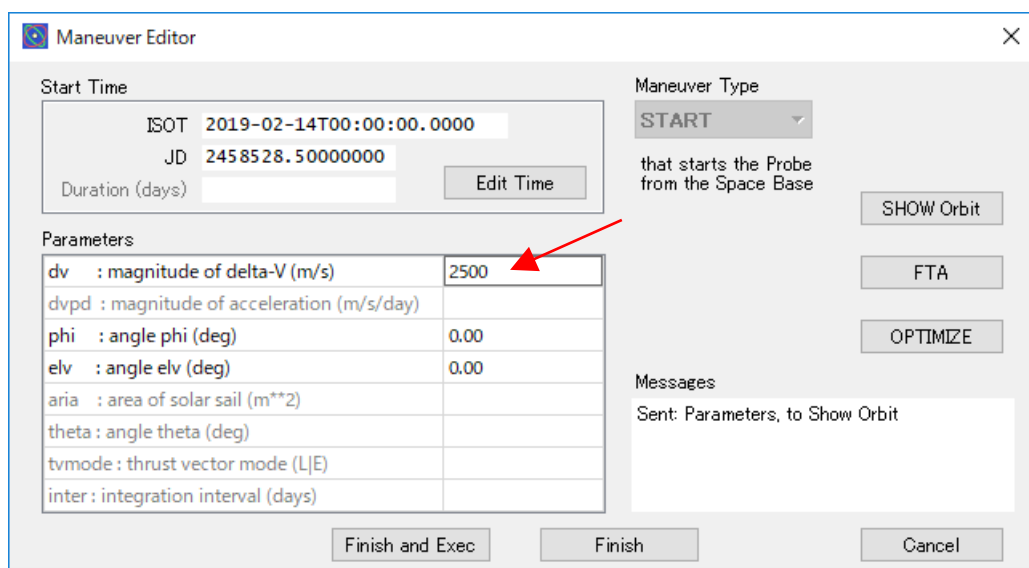
Figure 11　Maneuver Editor window (editing a START Maneuver)

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. Confirm that the Maneuver Table on the SSVG window contains the START Maneuver and the indication of "Next" is on the second line (row).

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; let us 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. A Maneuver Editor window appears again. In this case, you should click the drop-down list of Maneuver Type and select "FLYTO". The Maneuver Editor window becomes the one for a FLYTO Maneuver, and a Show Orbit window appears again.

In this tutorial, 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" of the FLYTO Maneuver on the Maneuver Editor window. As you click the button, the "End Time" of the Maneuver Editor window (ISOT, JD, and Duration) goes ahead by ten days.
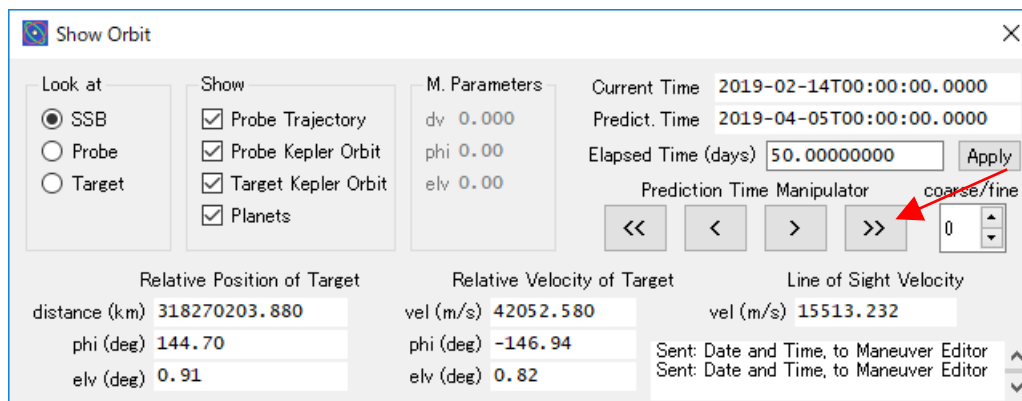
Figure 12   Set the End Time ahead

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 the 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 the 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. A Maneuver Editor window appears. Select "CP" for the Maneuver Type of this window.

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For a CP Maneuver, there are three parameters to be specified, "dv", "phi", and "elv". The parameter "dv" defines magnitude of the 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 the 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 (i.e. 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 of the editing Maneuver 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.
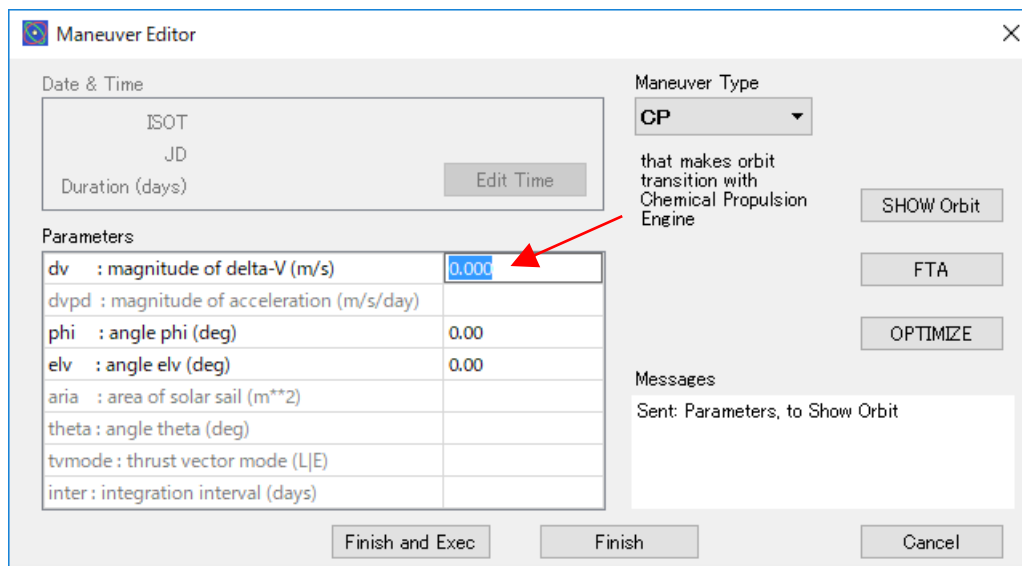
Figure 13   Maneuver Editor window for CP

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.
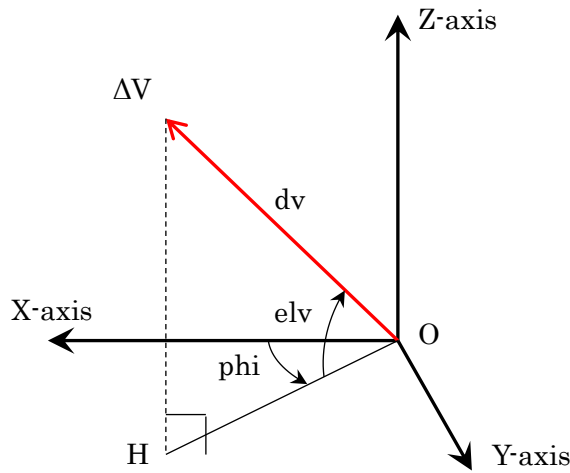
Figure 14　Defining parameters for delta-V

The origin (point O) of the axes is a Probe.　The orbital plane of the Probe about the Sun defines X-Y plane, and the velocity vector of the Probe defines the X-axis.　The Z-axis is normal to the orbital plane of the Probe.　The direction of Y-axis is to approach the 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 the ΔV to the X-Y plane, and name the foot point as "H".　The parameter "phi" is the angle from the X-axis to the line segment OH.　The parameter "elv" is the angle from the line segment OH to the 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; it means parameter "phi" should be 180.0 (degrees) and parameter "elv" should be 0.0 (degrees).　For several values of "dv", try decelerating the Probe and observing 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 <u>Figure 14</u> again.

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 trials satisfied you, click [Finish and Exec] button on the Maneuver Editor window to finish 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 fight 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 Maneuvers. However, it is not enough to fly the Probe freely. It is important to use FLYTO Maneuvers combined with CP Maneuvers. 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." Only when we edit the "Next Line" can we 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 SSVG window.
- By clicking [EXECUTE] button, the indicator shifts downward by one line

- By clicking [CLEAR] button, the indicator moves to the top line

Fly the Probe toward Mars

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

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 compose a Flight Plan toward Mars. 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 center 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 flew the Probe, the Target moved within the flight time. When you accelerated the Probe, the size of the orbit changed also. The orbital 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 in bringing 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 brings 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: Earth L2

- Add and execute a START Maneuver. Parameters are as follows. To edit the Start Time, click [Edit Time] button in the "Start Time" group.
  - Start Time: 2020-03-26T00:00:00.000000
  - dv: 9058.071

- o phi: `-4.80`
- o elv: `-8.15`

- Add and execute a FLYTO Maneuver. Duration of the flight should be 428 days. To edit Duration, click [Edit Time] button in the "End Time" group and select "Edit by Duration" radio button.
  (End Time should become `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 it 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 Show Orbit window) of the Probe is a two-body orbit. It means that the orbit is computed using gravitational pull of the 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 the 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. The targeting point can be the center of the Target or a point in the vicinity of the Target. We can use one of the two sets of coordinates to specify the point near the Target, 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,
  - o Select [Specify Now] radio button,
  - o Enter `150` to the "Time to Arrival (days)" field.

- In the "Precise Targeting" group,
  - o Select [B-plane Coordinates] radio button.

- In the sub-group of [B-plane Coordinates], enter following values (*):
  - o For the "offset distance (km)" field: `5000000` (five million)
  - o 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, which is a two-body orbit about the Sun. See B-plane Coordinate System subsection.
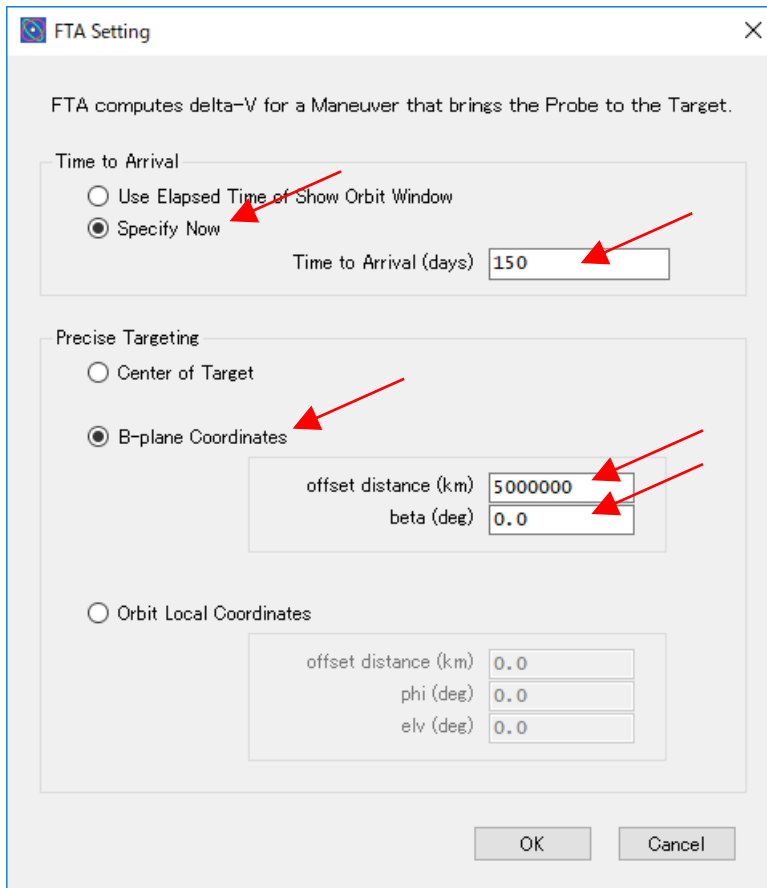
Figure 15　Setting the FTA function

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 flew by Jupiter.　Click [REVIEW Recent] button on the SSVG window.　A Flight Review window replaces existing Show Orbit window.　By clicking buttons in the "Review Manipulator" of the Flight Review window, 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 transitions 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] button on the SSVG window. The first line will be the "Next Line".
- Click [EXECUTE] 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 subsections.

Flight Plan toward Venus

Let us create a Flight Plan toward Venus, the twin planet of the 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 the 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.

Create New Flight Plan

Create 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, "Earth L1" or "Earth L2". Which one is better? Both Space Bases lie 1.5 million kilometers from Earth, but opposite direction. "Earth L1" lies in the direction of the Sun, but "Earth L2" 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 the Sun), it is better to select "Earth L1" to minimize gravity effect from Earth the Probe suffers immediately after the start. If the initial flight direction is outward (the direction to leave the Sun), "Earth L2" 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 a short one. Because the Probe leaves Earth inward by this path, the "Earth L1" is better than "Earth L2".

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. A Maneuver Editor window for "START" Maneuver appears.

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. A Start Optimize Assistant window appears (see next figure).
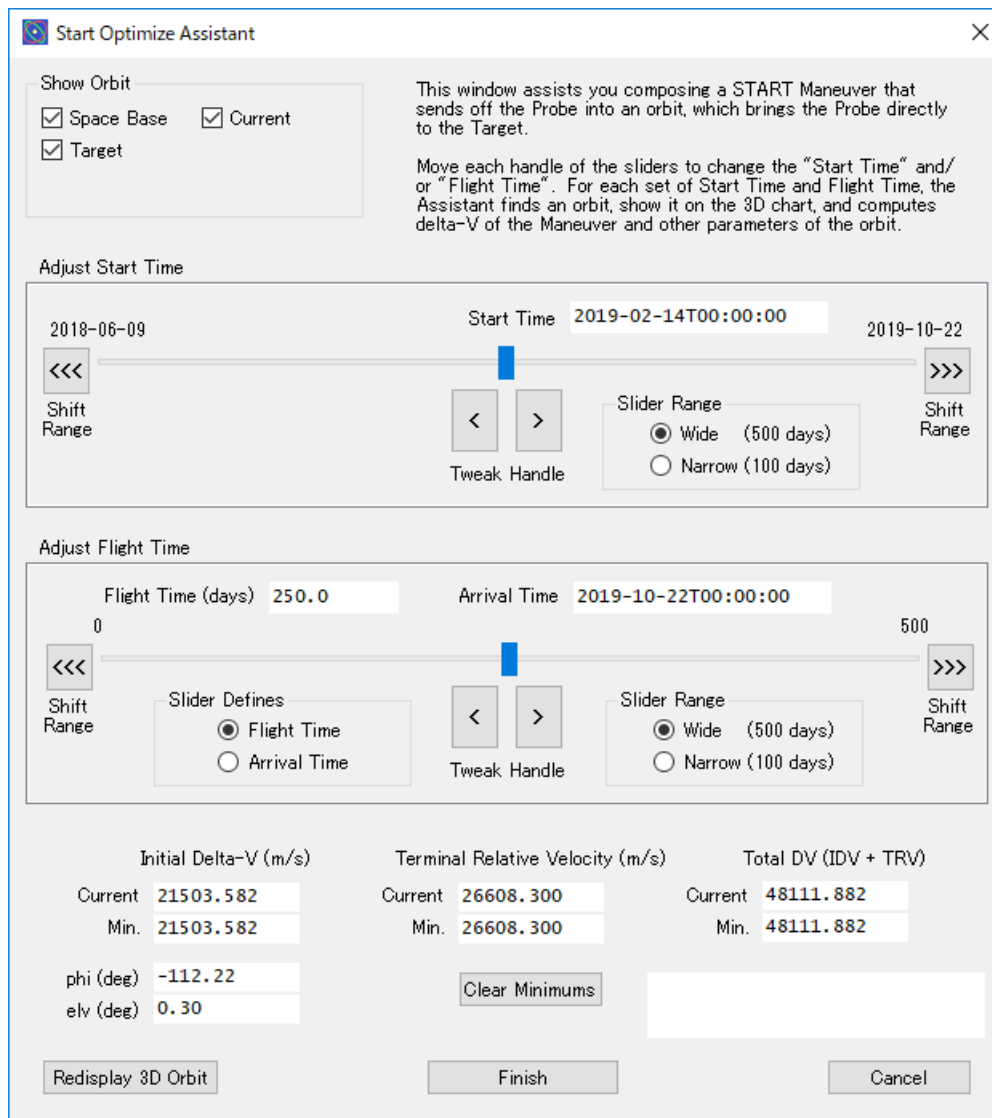
Figure 16   Start Optimize Assistant window

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

We use these two groups to adjust 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: sum of the Initial Delta-V and the Terminal Relative Velocity

(*) Following marks and lines are displayed on the 3D Orbit window.
- An X mark in red: the Probe at the Start Time
- A + mark in green: the Target at the Start Time
- An X mark in blue: the Probe and the Target at the arrival
- A curved line in red: the trajectory of the Space Base
- A curved line in green: two-body orbit of the Target
- A curved line in cyan: computed two-body orbit of the Probe
- A small disk in orange: the Sun

When you move a slider handle, Start Time or Flight Time changes, and mentioned values and the orbit (on the 3D Orbit window, curved line in cyan) changes also.   With that information, you can find favorable Start Time and Flight Time.

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Note that by clicking [<<<] or [>>>] buttons, you can shift the range of each slider by one-half of it. In addition, you can see <u>Start Optimize Assistant Window</u> subsection for more information.

Let us set the Start Time and the Flight Time to following initial values by moving slider handle and clicking [<<<] or [>>>] button of each group.

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

Then, let us look for favorable Start Time and Flight Time.

When you find favorable Start Time and Flight Time, make a note of the Flight Time and the Arrival Time, and click [Finish and Apply] button. The Start Time and the 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 the Optimize Assistant, is a two-body orbit that is computed from gravitational pull of the Sun only, the actual 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 Venus?

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 (*1), 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.

(*1) If you wish to minify the time interval by button operations to manipulate the Prediction Time, set the "coarse/fine" spinner to `-1`, `-2`, or less.

In the Precise Targeting group of the FTA Setting window, select the radio button of "B-plane Coordinates". See <u>B-plane Coordinate System</u> subsection, and set appropriate parameters. Click [OK] button and confirm the results of FTA. The results are 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 stores 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 the 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 the time point, and add a CP Maneuver that decelerate the Probe to reduce relative velocity of the Target to an appropriate value (*), the Probe will enter Venus orbit. You will be able to look it by adding and executing a FLYTO Maneuver, and reviewing it.

(*) Hints for the operation: At the point when you start editing of a CP Maneuver, the Show Orbit window shows values of "Relative Velocity of Target," and coordinates of the values are identical to the coordinates of delta-V of CP Maneuver. If you copy values of "Relative Velocity of Target" to parameters of dv, phi, and elv of the Maneuver Editor respectively, the CP Maneuver becomes the one that makes relative velocity of the Target to zero. If you wish the Probe to enter Venus orbit, the parameters are not appropriate and you should reduce the value for "dv", but you can use values for "phi" and "elv" without any changes.

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.

Choosing a small body for a Target of SSVG, we need an SPK file that provides positions and velocities of the body. We have an SPK file already, that is "de430.bsp" in the "SSVG_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 only binary files for asteroids, comets, and dwarf planets.   We have a sample of requesting such a file to HORIZONS system in Get SPK File of Celestial Small Body subsection.

Once we have acquired an SPK file for a celestial small body, we can choose it as the Target when we create a new Flight Plan, or when we edit an existing Flight Plan.   See New Flight Plan Window subsection.

Sample of Celestial Small Bodies

Next table shows small list of celestial small bodies.   The table contains SPKID (Identification number of celestial small body in HORIZONS system) of each body, it makes easy to download SPK files of celestial small bodies.

Table 3   Sample of Celestial Small Bodies

IAU No.	Name	Type	SPKID	Features
1	Ceres	Dwarf Planet	2000001	The largest body in the asteroid belt (*1). "Dawn" (*2) explored it precisely.
2	Pallas	Asteroid	2000002	A large body in the asteroid belt (*1). It has large orbital inclination.
3	Juno	Asteroid	2000003	A large body in the asteroid belt (*1).
4	Vesta	Asteroid	2000004	A large body in the asteroid belt (*1). "Dawn" (*2) explored it precisely.
433	Eros	Asteroid	2000433	One of the near-earth asteroids.
617	Patroclus	Asteroid	2000617	One of the Trojans (*3).
1566	Icarus	Asteroid	2001566	One of the near-earth asteroids.
1862	Apollo	Asteroid	2001862	One of the near-earth asteroids.
3753	Cruithne	Asteroid	2003753	One of the near-earth asteroids. Orbital period is very near to one year of the Earth.
4179	Toutatis	Asteroid	2004179	One of the near-earth asteroids.
25143	Itokawa	Asteroid	2025143	One of the near-earth asteroids. "Hayabusa" (*4) brought back samples to the Earth.
101955	Bennu	Asteroid	2101955	One of the near-earth asteroids. "OSIRIS-REx" (*5) is expected to bring back samples.
162173	Ryugu	Asteroid	2162173	One of the near-earth asteroids. "Hayabusa 2" (*4) is expected to bring back samples.
1P	Halley	Comet	1000036	One of the most famous periodic comets.
2P	Encke	Comet	1000025	A comet with very short orbital period.
67P	Churyumov-Gerasimenko	Comet	1000012	A comet with very short orbital period. "Rosetta" (*6) explored it precisely.

(*1) The area between Mars orbit and Jupiter orbit is often called "asteroid belt" or "main belt", because large part of asteroids has orbits in the area.

(*2) "Dawn" is a space probe of USA.   It was launched in 2007, and explored Vesta and Ceres precisely.

(*3) There are many asteroids around Lagrange points L4 and L5 of Jupiter.   They called as "Trojan asteroids".

(*4) "Hayabusa" and "Hayabusa 2" are space probes of Japan.   "Hayabusa" was launched in 2003 and returned to the Earth in 2010.   "Hayabusa 2" was launched in 2014 and it is expected to return to the Earth in 2020.

(*5) "OSIRIS-REx" is a space probe of USA.   It was launched in 2016 and it is expected to return to the Earth in 2023.

(*6) "Rosetta" is a space probe of the European Space Agency, ESA.   It was launched in 2004.

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 its destination.

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 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 large 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 the 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 the Sun, one from the planet) make a balance.　An object placed here (L1 or L2) orbits the Sun, along with the planet at the same orbital period.

(*) L1 and L2 around Earth are on the line through the 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 the Sun and there are no other planets.　Because no orbit is a perfect circle and the solar system has other planets, these points (L1 and L2) are approximations.　Objects placed at L1 (or L2) gradually drift away with time.　In SSVG, we suppose that there are mechanisms to hold Space Bases at prescribed positons.

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 the Sun by a "Distance Factor"; for L2, SSVG uses the 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 4　Space Bases

Planets	Space Bases at L1	Space Bases at L2	Distance Factors	Average Distances (million kilometers)
Mercury	Mercury L1	Mercury L2	0.00381	0.22
Venus	Venus L1	Venus L2	0.00934	1.0
Earth	Earth L1	Earth L2	0.01008	1.5
Mars	Mars L1	Mars L2	0.00476	1.1
Jupiter	Jupiter L1	Jupiter L2	0.06828	53
Saturn	Saturn L1	Saturn L2	0.04568	66
Uranus	Uranus L1	Uranus L2	0.02442	69
Neptune	Neptune L1	Neptune L2	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 subsection for precise information for those parameters.

Table 5 Types of Maneuvers

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

Flight Plan

In SSVG, a "Flight Plan" is a set of information about Probe and Target, and a sequence of Maneuvers to fly a 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 an 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 creating a Flight Plan, we define the 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 the Target at the creation of a 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 the Target, and on the second phase, we should choose Saturn as the Target.

Target

In SSVG, a 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 of editing the CP Maneuver.

On the other hand, selection of the Target (which celestial body is the Target at the time) does not affect execution of any Maneuvers including FLYTO Maneuvers that compute flight trajectories of the Probe.

Celestial bodies that can be chosen for a Target are in 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 SSB (*) centered SPK files. When we wish to choose a small body as a Target, we need an SPK file for the body. See Get SPK File of Celestial Small Body subsection.
  Except the moon of Earth, we cannot choose any moons of planets as a Target.

(*) SSB means Solar System Barycenter

Chemical Propulsion Engine

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

Liquid propellant rocket engines can 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 can be any value.

On the other hand, actual 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 subsection). 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). However, there are limitations in number of decimals of parameters.

Electric Propulsion Engine

A Probe of SSVG has an Electric Propulsion Engine, which is a simplified model of electric propulsion devises, such as ion thrusters or Hall-effect thrusters. Those devises 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 subsection) 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 turn on (or off) it at an instant.
- If we have turned 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). However, there are limitations in number of decimals of parameters.

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.

(*) JAXA: Japan Aerospace Exploration Agency

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 the Sun, but departing from the Sun.

A Solar Sail in SSVG has following characteristics:
- It is a double-sided perfect mirror.
- We can turn on (or off) it at an instant.
- When we turn on it, we specify area and orientation of the sail as parameters.
- There is no limitation of area of the sail.
- If we have turned on it, we can change its parameters at an instant.
- Mass of the sail is included in the total mass of the Probe.
- Its area and orientation of the sail contains no errors.   However, there are limitations in number of decimals of parameters.

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 subsection for details.

It is useful to know characteristics of Solar Sail as a propulsion device to achieve orbit transition. Some of them are as follows: (see Solar Sail Coordinate System subsection about theta and elv)
- Maximum thrust is achieved when the plane of sail faces directly to the 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 of the thrust force, 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 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 elv = `35.26` or `-35.26` (with "tvmode" = "L").

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

Trajectory and Orbit

In SSVG, we use both terms of "Trajectory" and "Orbit" to express flight paths of Probes. However, we use the two terms quite differently as follows.

Trajectory

Trajectories are realistic flight paths of Probes computed by numerical integration. The computation uses almost all forces that affect to the Probe as follows:

- Gravitational pull of the Sun
- Gravitational pull of planets and the moon of Earth
- Thrust force of the Electric Propulsion Engine and the Solar Sail

We use the terms of "actual trajectory" for the same meaning.

Orbit

Orbits are idealized flight paths of Probes computed from two-body motion about the Sun. The computation uses gravitational pull of the Sun only, and does not use other forces including gravitational pull of planets and thrust forces of propulsion systems.

We use the terms of "two-body orbit" and "Kepler orbit" for the same meaning.

Windows and Operations

SSVG Window

The 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 bar: we can execute several important functions from the menu bar.
- Buttons: there are three groups of buttons: REVIEW/SHOW buttons, EXECUTE buttons, and EDIT buttons.
- Maneuver Table: a 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 name, Space Base, Flight Plan file name
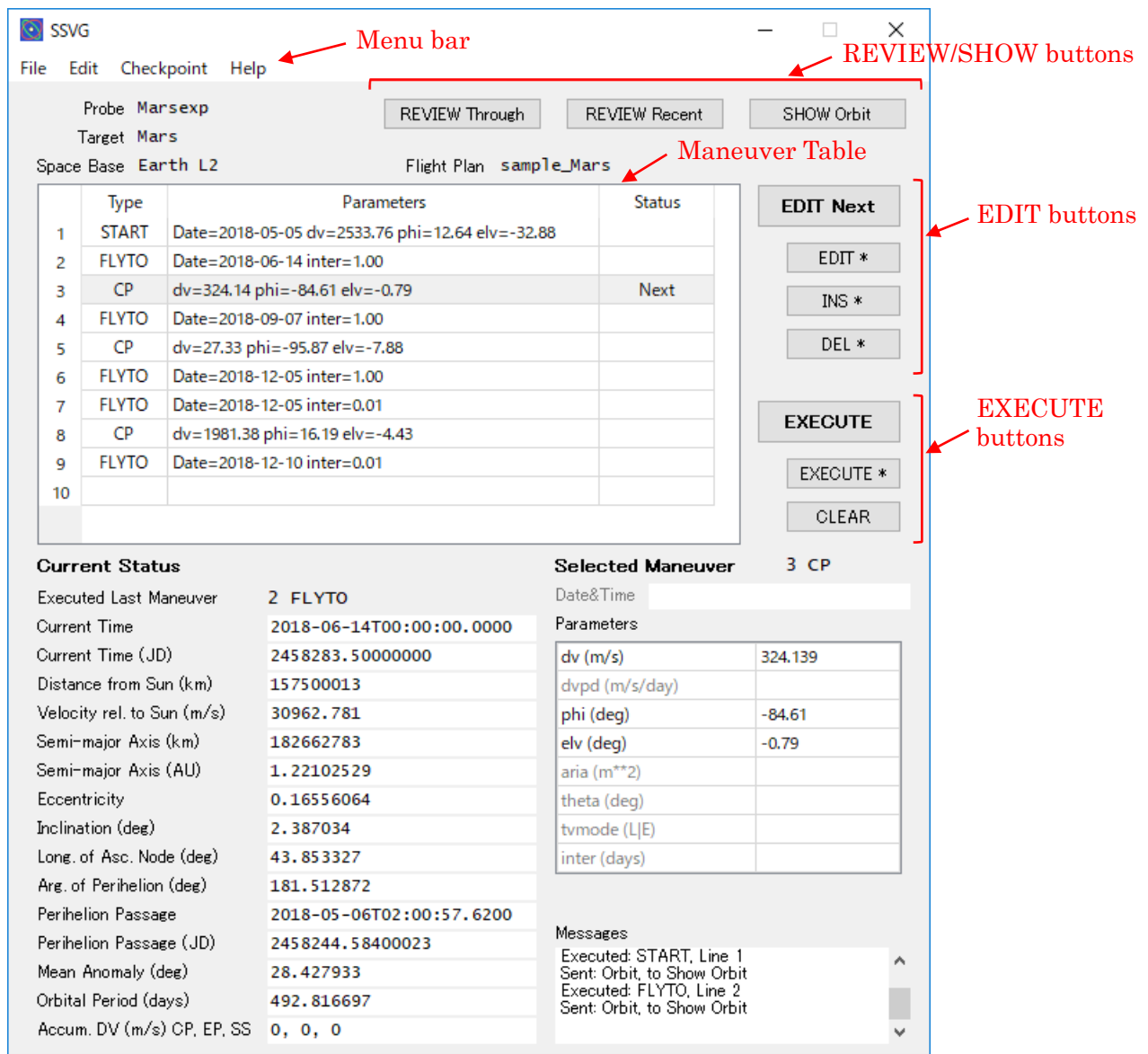- Messages: messages from SSVG about its behavior

Figure 17　SSVG window

Menu bar

<p align="center">Table 6　Menu bar of the SSVG window</p>

Menu Items	Subitems	Functions
File	Open	SSVG opens 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 selecting of Target 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 state (*2) 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] button or by other means, the Checkpoint will be lost.

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

Buttons

<p align="center">Table 7　Buttons on the SSVG window</p>

	Face Name	Function
REVIEW/SHOW Buttons	REVIEW Through	When clicked, SSVG opens a Review Throughout window that allows us to review through all executed Maneuvers.　If the 3D Orbit window does not exist, SSVG opens it
	REVIEW Recent	When clicked, SSVG opens a Flight Review window that allows us to review the recently executed FLYTO Maneuver.　If the 3D Orbit window does not exist, SSVG opens it
	SHOW Orbit	When clicked, SSVG opens a Show Orbit window if not exists, that allows us to observe position and orbit of the Probe.　If the 3D Orbit window does not exist, SSVG opens it
EDIT Buttons	EDIT Next	When clicked, SSVG opens a Maneuver Editor window and start editing of the Next Line of the Maneuver Table
	EDIT *	When clicked, SSVG opens a Maneuver Editor Window and start editing of 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 (*)
	INS *	When clicked, SSVG 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 (*)
	DEL *	When clicked, SSVG 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 (*)
EXECUTE Buttons	EXECUTE	When clicked, SSVG executes the Maneuver on the Next Line of the Maneuver Table
	EXECUTE *	When clicked, SSVG executes Maneuvers on the Maneuver Table in succession, from the Next Line through the selected line
	CLEAR	When clicked, SSVG clears the execution state of the Flight Plan. The first line of the Maneuver Table becomes the Next Line

(*) If there is a Checkpoint above the line (edited, inserted, or deleted line), the execution state will not be lost, but SSVG restores the execution state from the Checkpoint instead.

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 the 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 Current Status:
(Phrases in brackets show supplementary word(s) and/or explanations)

- Executed Last Maneuver (sequential number of the line that contains recently executed Maneuver, and type of the Maneuver)
- Current time (of SSVG; ISOT and JD)
- (The Probe's) Distance from the Sun
- (The Probe's) Velocity rel.(ative) to the 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,
  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
- 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 on top of this window and its vicinity:
- 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

Messages

SSVG displays messages about its behavior.

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 the 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 a Show Orbit Window.
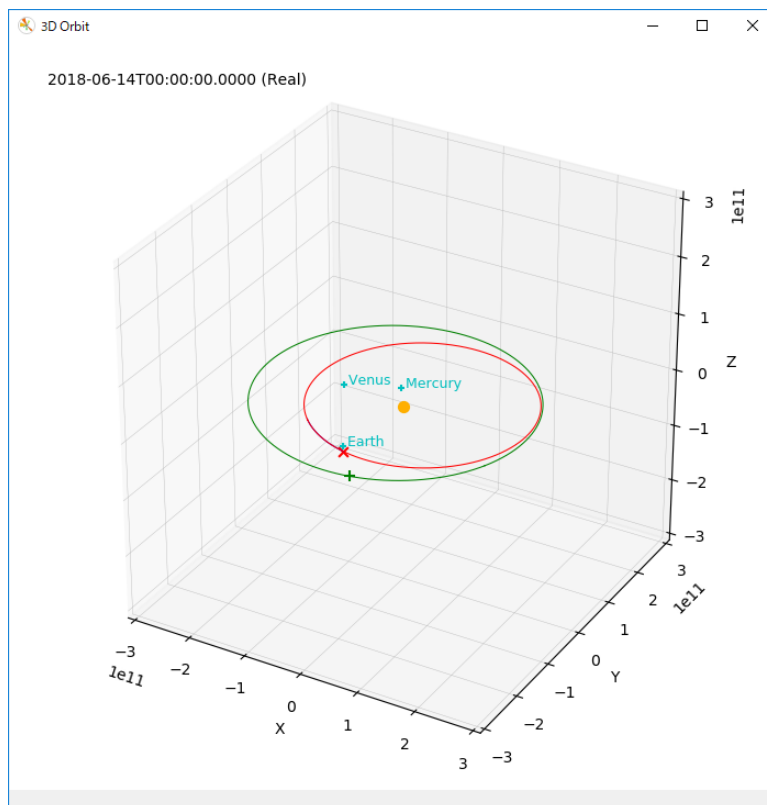

Figure 18   3D Orbit window

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

Table 8   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 appear next to the mark
A curved line in red	Two-body orbit (Kepler orbit) of the Probe: when using Start Optimize Assistant, the line 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 disk in orange	The 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 actual length of "1" of the scale, and the length is measured by meters. Each scale may have an indication of offset
Time information	On the upper left corner of the window, SSVG displays the time corresponds to the positions of objects, and its attribute (Real or Predicted)

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

Table 9   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
Resize	By dragging each side or corner of the 3D Orbit window, you can resize the window with the 3D chart
Place the Probe or the Target at the center of the chart	We cannot do those manipulations on this window. See Show Orbit Window, Flight Review Window, or Review Throughout Window subsections

Show Orbit Window

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

- Into the 3D Orbit window,
    - the Probe, its two-body orbit, and its actual 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 displayed information, is a specified time. It can be not only the current time, but also a time in the future or in the past, we call them as "Prediction Time". A Show Orbit window computes position of the Probe at Prediction Time from two-body motion of the Probe.

A Show Orbit window does not count all forces that affect the Probe but gravitational pull of the Sun, in computations of the positions and orbit of the Probe. Those forces, gravitational pulls of the planets and thrusts of the Electric Propulsion Engine and/or Solar Sail, will affect computation of the trajectory of the Probe in execution of a FLYTO Maneuver.

A Show Orbit window can display information only when the Prediction Time is within the time range of SSVG. Although you can set the Prediction Time outside of the range, the Show Orbit window does not display the Probe and the Target on the 3D Orbit window, and does not renew relative positions and velocities of the Target on itself. See Time subsection for time range of SSVG.

A 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.
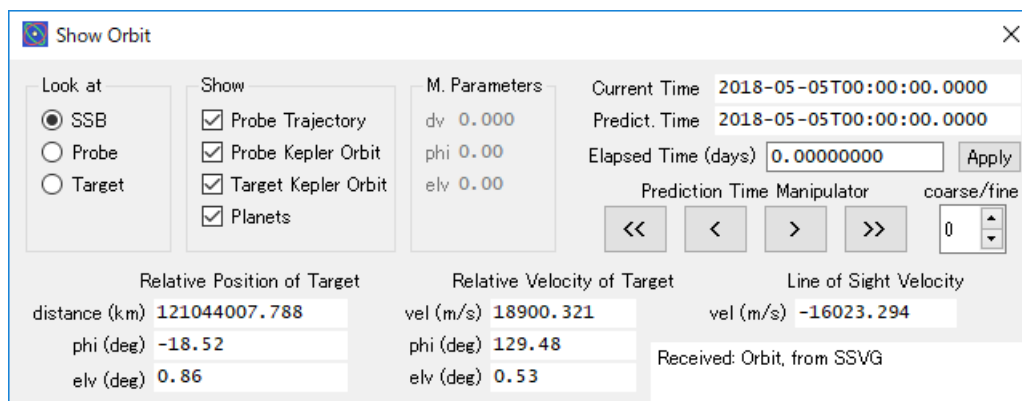
Figure 19　Show Orbit window

There are five item groups as follows on the upper part of the Show Orbit window:
- Look at: three radio buttons to select center 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

Group Names	Labels/Names	Explanations
Look at	SSB	When selected, SSB, the Solar System Barycenter, lies at the center of the 3D chart
	Probe	When selected, the Probe lies at the center of the 3D chart
	Target	When selected, the Target lies at the center of the 3D chart
Show	Probe Trajectory	When checked, the actual 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 Start Time	Current time of SSVG (except you are editing a START Maneuver)
		Start time, applied temporarily by the Maneuver Editor window (while you are editing a START Maneuver)
	Predict. Time	Prediction Time
	Elapsed Time (days) and [Apply] button	Elapsed time, from Current Time (or Start Time) to Prediction Time
		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 [<] button (*)
	[<] button	Backward: when clicked, Prediction Time goes back (*)
	[>] button	Forward: when clicked, Prediction Time goes forward (*)
	[>>] button	Fast forward: when clicked, Prediction Time goes forward by ten times of the [>] button (*)
	coarse/fine	A spinner that specifies the coarseness/fineness of the Prediction time manipulated by buttons
		When the value enlarged, manipulation becomes coarse. When the value minified, manipulation becomes fine.

(*) 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 11   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)

In addition, there is a text field around the bottom-right corner of the window.   SSVG displays messages about its behavior in it.

Flight Review Window

A Flight Review window allows us to review the result of execution of a FLYTO Maneuver, immediately after the execution. For each integration step of the Maneuver, it displays information as follows:
- Into the 3D Orbit window,
  - the Probe, its actual trajectory, and its two-body 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 is 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 is 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 of each integration step of the Maneuver at a time.   We call the integration step as the "current step".

A Flight Review window appears when the user clicked [REVIEW Recent] button of the SSVG window.
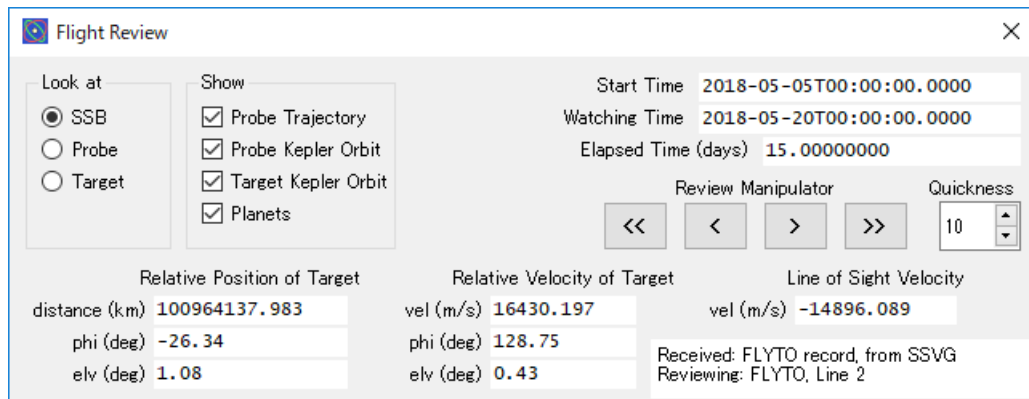
Figure 20　Flight Review window

There are four item groups as follows on the upper part of the Flight Review window:
- Look at: three radio buttons to select center 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 12　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 center of the 3D chart
	Probe	When selected, the Probe lies at the center of the 3D chart
	Target	When selected, the Target lies at the center of the 3D chart
Show	Probe Trajectory	When checked, the actual 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 Quickness
	[<] 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 Quickness
	Quickness	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 current step.　Data items and their meanings are the same to the Show Orbit window.　See Table 11　Lower part of the Show Orbit window.

In addition, there is a text field around the bottom-right corner of the window.　SSVG displays messages about its behavior in it.

Review Throughout Window

A 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)
  - actual trajectory of the Probe, and two-body 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 is 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 is 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 the execution of the current Maneuver.　For FLYTO Maneuvers, it displays information of each integration step of the Maneuver.

A Review Throughout window appears when the user clicked [REVIEW Through] button of the SSVG window.
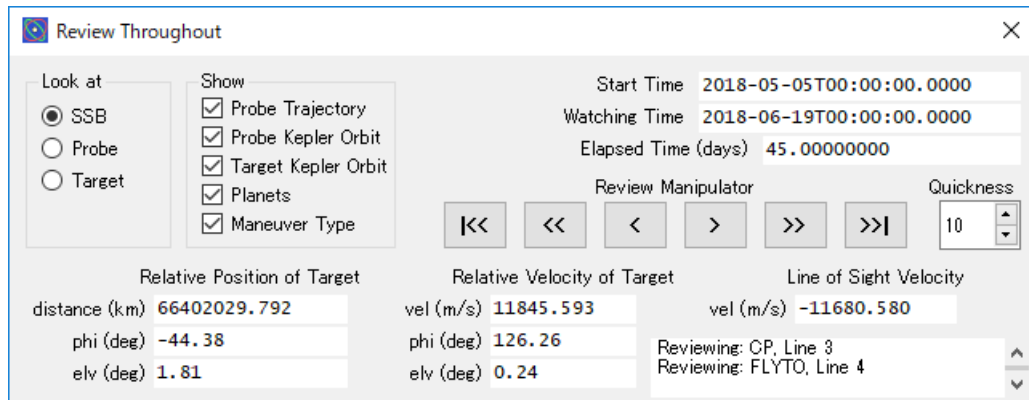
Figure 21　Review Throughout window

There are four item groups as follows on the upper part of the Review Throughout window:
- Look at: three radio buttons to select center 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

Group Names	Labels/Names	Explanations
Look at	SSB	When selected, SSB, the Solar System Barycenter, lies at the center of the 3D chart
	Probe	When selected, the Probe lies at the center of the 3D chart
	Target	When selected, the Target lies at the center of the 3D chart
Show	Probe Trajectory	When checked, the actual 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)
	Quickness	(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 current step). Data items and their meanings are the same to the Show Orbit window. See Table 11 Lower part of the Show Orbit window.

In addition, there is a text field around the bottom-right corner of the window. SSVG displays messages about its behavior in it.

Maneuver Editor Window

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

A 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 we edit a Maneuver that contained in the "Next Line".

Figure 22   Maneuver Editor window

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

Groups/ Table/Buttons	Relating Maneuver type(s)	Explanations
Maneuver Type (a drop-down list)	all types	This drop-down list displays the type of the editing Maneuver When we edit a blank line of the Maneuver Table (except the first line), we have to click this list and select one of the Maneuver Types We cannot change the Type of existing Maneuver
Start Time (text fields and the [Edit Time] button)	START	Text fields show current Start Time of the Probe in two formats: ISO format (ISOT) and Julian Date (JD) We can modify the Start Time by clicking [Edit Time] button (*1), and the edited time will be applied temporarily to the Show Orbit window and 3D chart
or End Time (text fields and the [Edit Time] button)	FLYTO	Text fields show current End Time and Duration (*2) of the editing FLYTO Maneuver. End Time appears in two formats: ISO format (ISOT) and Julian Date (JD) We can modify the End Time or Duration by clicking [Edit Time] button (*1), and the edited time will be applied temporarily to the Show Orbit window and 3D chart 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 date/time of the editing Maneuver. Left column contains names and short explanations of parameters. Right column contains values of parameters. See the next table (Table 14) We can modify each value of parameters by double-clicking of appropriate cell
[SHOW Orbit] button	all types	When clicked, SSVG applies editing parameters temporarily to the Show Orbit window and 3D chart
[FTA] button	START CP	When clicked, SSVG invokes FTA function (*3) to assist user to configure the editing Maneuver. See FTA Setting Window subsection
[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 subsections
Messages (a text field)	all types	The text field shows messages from SSVG about its behavior
[Finish and Exec] button	all types	When clicked, SSVG stores the editing Maneuver into the Maneuver Table, closes the window, and executes the edited Maneuver
[Finish] button	all types	When clicked, SSVG stores the editing Maneuver into the Maneuver Table, and closes the window
[Cancel] button	all types	When clicked, SSVG cancels the editing

(*1) When you clicked [Edit Time] button, a small dialog appears and you can edit one of the text fields of ISOT, JD, or Duration (when you are editing a FLYTO Maneuver on the Next Line).   Edited time will be applied to other field(s).

(*2) "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.   If the Duration is edited, the End Time is computed from current time of SSVG and the Duration.

(*3) At this point, 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 15 Parameter items on the Maneuver Editor window

Parameter item	Relating Maneuver type	Limit of Places (*1)	Explanation
dv	START CP	3	Magnitude of the delta-V, in meters per second
dvpd	EP_ON	3	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	2	Angle "phi" to indicate direction of the delta-V, in degrees See Orbit Local Coordinate System
elv	START CP EP_ON SS_ON	2	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	1	Area of the Solar Sail, in square meters
theta	SS_ON	2	Angle "theta" to indicate orientation of the Solar Sail, in degrees See Solar Sail Coordinate System
tvmode	EP_ON SS_ON	N/A	Thrust Vector Mode, "L" or "E" See Thrust Vector Mode
inter	FLYTO	5	Interval of numerical integration, in days (*2) SSVG computes positions and velocities of the Probe at this interval This value should be greater than or equal to 0.00001

(*1) This column shows limit of number of places of decimals for the value of each parameter. If you define more places, the value will be rounded to shown number of places of decimals.

(*2) Be careful to assign small value for "inter". If you assign small value (e.g. 0.001 days) of "inter" for a FLYTO Maneuver with long duration (e.g. 100 days), the execution of this Maneuver takes long computation time of your PC.

New Flight Plan Window

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

A New Flight Plan window appears when we execute "New" of "File" from the menu bar of the SSVG window.

Figure 23　New Flight Plan window

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

Table 16　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 (the moon of Earth), and Pluto
	Small Body (a radio button with a subgroup)		When selected, we choose a celestial small body as the Target.　We need an SPK file for the body, and we should specify properties of the small body in the "Properties" sub-group
	Properties	SPK file (a text field and [Find] button)	Click [Find] button and open the SPK file (*1) of the celestial small body
		SPKID (a drop-down list)	Check the SPKID, or click and select one of the SPKIDs (*2)
		Name (an input field)	Enter the name 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) In advance, get an SPK file of the celestial small body (see Get SPK File of Celestial Small Body), and store it into "SSVG_data" folder within the folder SSVG was installed.

(*2) Usually an SPK file contains data for only one celestial small body, and you only need to check the SPKID shown on the drop-down list.　However, you can get an SPK file that contains data for more than one celestial small body, and you should select an appropriate SPKID.

FTA Setting Window

On an 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.

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

Figure 24   FTA Setting window

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

Table 17　Groups/Items of FTA Setting window

Groups	Items		Explanations
Time to Arrival	Use 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 Now (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 `1.0`
Precise Targeting	Center of Target (a radio button)		When selected, center of the Target is the targeting point
	B-plane Coordinates (a radio button)		When selected, the user specifies the targeting point with B-plane Coordinates.　See <u>B-plane Coordinate System</u>
	(subgroup)	offset distance (km) (an input field)	Enter offset distance of the targeting point, in kilometers
		beta (deg) (an input field)	Enter angle beta of the targeting point, in degrees
	Orbit Local Coordinates (a radio button)		When selected, the user specifies the targeting point with Orbit Local Coordinates from the center of the Target.　See <u>Orbit Local Coordinate System</u>
	(subgroup)	offset distance (km) (an input field)	Enter distance of the targeting point from center of the Target, in kilometers
		phi (deg) (an input field)	Enter angle phi of the targeting point, in degrees
		elv (deg) (an input field)	Enter angle elv of the targeting point, in degrees
(None)	[OK] button		When clicked, SSVG executes FTA function, shows you the results, and requests confirmation.　If the results are confirmed, SSVG applies them 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

A 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 the two-body orbit of the Probe.

Note that the words "current *something*" in this subsection means "*something* currently being tried in this window", except otherwise mentioned.

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

Figure 25　Start Optimize Assistant window

At the top of the window, there is one group of items for options as follows:

Table 18　Options of the Start Optimize Assistant window

Groups	Items	Explanations
Show Orbit	Space Base (a check box)	When checked, SSVG shows the trajectory of the Space Base on the 3D Orbit window (a curved line in red)
	Target (a check box)	When checked, SSVG shows the two-body orbit (Kepler orbit) of the Target on the 3D Orbit window (a curved line in green)
	Current (a check box)	When checked, SSVG shows current two-body orbit (Kepler orbit) of the Probe on the 3D Orbit window (a curved line in cyan)

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

Table 19   Adjust Start Time and Flight Time

Groups	Items		Explanations
Adjust Start Time	Start Time (a text field)		SSVG shows current Start Time
	(a slider)		Moving the handle changes current Start Time
	Shift Range	[<<<] button	When clicked, the range of the slider shifts backward in time by one-half of the range
		[>>>] button	When clicked, the range of the slider shifts forward in time by one-half of the range
	Tweak Handle	[<] button	When clicked, the handle of the slider moves left by one pixel
		[>] button	When clicked, the handle of the slider moves right by one pixel
	Slider 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
Adjust Flight Time	Flight Time (days) (a text field)		SSVG shows current Flight Time in days
	Arrival Time (a text field)		SSVG shows current Arrival Time
	(a slider)		Moving the handle changes current Flight Time and current Arrival Time
	Shift Range	[<<<] button	When clicked, the range of the slider shifts to shorter flight time (or backward in time) by one-half of the range
		[>>>] button	When clicked, the range of the slider shifts to longer flight time (or forward in time) by one-half of the range
	Tweak Handle	[<] button	When clicked, the handle of the slider moves left by one pixel
		[>] button	When clicked, the handle of the slider moves right by one pixel
	Slider Defines	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	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

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

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 magnitude of start velocity 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 magnitude of relative velocity of the Target up to this point
Total DV (IDV + TRV)	Current	SSVG shows total DV, the sum of magnitude of start velocity and magnitude of relative velocity of Target.
	Min.	SSVG shows minimum value of total DV up to this point
(None)	[Clear Minimums] button	When clicked, SSVG clears all minimums
	(a text field)	SSVG shows messages about its behavior
	[Redisplay 3D Orbit] button	When clicked, SSVG shows the 3D Orbit window if not exist
	[Finish] button	When clicked, SSVG closes the window and applies current Start Time and current start velocity to the Maneuver Editor window
	[Cancel] button	When clicked, SSVG closes the window

CP Optimize Assistant Window

A 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 the 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 subsection means "*something* currently being tried in this window", except otherwise mentioned.

A CP Optimize Assistant window allows us to try various Maneuver Times. However, there are some important notices as follows:

- Even if you selected a new Maneuver Time, SSVG does not apply the time to any Maneuvers, including the editing CP Maneuver. You should modify preceding FLYTO Maneuver or START Maneuver to use the results.

- SSVG assumes two-body motion of the Probe for modifying Maneuver Time. It means that in several circumstances (e.g. the Electric Propulsion Engine is ON) the CP Optimize Assistant does not yield appropriate Maneuver Time and/or delta-V.

A CP Optimize Assistant window appears when the user clicked the [OPTIMIZE] button of the Maneuver Editor window that was editing a CP Maneuver.
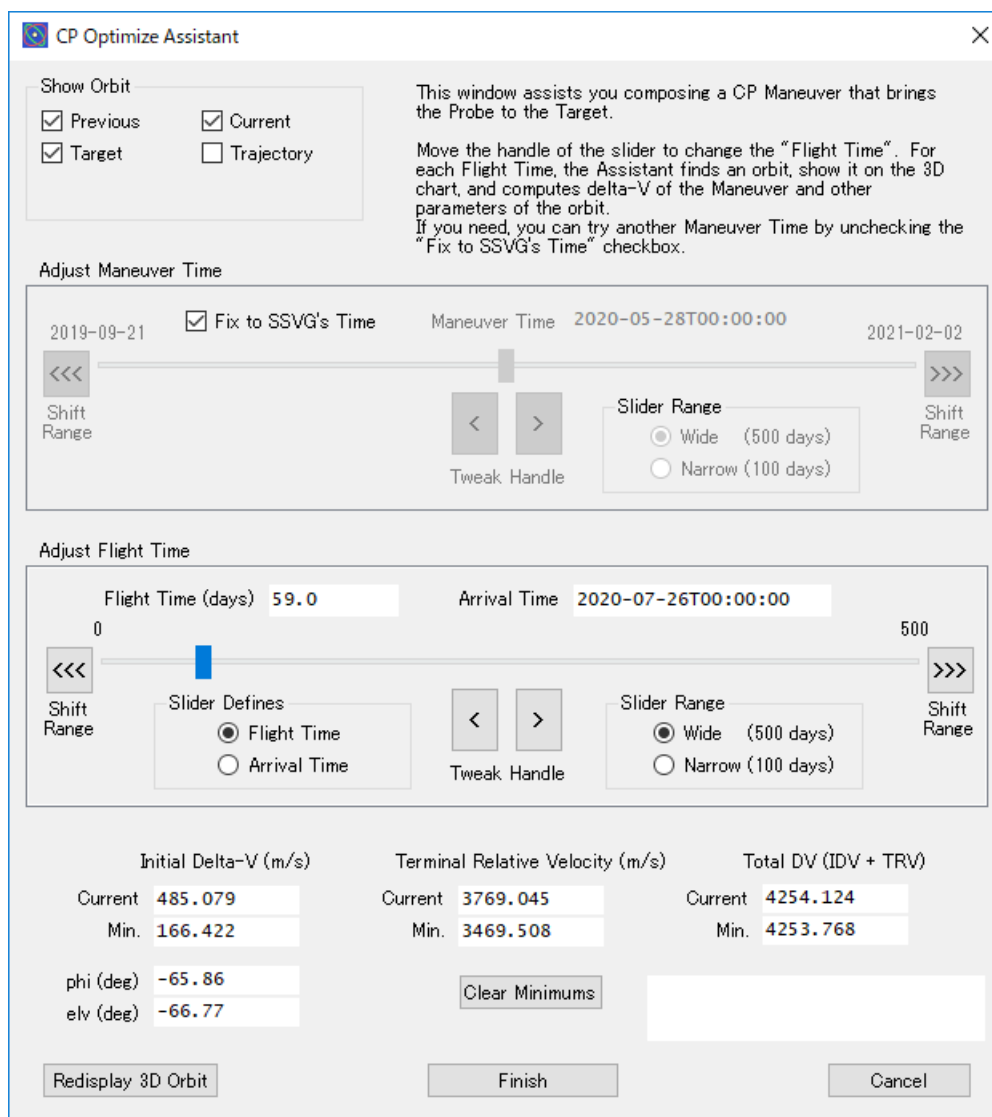
Figure 26　CP Optimize Assistant window

At the top of the window, there is one group of items for options as follows:

Table 21　Options of the CP Optimize Assistant window

Groups	Items	Explanations
Show Orbit	Previous (a check box)	When checked, previous (before the orbit transition) 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 actual 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 adjust Maneuver Time and Flight Time as follows:

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<p style="text-align:center">Table 22   Adjust Maneuver Time and Flight Time</p>

Groups	Items		Explanations
Adjust 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
	Maneuver Time (a text field)		SSVG shows current Maneuver Time
	(a slider)		Moving the handle changes current Maneuver Time
	Shift Range	[<<<] button	When clicked, the range of the slider shifts backward in time by one-half of the range
		[>>>] button	When clicked, the range of the slider shifts forward in time by one-half of the range
	Tweak Handle	[<] button	When clicked, the handle of the slider moves left by one pixel
		[>] button	When clicked, the handle of the slider moves right by one pixel
	Slider 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
Adjust Flight Time	Flight Time (days) (a text field)		SSVG shows current Flight Time in days
	Arrival Time (a text field)		SSVG shows current Arrival Time
	(a slider)		Moving the handle changes current Flight Time and current Arrival Time
	Shift Range	[<<<] button	When clicked, the range of the slider shifts to shorter flight time (or backward in time) by one-half of the range
		[>>>] button	When clicked, the range of the slider shifts to longer flight time (or forward in time) by one-half of the range
	Tweak Handle	[<] button	When clicked, the handle of the slider moves left by one pixel
		[>] button	When clicked, the handle of the slider moves right by one pixel
	Slider Defines	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	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

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

Table 23   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 magnitude of delta-V up to this point
	phi	SSVG shows angle phi of current delta-V of the orbit transition, in degrees. See <u>Orbit Local Coordinate System</u>
	elv	SSVG shows angle elv of current delta-V of the orbit transition, in degrees. See <u>Orbit Local Coordinate System</u>
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 magnitude of relative velocity of the Target up to this point
Total DV (IDV + TRV)	Current	SSVG shows total DV, the sum of magnitude of delta-V and magnitude of relative velocity of the Target
	Min.	SSVG shows minimum value of total DV up to this point
(None)	[Clear Minimums] button	When clicked, SSVG clears all minimums
	(a text field)	SSVG shows messages about its behavior
	[Redisplay 3D Orbit] button	When clicked, SSVG shows the 3D Orbit window, if not exist
	[Finish] button	When clicked, SSVG closes the window and applies current delta-V to the Maneuver Editor window (*)
	[Cancel] button	When clicked, SSVG closes the window

(*) Even if you modified Maneuver Time, SSVG does not apply the time to any Maneuvers, including the editing Maneuver.   You should modify preceding Maneuver(s) and force SSVG to execute the editing Maneuver at the appropriate time.   SSVG copies adjusted Maneuver Time (ISOT format) into system clipboard to assist this modification.

Coordinate systems
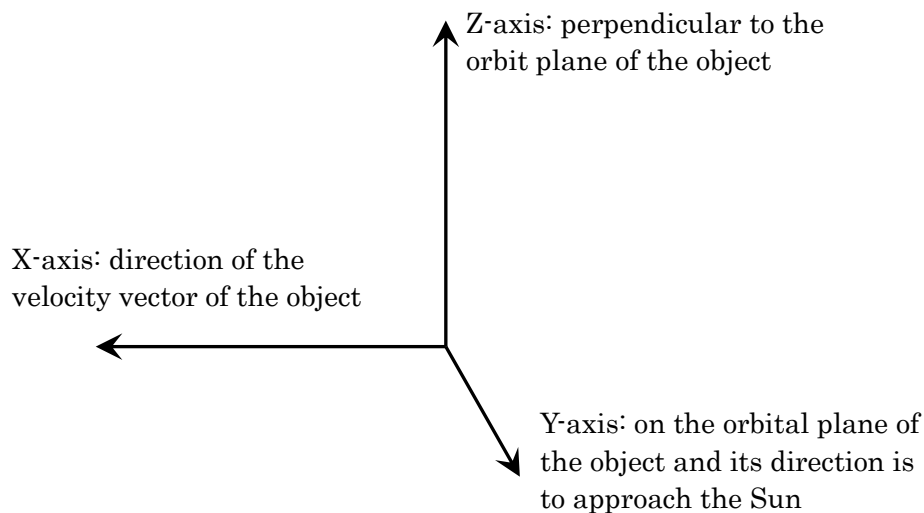
Ecliptic Coordinate System

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 the 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 the Sun. Objects include Probes, Space Bases, and Targets. The orbit local coordinate system is a Cartesian system fixed to an object.
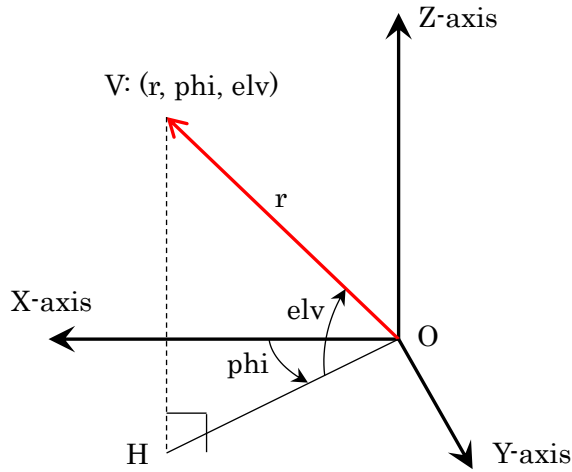
The origin of the axes (X, Y, and Z) is at the center of the object. The orbital plane of the object defines the X-Y plane, the velocity vector of the object relative to the Sun defines X-axis, Y-axis is on the orbital plane and its direction is to approach the Sun, and Z-axis is perpendicular to the 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.

Z-axis: perpendicular to the orbit plane of the object

X-axis: direction of the velocity vector of the object

Y-axis: on the orbital plane of the object and its direction is to approach the Sun

Figure 27 Orbit Local Coordinate System

Next figure shows polar coordinates (r, phi, elv) of vector V on the orbit local coordinate system. Drop a perpendicular line from the point of V to the X-Y plane, and name the foot point as "H". "phi" is the angle from the X-axis to the line segment OH. "elv" is the angle from the line segment OH to V. "r" is the magnitude (length) of V.

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 the 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 the 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.
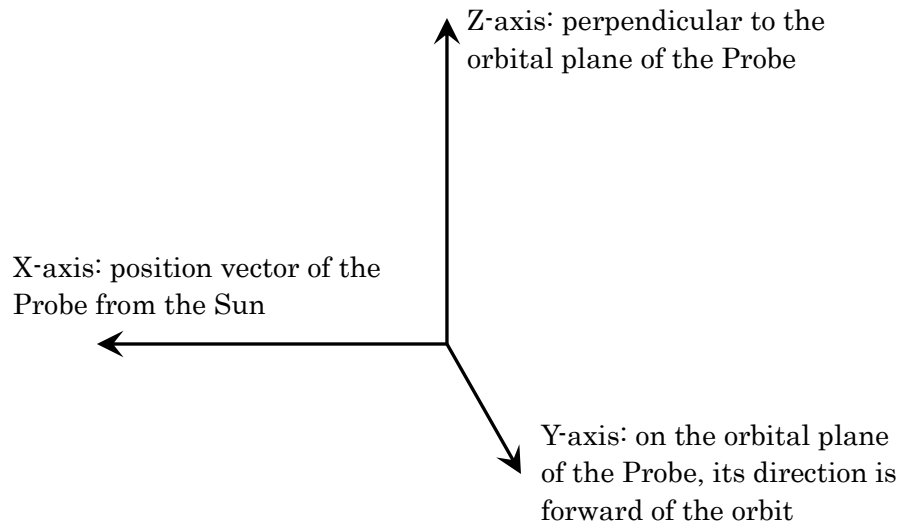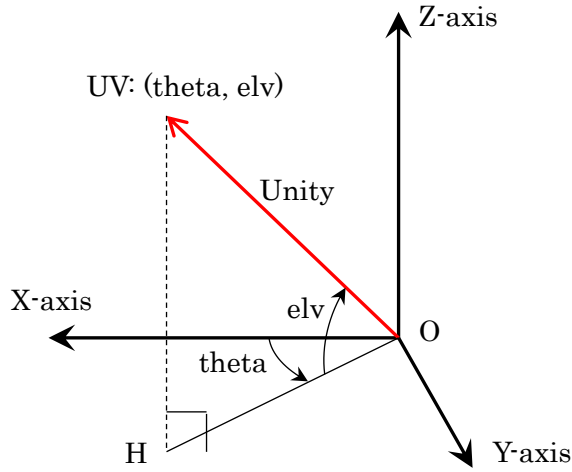

Figure 29   Solar Sail Coordinate System

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 the Sun.

The Next figure shows polar coordinates of the unit vector UV on the solar sail coordinate system.   Drop a perpendicular line from the point of UV to the X-Y plane, and name the foot point as "H".   "theta" is the angle from the X-axis to the line segment OH.   "elv" is the angle

from the line segment OH to UV.

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 the 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 the Sun, and define:
- Relative Motion of Probe: two-body motion of the Probe relative to the Target
- B-point: the nearest point of Relative Motion of Probe from the Target
- Relative Velocity: a velocity vector of Relative Motion of Probe 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 the 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.
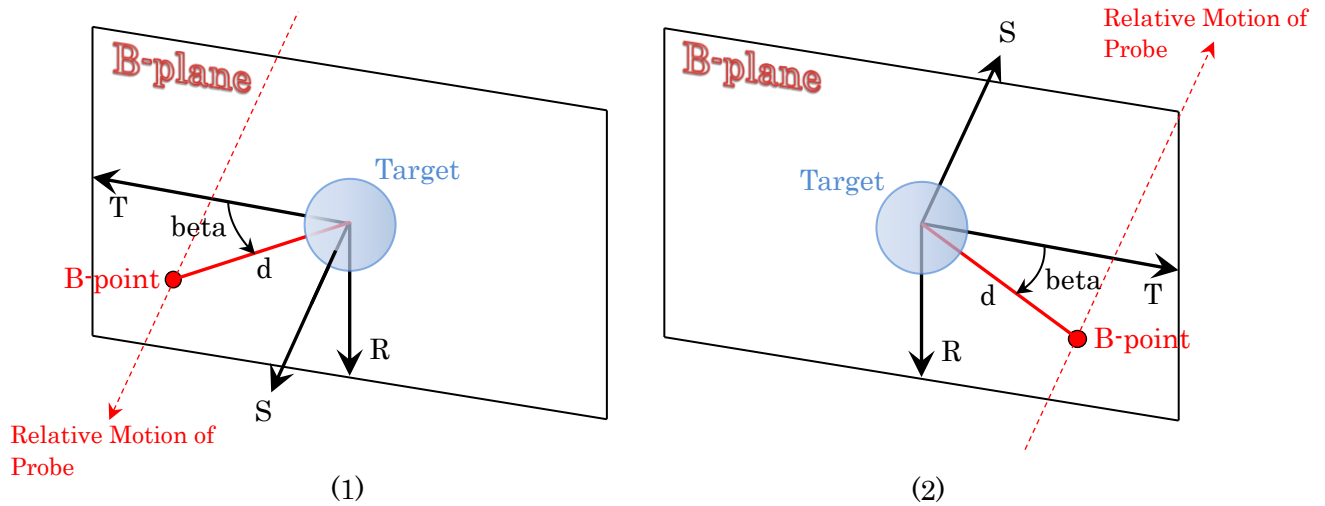
Figure 31　B-plane Coordinate System

Two subfigures of Figure 31 show different cases of fly-bys respectively.　The subfigure 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 subfigure 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 subfigure, we are looking at the Target from behind of its orbiting motion; the Sun is far left of the Target.

Miscellaneous Information

Folders for Users

The folder in which SSVG is installed contains three subfolders (subdirectories) the user can use. They are "SSVG_data", "SSVG_i18n", "SSVG_log", and "SSVG_plan".　The author assumed usages of these folders as follows:

- SSVG_data: to store SPK files
  At the immediately after installation, the folder contains an SPK file named "2000002_Pallas_21.bsp".　A sample Flight Plan named "sample_Pallas" uses the file. During installation of SSVG, the user download and store an SPK file named "de430.bsp" into this folder.　See Install and Uninstall SSVG section.
  The author assumed the user stores here downloaded SPK files of celestial small bodies.

- SSVG_i18n: to store files for internationalization of SSVG user interface
  User interface of SSVG uses English or Japanese, but you can extend it to other languages without modification of Python scrips.　See Extending to Other Languages subsection.

- SSVG_log: SSVG stores its log files

- SSVG_plan: to store Flight Plan files
  At the immediately after installation, the folder contains several sample Flight Plans. The author assumed the user stores here new Flight Plans.

The folder in which SSVG is installed contains many other folders and files. Except previous four folders, the user should not delete, move, and/or modify them.

The user may put here new folders and store files within them; the author recommends that the name of new folders start with "SSVG_" to be easily distinguishable from other folders.

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 a 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 Flight Plan that uses a celestial small body as Target can fly its Probe within the time range of SPK file of the Target.

Numerical Integration of the Probe Trajectory

When executing a FLYTO maneuver, SSVG computes actual trajectory (positions and velocities) of a Probe by numerical integration of forces, which affect motion of the Probe.　SSVG considers following forces, and neglects others:
- Gravitational attraction of the Sun
- Gravitational attractions of the eight planets and the moon of Earth
- Propulsive forces of the Electric Propulsion Engine and the Solar Sail

Note that SSVG does not use gravitational pull of celestial small bodies (except the moon of Earth) including relatively heavy dwarf planets (e.g. Ceres, Pluto) for computation of actual trajectory of a Probe.　It means that if a Probe comes close to a small body, the body does not affect any gravitational pull to the Probe, and the Probe cannot enter an orbit that go around the body.

Two-body Motion of the Probe

SSVG computes actual trajectory of a Probe by numerical integration as mentioned above. However, all other computations about orbits, positions, and velocities of the Probe are performed based on two-body motion about the 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 the 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 focuses of attention of actual space flights. We have an equation that governs relation between magnitude of 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 ：Magnitude of delta-V of orbit transition

I_{sp} ：Specific impulse of the propulsion system

g ：Standard gravitational acceleration of the Earth

$exp(\ )$ ：Exponential function

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

Next two tables show samples of computational 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 24　Results of Rocket Equation (Liquid Propellant Engine, I_{sp} = 300)

ΔV (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 25　Results of Rocket Equation (Ion Engine, I_{sp} = 3000)

ΔV (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

HORIZONS system of NASA/JPL generates SPK files for celestial small bodies (asteroids, comets, and dwarf planets) on demands of users. HORIZONS system can generate SPK files in one of the two formats, ASCII or Binary, but SSVG can read SPK files in Binary format only.

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

In this subsection, we show you a procedure to make a request to HORIZONS system for generating SPK files. Previous web page does not provide this procedure, but I believe this is one of the easiest ways for our purpose.

Before making a request, you need:
- to find name, number, designation, or SPKID of the body, and,
- to decide a time range in which you wish to fly the Probe. (*)

(*) At this time (February of 2019), HORIZONS system can generate SPK files within following time range.
- From: 1000-Jan-01 (January 1, 1000)
- To: 2101-Jan-01 (January 1, 2101)

You can check the time range by accessing HORIZONS system with TELNET interface. See previously mentioned HORIZONS web page.

Then, open the "Asteroid & Comet SPK File Generation Request" page of HORIZONS system by clicking the following link.
<https://ssd.jpl.nasa.gov/x/spk.html>

Your web browser shows following page (the figure shows top half of the page).

Figure 32 "Asteroid & Comet SPK File Generation Request" page

We use the top half of this page.　There are one table with input fields and radio buttons, and three push buttons.　Following table shows operations about those items.

Table 26　Operations of SPK File Generation Request

	Items	Operations and Explanations
Table	Object (an input field)	Enter name, number, designation, or SPKID of the celestial small body
	SPK start date (TDB) (an input field)	Enter start date with a format of "YYYY-Mon-DY".　For example, 2000-Jan-01 for January 1, 2000 (*)
	SPK stop date (TDB) (an input field)	Enter stop date with a format of "YYYY-Mon-DY".　For example, 2100-Dec-31 for December 31, 2100 (*)
	E-mail contact address (an input field)	Enter your E-mail address
	SPK file format (two radio buttons)	Select "Binary" radio button
Buttons	[Look up]	When clicked, HORIZONS system shows candidate(s) of the celestial small body
	[Make SPK]	When clicked, HORIZONS system makes an SPK file and your browser downloads it
	[Clear Form]	When clicked, information entered in the table is cleared

(*) At this time (February of 2019), HORIZONS system can generate SPK files within following time range.
- From: 1000-Jan-01 (January 1, 1000)
- To: 2101-Jan-01 (January 1, 2101)

You can check the time range by accessing HORIZONS system with TELNET interface.　See previously mentioned HORIZONS web page.

As a sample, let us try to get an SPK file of comet Halley.　Enter "Halley" into "Object" field, and click [Look up] button.　The web page shows you following two groups of text lines.


```
Object Name       = 2688 Halley
Primary SPKID     = 2002688
Primary designation= 1982 HG1
Aliases           = 1978 UO, 1978 TE9, 1978 SH6, 1955 QN1, J82H01G

Object Name       = Halley
Primary SPKID     = 1000036
Primary designation= 1P
Aliases           = 1982 U1, 1909 R1, 1835 P1, 1758 Y1, 1682 Q1, 1607 S1, 1531 P1, 1456 K1, 1378 S1,
1301 R1, 1222 R1, 1145 G1, 1066 G1, 989, 989 N1, 912, 912 J1, 837, 837 F1, 760, 760 K1, 684, 684 R1,
66, 607, 607 H1, 530, 530 Q1, 451, 451 L1, 374, 374 E1, 295, 295 J1, 218, 218 H1, 1986 III, 1982i,
1910 II, 1909c, 1835 III, 1759 I, 1682, 1607, 1531, 1456, 141, 141 F1, 1378, 1301, 1222, 1145, 1066,
66 B1, -11 Q1, -86 Q1, -163 U1, -86, -239 K1, -239, -163, -11, 4000001
```

Figure 33　The Result of "Look up" of "Halley"

From this result, you can see:
- There are two objects named "Halley"
- The first one (2688 Halley) is an asteroid (search it on JPL Small-Body Database Browser <https://ssd.jpl.nasa.gov/sbdb.cgi>)
- The second is the object we wish to get SPK file.

Copy Primary SPKID of the second object (1000036) into the clipboard, and return to the previous page.

Paste the SPKID into "Object" field, and click [Look up] button.　You will see information for only one object, and that is for comet Halley.　Return to the previous page.

Fill remaining fields, select "Binary" radio button, and click [Make SPK] button.　HORIZONS system makes the SPK file, and your browser starts downloading of the file.　File name is 1000036.bsp by default (it is [SPKID].bsp).

Copy the downloaded file into "SSVG_data" folder within the folder where SSVG is installed. At this point, you may change the name of the SPK file. However, you should leave the extension of the file name unchanged (that is "bsp").

That is all. Now you can select comet Halley as a Target of SSVG! The comet is supposed to come to central region of the solar system in 2061.

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 "SSVG_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 require long operating 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 the Electric Propulsion Engine, or solar sail coordinate system for the Solar Sail, during one 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 one operation (*) of each propulsion system. At the time an operation is initiated by an EP_ON Maneuver or by an SS_ON Maneuver, SSVG computes thrust vector direction in the ecliptic coordinate system. SSVG uses this direction during the 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.

(*) "One operation" of a thruster starts when SSVG executes an activating Maneuver (EP_ON or SS_ON) of the thruster, ends when SSVG executes a deactivating Maneuver (EP_OFF or SS_OFF) or another activating Maneuver of the thruster. Executions of other Maneuvers do not affect the Thrust Vector Mode. Operations of the Electric Propulsion Engine and the Solar Sail can be executed independently.

Extending to Other Languages

SSVG was internationalized. You can extend the user interface of SSVG to other languages without modification of Python scripts. The subsection describes the how of the extending.

Note that most data files for internationalization of SSVG are stored in the "`SSVG_i18n`" folder. Except otherwise mentioned, all files should be stored in this folder.

Tools

You need Qt environment with "Qt Linguist" and its release tool "lrelease". In my environment (Windows 10 and Anaconda 3.5), those tools are "`linguist.exe`" and "`lrelease.exe`" in "`[Python root]¥Library¥bin`".

Procedures (part one)

If your language uses European font only, try following procedures. In this description, the language is Spanish (the language code is "es").

(1) Create SSVG translation file (source) for Spanish

- Copy the SSVG translation file for Japanese (`ssvg_ja.ts`) and create an SSVG translation file for Spanish (`ssvg_es.ts`).

- Run "Qt Linguist" and open `ssvg_es.ts`. Translate source text in English into Spanish and replace Japanese texts with it for all contexts except "Language" context.

- The "Language" context contains only one source text "en". Translate this text to the same text "en". Do not translate to the text "es".

- Run "lrelease" to create compressed SSVG translation file. In Windows environment, try following command on "command prompt" window.
  ```
  > lrelease -compress ssvg_es.ts
  ```
  A file named "ssvg_es.qm" will be created.   This is the compressed SSVG translation file for Spanish.

(2) Copy two Qt translation files
   You need two files, `qt_es.qm` and `qtbase_es.qm`.   In my environment, those files are in `[Python root]¥Library¥translations`
   Copy them from your Qt environment into the `SSVG_i18n` folder.

If your language requires only European font, that is all.   Run SSVG and check it.   If 3D orbit window shows invalid characters, it means you need to install font file.   Follow procedures (part one) and additional procedures (part two) described in the next subsection.

Procedures (part two)
In this description, the language is Korean (the language code is "ko").

(3) Get font file for your language
   I recommend getting True Type font file.   You need font file (e.g. `hangul.ttf`) and font name (e.g. `HangulFont`).

(4) Store the font file into appropriate folder

- If you are using Windows executable of SSVG, store the font file into the folder
  ```
  mpl-data¥fonts¥ttf
  ```
  within the folder of SSVG.

- If you are using Python script of SSVG, store the font file into font folder of the matplotlib module.   The folder may be

```
[Python root]¥Lib¥site-packages¥matplotlib¥mpl-data¥fonts¥ttf
```
In this case, you need to erase font cache file of matplotlib module.   In my environment, the file is
```
[user folder]¥.matplotlib¥fontList.json
```

⑸ Modify SSVG translation file
Run "Qt Linguist" and open `ssvg_ko.ts` (you created and edited it in "part one" already). Translate "en" in "Language" context to language code of your language (e.g. "ko").   Then run "`lrelease`" again and create `ssvg_ko.qm` (this is compressed SSVG translation file for Korean).

⑹ Resister the font name
Open a file named 3DOrbitFont.json within `SSVG_i18n` folder with your text editor.   Add a line that combines language code and font name as follows.
before editing:
```
{
    "en": "sans-serif"
    "jp": "IPAexGothic"
}
```
after editing:
```
{
    "en": "sans-serif"
    "ko": "HangulFont"
    "jp": "IPAexGothic"
}
```

That is all.   Run SSVG and check it.

Samples of Flight Plans

SSVG has several samples of Flight Plans.   They are stored in the "SSVG_plan" folder within the installed folder of SSVG, and they can be opened easily by File-Open command of SSVG. The samples are as follows:

sample_Mars

This is a Flight Plan for a Mars exploration mission.

The Probe starts its space flight from Earth L2 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.

sample_Mars_SS

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

The Probe starts its space flight from Earth L2 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.

sample_Mercury

This is a Flight Plan for Mercury exploration mission.

The Probe starts its space flight from Earth L2 Space Base, and it enters Mercury orbit.   To minimize total delta-V from Chemical Propulsion Engine, the Probe 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.

sample_Pallas

This is a Flight Plan for an exploration mission of asteroid Pallas.   Because orbital inclination of Pallas is large (34.8 degrees), direct flight from earth requires very large total delta-V.   The Probe uses gravity assist from Jupiter to reduce total delta-V of the space flight.

The Probe leaves Earth L2 Space Base on February 23 of 2030, makes Jupiter swing-by on May 4 of 2034, and finally comes to Pallas on November 4 of 2037.

sample_Venus

This is a Flight Plan that replicates the flight of "AKATSUKI", a space probe of JAXA, Japan Aerospace Exploration Agency.

The Probe started its space flight from Earth L2 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.

sample_Voyager2

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 Earth L2 Space Base at August 20, 1977.   It flew by Jupiter, Saturn, Uranus, and Neptune sequentially, and performed invaluable 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

1. 室津義定, 宇宙航行力学, 宇宙工学の基礎 I, 共立出版株式会社, Japan, 1998

2. Kluever, Craig A., Space Flight Dynamics, John Wiley & Sons Ltd, UK, 2018

3. https://ssd.jpl.nasa.gov/?horizons   Accessed June 15, 2018

4. https://voyager.jpl.nasa.gov/   Accessed June 15, 2018

5. http://www.ieice-hbkb.org/files/11/11gun_02hen_04.pdf   Accessed June 15, 2018

6. http://www.ecei.tohoku.ac.jp/inuta/souzoukougaku/takasho/takasho01.htm   Accessed June 15, 2018

7. http://astro-dic.jp/   Accessed June 18, 2018

8. http://ccar.colorado.edu/imd/2015/documents/BPlaneHandout.pdf   Accessed June 20, 2018

9. https://en.wikipedia.org/wiki/Solar_sail   Accessed June 22, 2018

10. http://global.jaxa.jp/projects/sat/ikaros/   Accessed November 12, 2018

11. https://ssd.jpl.nasa.gov/sbdb.cgi   Accessed November 15, 2018

12. http://www.jaxa.jp/   Accessed February 10, 2019

13. https://www.nasa.gov/   Accessed February 10, 2019

14. https://www.esa.int/ESA   Accessed February 10, 2019

15. https://www.nao.ac.jp/   Accessed February 10, 2019

16. https://doc.qt.io/qt-5/reference-overview.html   Accessed February 10, 2019