SSVG Users Guide

Solar System Voyager

植月修志　(Shushi Uetsuki/whiskie14142)
Jan. 29, 2017
Version 0.5.0 Beta

What is SSVG?

SSVG (Solar System Voyager) is simulation software which enables users to fly their 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.

License of SSVG

SSVG is free software; you can redistribute it and/or modify it under the terms of the GNU General Public License as published by the Free Software Foundation; either version 3 of the License, or (at your option) any later version.

This program is distributed in the hope that it will be useful, but WITHOUT ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the GNU General Public License for more details.

You should have received a copy of the GNU General Public License along with this program; if not, see <http://www.gnu.org/licenses>

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

SSVG uses following programs and modules:

Numpy: http://www.numpy.org/
Copyright (c) 2005-2016, NumPy Developers.
All rights reserved.

Scipy: http://scipy.org/
Copyright (c) 2001, 2002 Enthought, Inc.
All rights reserved.
Copyright (c) 2003-2013 SciPy Developers.
All rights reserved.

matplotlib: http://matplotlib.org/
Copyright (c) 2012-2013 Matplotlib Development Team;
All Rights Reserved

PyQt4: https://www.riverbankcomputing.com/news/

jplephem: https://github.com/brandon-rhodes/python-jplephem/

julian: https://github.com/dannyzed/julian/
Copyright (c) 2016 Daniel Zawada

pytwobodyorbit: https://github.com/whiskie14142/pytwobodyorbit/
Copyright (c) 2016 Shushi Uetsuki (whiskie14142)

spktype01: https://github.com/whiskie14142/spktype01/

PyInstaller: http://www.pyinstaller.org/

License of this document

Get started

Install SSVG

Windows executable

Windows executable of SSVG can be retrieved from following address as a compressed file (zip file). Download it and open it with your convenient tool. Copy the SSVG folder (directory) on your PC.
<http://yahoo.jp/box/A0fffK>

PC environment

Windows executable of SSVG has been tested on Windows 8.1 (64bit) and Windows 10 (64bit).
Recommended display sizes are 1024 pixel x 1600 pixel or more.

Get SPK file

Program package does not contain an essential data file to compute position and velocity of the sun and planets. Get the data file (SPK file, named de430.bsp) from following address, and place it in the "data" directory under the "SSVG" directory.
<http://naif.jpl.nasa.gov/pub/naif/generic_kernels/spk/planets/de430.bsp>

Python source program

If you have Python 3.5 with Numpy/Scipy/matplotlib/PyQt4, you may run SSVG on your Python environment. You can retrieve Python source program of SSVG from GitHub.
<https://github.com/whiskie14142/SolarSystemVoyager/>

PC environment

Python 3.5
Recommended display sizes are 1024 pixel x 1600 pixel or more.

Packages used and their versions

Numpy 1.10.4, Scipy 0.17.0, matplotlib 1.5.1, pyqt 4.11.4, jplephem 2.6, julian, pytwobodyorbit 0.1.0, spktype01 0.1.0
For additional four packages (jplephem, julian, pytwobodyorbit, spktype01), you can install them by pip command.

Get SPK file

Program package does not contain an essential data file to compute position and velocity of the sun and planets. Get the data file (SPK file, named de430.bsp) from following address, and place it in the "data" directory under the source directory.
<http://naif.jpl.nasa.gov/pub/naif/generic_kernels/spk/planets/de430.bsp>

Run SSVG

Windows executable

Double click SSVG.exe which is contained in the SSVG directory.

Python source program

Run SSVG.py from Python. SSVG.py is contained in the source directory.

Run a sample of Flight Plan

Open a Flight Plan

When you run SSVG, two windows will appear: the SSVG window and the 3D Orbit window. Because you have no valid Flight Plan yet, these windows do not display any meaningful information.

On the menu bar of SSVG window, execute File → Open. There is a directory named "sampleplan" in the installed directory, and it contains several samples of Flight Plan. Select "mars01.json" among them and open it.

In this Flight Plan, a probe named "Marsexp" starts from the space base EarthL2, and flies to Mars. SSVG window displays the Flight Plan as a table. Each line of the table contains a maneuver command for the probe (so we call the table as "Maneuver Table"). When you execute each command from top to bottom of the Maneuver Table, the probe flies from the space base to Mars.

Execute Each Maneuver

The Maneuver Table contains three columns, and they are labeled "Type", "Parameters", and "Exec" respectively. There is one line which shows "Next" in Exec column; it is a flag indicating that next execution of maneuver uses type and parameters of this line. We call this line as "Next Line."

Click the [Exec Next] button of the SSVG window. The maneuver of the Next Line will be executed. SSVG opens a new window named "Show Orbit," and 3D Orbit window displays following information after the execution of the maneuver:

Position of the probe (red X mark)
Orbit of the probe (ellipse of red line)
Position of the target (green + mark)
Orbit of the target (ellipse of green line)
Position of the sun (small circle)
Positions and names of major celestial objects in the solar system (+ and name of cyan)

You can manipulate the figure displayed on the 3D Orbit window. Please consult 3D Orbit window and Show Orbit window.

By clicking the [Exec Next] button, every line of the Maneuver Table will be executed one by one, from top to bottom.

In SSVG, each maneuver has one type out of seven types. This sample uses following three of them:

START: Start the flight. The probe leaves the space base with specified velocity.
FLYTO: Fly until specified time.
CP: Chemical propulsion. Probe activates its rocket engine, and gets specified delta-V.

Explanations of all seven types are in Maneuver Editor window.

Review last flight

Immediately after the execution of a FLYTO maneuver, you can review the fight. Click [Review Recent FLYTO] button of the SSVG window. The Flight Review window will appear, and when you operate buttons of the Review Manipulator of the Flight Review window, you can see progress of that flight on the 3D Orbit window.

When you perform Flight Review immediately after the execution of the last maneuver (FLYTO on the line 9) of the sample Flight Plan (mars01) and close up to the target, you can see that the probe is orbiting around the target Mars.

Compose a Flight Plan

Let's compose a new Flight Plan. In this tutorial, the probe will fly from the Earth to Venus. The flight plan will make the probe arrive Venus in 2020.

Generate new Flight Plan

On the menu bar of the SSVG window, execute File → New. The New Flight Plan window will appear.

Specify name and mass of the probe in the "Probe Properties" aria. You can select a space base on the drop-down list. SSVG provides sixteen space bases to start your probe from; each base is placed on a Lagrangian point L1 or L2 of a planet. On this tutorial, select "EarthL2." This space base is placed on the Lagrangian point L2 of the Sol-Earth system. It means that the space base is about 1.5 million kilometers from the Earth, opposite to the sun.

Specify the target in the "Target" aria. Select the Planet/Moon radio button, and select Venus on the drop-down list. When you click [OK] button, a Flight Plan will be generated.

You have a new Flight Plan, so it is wise to save it. On the menu bar of the SSVG window, execute File → Save as... and save it with a convenient name.

START

Let's define the first maneuver which instructs the probe to leave the space base. At this point, the Maneuver Table has only one blank line, and it has the Next flag. Click [Edit Next] button to start editing of this maneuver. The Maneuver Editor window will appear.

Specify the Type of maneuver. On the drop-down list of the Maneuver Editor window, select "START" and click adjacent [Apply] button.

For the START maneuver, you need to specify the start time when the probe leaves the space base, and need to specify the velocity of the probe with which it leaves. It requires some "Cut and Try" to decide the start time; let's use Optimize Assistant of the SSVG. Click the [Optimize] button of the Maneuver Editor window. The Start Optimize Assistant window will appear.

On the Start Optimize Assistant window, you can select the start time and the length of the flight (flight duration) with sliders and buttons (<< and >>). Consult Start Optimize Assistant window for details of this operation. At first, set the length of the flight (Flight Duration) to 200.0 days with the slider of the Arrange Flight Duration group.

Let's select preferable start time. Move the slider and click buttons (<< and >>) of the Arrange Start Time group. Along with the change of the start time, following lines and marks on the 3D Orbit window will move and change.

Curved line of cyan: Orbit of the probe (correspond to the start time and the flight duration)
X mark of red: Position of the probe at the start time
+ mark of green: Position of the target Venus at the start time
X mark of blue: Position of the probe when it arrive the target
Curved line of red: Trajectory of the space base
Curved line of green: Orbit of the target Venus

On the lower portion of the Start Optimize Assistant window, following information will be displayed.

Initial Delta-V: The velocity of the probe to leave the space base
Terminal Relative Velocity: Relative velocity of the target when probe arrives
Total DV: Summation of Initial Delta-V and Terminal Relative Velocity

There are many aspects to select preferable orbit, but in this tutorial, let's select an orbit which has minimum Total DV and the probe arrives the target in 2020.

When you find a comfortable start time, let's click the [Finish and Apply] button on the Start Optimize Assistant window. Then the window will be closed, and parameters to start the probe will be applied to the Maneuver Editor.

That's all for this maneuver. When you click [Finish and Exec] button on the Maneuver Editor window, SSVG finishes the editing and executes that maneuver. On the 3D Orbit window, you can see that the probe is now on the orbit which reaches Venus after 200 days journey. Please try some operations about "Prediction Time Manipulator" on the Show Orbit window.

FLYTO (1)

Because Optimize Assistant only considers gravity attraction of the sun, the trajectory of the probe will gradually deviate from the predicted one with time, particularly when the probe flies near the Earth or other planets. Fly the probe long enough, and then correct the velocity of the probe. In this tutorial, let's fly the probe 150 (one hundred and fifty) days.

Confirm that the second line of the Maneuver Table is a blank line with the Next flag, and click [Edit Next] button. The Maneuver Editor window will appear.

Select "FLYTO" for maneuver type, and click the adjacent [Apply] button on the Maneuver Editor window. With clicking fast forward button [>>] several times on the Show Orbit window, set the DT value to 150.0 , then the Flight Duration on the Maneuver Editor window will be the same, and 3D Orbit window displays the probe, the target, and planets at that point.

When you click [Finish and Exec] button of the Maneuver Editor window, SSVG finishes the editing and executes the maneuver.

CP

To guide the probe to very near region of Venus, add a "CP" maneuver which trims the orbit of the probe with chemical propulsion engine. Confirm that the third line of the Maneuver Table is a blank line with the Next flag, and click [Edit Next] button. The Maneuver Editor window will appear.

Select "CP" for maneuver type, and click the adjacent [Apply] button.

Let's specify delta-V with which the probe trims its orbit. You can use the FTA function of SSVG to compute appropriate delta-V. When you specify arriving time to the target, FTA function computes delta-V with two-body model. By clicking fast forward button [>>] on the Show Orbit window several times, set the DT to 50.0 and prediction time (labeled as "P. Time") to scheduled arrival time, and click the [FTA] button of the Maneuver Editor window. The FTA Setting window will appear.

In this case, we specify the arriving point of the probe precisely. In this tutorial, the arriving point is: opposite to the sun from Venus, distant 40,000 kilometers from the center of Venus. Set parameters in the "Set Probe's Sights on" area on the FTA Setting window as follows:

Range from Target Center (km)	40000 (forty thousand)
Angle phi from Target Center (deg)	-90 (minus ninety)
Angle elv from Target Center (deg)	0 (zero)

You can find explanations about angle phi and elv in Orbital local coordinate system.

When you click [OK] button on the FTA Setting window, SSVG computes the delta-V. When you confirm the result, they are applied to parameters in the Maneuver Editor window. When you click the [Finish and Exec] button on the Maneuver Editor window, SSVG finishes editing and executes the maneuver.

FLYTO (2)

Fly the probe 45 (forty five) days, until five days before the day of fly-bye. Add a "FLYTO" maneuver, and execute it. At the end of this maneuver, you can find that the voyage is favorable, and orbit of the probe has been changed slightly by the gravitational attraction of Venus.

FLYTO (3)

Fly the probe 10 (ten) days, until five days after the day of fly-bye. Add a "FLYTO" maneuver, and execute it. Because the probe will pass through near-Venus region and orbit of the probe will change violently, we need shorter integration intervals for numerical integration of probe trajectory. For the parameter labeled "inter : Integration Interval (days)" on the Maneuver Editor window, set a value 0.01 (zero point zero one).

Review the flight immediately after the execution of the maneuver. The probe pass through Venus, and fly-bye time is earlier than the predicted by a half day. When you put a check mark on the "Probe Kepler Orbit" check box on the Flight Review window, you can see Kepler orbit of the probe for each step of numerical integration.

Flight Plan towards a small body

Get SPK file for the small body

You can choose one of the small bodies of the solar system as a target of the flight. Solar system small bodies are asteroids, comets, and dwarf planets.

For this purpose, you need to get a SPK file for the small body. You can get the SPK file when you request it to HORIZONS system of NASA/JPL. There are several ways for requesting and you can see them on <http://ssd.jpl.nasa.gov/?horizons>, this document shows you one of the ways through web-interface.

Open following page with your web browser:
<http://ssd.jpl.nasa.gov/x/spk.html>

Enter the name or designation or asteroid number of the small body into the "Object" field, and click [Look up] button. One or more candidate(s) of the body will appear. Choose correct one and copy its "Primary SPKID." Return to the previous page, paste the SPKID into the "Object" field, and fill other fields. Select "Binary" for the "SPK file format".

Click the [Make SPK] button, and save the SPK file. It is convenient for you to save it in the "data" folder where you placed the "de430.bsp" file.

Please write down the SPKID, we need it later.

Generate new Flight Plan towards a small body

On the menu bar of the SSVG window, execute File → New.　The New Flight Plan window will appear.

Specify name and mass of the probe in the "Probe Properties" aria.

Specify the target in the "Target" aria.　Select Small Body radio button.　Enter name and SPKID of the small body.　For SPK file, click [...] button and select SPK file for the small body.

When you click [OK] button on the New Flight Plan window, the Flight Plan will be generated, and you will be able to compose the Flight Plan.

Reference

Operations and Information

SSVG window

Table 1　Buttons on the SSVG window

Face Name	Function
Review Throughout	Review throughout all executed maneuvers
Review Recent FLYTO	Review the recently executed FLYTO maneuver
Show Orbit	Open the Show Orbit window if not exist, and display information about the probe on the 3D Orbit window
Exec Next	Execute the maneuver on the Next Line
Exec to *	Execute maneuvers from the Next Line through the selected line
Ex Initialize	Cancel executed all maneuvers and set the Next flag on the first line
Edit Next	Edit the maneuver on the Next Line
Edit *	Edit the maneuver on the selected line.　When the selected line is not the Next Line, only part of full functions of the Maneuver Editor can be used. When the maneuver on the selected line had been executed previously, executions of all maneuvers are canceled if the editing were finished
Insert *	Insert a blank line before the selected line
Delete *	Delete the selected line

Table 2　Manipulate Maneuver Table on the SSVG window

Manipulation	Function
Click a line	Select the line
Double-click a line	Start Editing of the line.　Please consult "Edit *" in the previous table

Table 3　Menu items of the SSVG window

Menu item	Function
File → Open	Open a saved Flight Plan
File → New	Start to generate a new Flight Plan
File → Save	Save the Flight Plan to current file
File → Save as...	Save the Flight Plan to specified file
File → Quit	Quit SSVG
Edit → Probe	Edit probe properties of the Flight Plan
Edit → Target	Change the target of the Flight Plan
Checkpoint → Create	Create the checkpoint †
Checkpoint → Resume	Resume execution at the checkpoint
Help → about SSVG	Show information about SSVG

† SSVG creates the checkpoint with current execution state of the Flight Plan, and displays "checkpoint" at the appropriate position of the Maneuver Table.　When you command "Resume", SSVG restores the execution state from the checkpoint.　When you cancel executed all

maneuvers by clicking [Ex Initialize] or by other means, the checkpoint will be lost.

Table 4　Information on the SSVG window

Item name	Content
Current status	Current status of the probe immediately after the executed last maneuver
Selected maneuver	Precise parameters of the maneuver which is selected on the Maneuver Table

3D Orbit window

Table 5　Manipulate figures on the 3D Orbit window

What to do	How to do
Rotate the figures	Drag the mouse with the left button
Change the magnification	Drag the mouse up or down with the right button
Change the pointing place of the figure	You cannot perform this manipulation on this window. On the Show Orbit window, on the Flight Review window, or on the Review Throughout window, select an object to be placed on the center of the figure

Table 6　Marks on the 3D Orbit window

Mark	What is it?
red X mark	Position of the probe
red line	Predicted Kepler orbit of the probe. It is a conic section computed as a two-body problem. When using Start Optimize Assistant, it shows trajectory of the space base
blue line	Actual trajectory of the probe. It is a result of numerical integration
green + mark	Position of the target
green line	Kepler orbit of the target. It is a conic section computed as a two-body problem
blue X mark	Position where the probe arrives the target. (When using Optimize Assistant)
cyan line	Predicted Kepler orbit of the probe. (When using Optimize Assistant)
small circle	Position of the sun
+ mark and name of cyan	Positions and names of major bodies in the solar system. The moon of the Earth is indicated by a mark without name
axes	Axes of the ecliptic coordinate system. Origin is the solar system barycenter, and unit of length is a meter
time	The time corresponds to the position is displayed upper left corner of the 3D Orbit window

Show Orbit window

On the Show Orbit window, you can manipulate the figure displayed on the 3D Orbit window. Two major tasks of this window are as follows:

- Select the point which is displayed at the center of the figure
- Manipulate prediction time† which is used to display positions of the probe, of the target, and of major bodies of the solar system.

† About prediction time:

Basically, the 3D Orbit window displays positions at the end of last maneuver. But the Show Orbit window allows you to manipulate the time to be used, and we call it "prediction time." Because SSVG computes position of the probe at the prediction time as a two-body problem, the predicted position of the probe does not contain effects of gravitational attraction of planets including the target, and does not contain acceleration from the electric propulsion engine or the solar sail.

Table 7 Operation of the Show Orbit window

Item group	Item	Operation
Look at	SSB	When selected, the SSB, Solar System Barycenter, is placed at the center of the figure displayed on the 3D Orbit window
	Probe	When selected, the probe is placed at the center of the figure displayed on the 3D Orbit window
	Target	When selected, the target is placed at the center of the figure displayed on the 3D Orbit window
Show	Probe Trajectory	When checked, the trajectory of the probe is displayed on the 3D Orbit window
	Probe Kepler Orbit	When checked, the Kepler orbit of the probe is displayed on the 3D Orbit window
	Target Kepler Orbit	When checked, the Kepler orbit of the target is displayed on the 3D Orbit window
	Planets	When checked, the mark and name of major bodies of the solar system are displayed on the 3D Orbit window
Time	DT (days)	This field displays elapsed time from current time (C. Time) to prediction time (P. Time). You can type a new value also.
	[Apply] button	When clicked, the value of DT (days) will be applied to the prediction time (P. Time)
Prediction Time Manipulator	[<<] button	Fast backward. When clicked, prediction time (P. Time) will go back by a step of ten times of the one specified by the scale
	[<] button	Backward. When clicked, prediction time (P. Time) will go back by a step specified by the scale
	[>] button	Forward. When clicked, prediction time (P. Time) will go forward by a step specified by the scale
	[>>] button	Fast forward. When clicked, prediction time (P. Time) will go forward by a step of ten times of the one specified by the scale
	Scale (a spinner)	Specify the time step of one operation of the [<] button and [>] button. The value means an exponent of ten. When the value is 0 (zero), the step is one day, when the value is 1 (one), the step is 10 (ten) days, and so on.

Table 8　Information displayed on the Show Orbit window

Item group	Explanation
Parameters for CP	During the editing of a maneuver of "CP" or "START", specified delta-V is displayed in this area. The values are used to compute Kepler orbit and position of the probe to be displayed on the 3D Orbit window
Time	C. Time (current time), P. Time (prediction time), and DT (elapsed time) are displayed in this area. The current time is the end time of the executed last maneuver. The prediction time is the time to be combined to the position of object to be displayed
Relative Position of Target	Position of the target relative to the probe. You will find explanations about phi and elv in Orbital local coordinate system
Relative Velocity of Target	Velocity of the target relative to the probe. You will find explanations about phi and elv in Orbital local coordinate system
Line of Sight Velocity (departing)	Line of sight velocity of the target from the probe. When the value is positive, the target is departing from the probe

Flight Review window

On the Flight Review window, you can manipulate the figure displayed on the 3D Orbit window when you review the executed last FLYTO maneuver.

Table 9　Operation of the Flight Review window

Item group	Item	Operation
Look at	SSB	When selected, the SSB, Solar System Barycenter, is placed at the center of the figure displayed on the 3D Orbit window
	Probe	When selected, the probe is placed at the center of the figure displayed on the 3D Orbit window
	Target	When selected, the target is placed at the center of the figure displayed on the 3D Orbit window
Show	Probe Trajectory	When checked, the trajectory of the probe is displayed on the 3D Orbit window
	Probe Kepler Orbit	When checked, the Kepler orbit of the probe is displayed on the 3D Orbit window
	Target Kepler Orbit	When checked, the Kepler orbit of the target is displayed on the 3D Orbit window
	Planets	When checked, the mark and name of major bodies of the solar system are displayed on the 3D Orbit window
Review Manipulator	[<<] button	Fast backward. When clicked, current time (C. Time) will go back by integration interval multiplied by the "Hopping"
	[<] button	Backward. When clicked, current time (C. Time) will go back by one integration interval.
	[>] button	Forward. When clicked, current time (C. Time) will go forward by one integration interval
	[>>] button	Fast forward. When clicked, current time (C. Time) will go forward by integration interval multiplied by the "Hopping"
	Hopping (a spinner)	Specify the count to multiply integration interval when you click the [<<] button or the [>>] button

Table 10 Information displayed on the Flight Review window

Item group	Explanation
Time	S. Time (start time), C. Time (current time), and DT (elapsed time) are displayed in this area. The start time is the time last FLYTO maneuver has started, and the current time is the time corresponds to the position of the object to be displayed
Relative Position of Target	Position of the target relative to the probe. You will find explanations about phi and elv in Orbital local coordinate system
Relative Velocity of Target	Velocity of the target relative to the probe. You will find explanations about phi and elv in Orbital local coordinate system
Line of Sight Velocity (departing)	Line of sight velocity of the target from the probe. When the value is positive, the target is departing from the probe

Review Throughout window

Table 11 Operation of the Review Throughout window

Item group	Item	Operation
Look at	SSB	When selected, the SSB, Solar System Barycenter, is placed at the center of the figure displayed on the 3D Orbit window
	Probe	When selected, the probe is placed at the center of the figure displayed on the 3D Orbit window
	Target	When selected, the target is placed at the center of the figure displayed on the 3D Orbit window
Show	Probe Trajectory	When checked, the trajectory of the probe is displayed on the 3D Orbit window
	Probe Kepler Orbit	When checked, the Kepler orbit of the probe is displayed on the 3D Orbit window
	Target Kepler Orbit	When checked, the Kepler orbit of the target is displayed on the 3D Orbit window
	Planets	When checked, the mark and name of major bodies of the solar system are displayed on the 3D Orbit window
Review Manipulator	[|<] button	Move to the previous maneuver. When reviewing halfway of a FLYTO maneuver, move to the start of that maneuver
	[<<] button	Fast backward. When clicked, current time (C. Time) will go back by integration interval multiplied by the "Hopping"
	[<] button	Backward. When clicked, current time (C. Time) will go back by one integration interval.
	[>] button	Forward. When clicked, current time (C. Time) will go forward by one integration interval
	[>>] button	Fast forward. When clicked, current time (C. Time) will go forward by integration interval multiplied by the "Hopping"
	[>|] button	Move to the next maneuver. When reviewing halfway of a FLYTO maneuver, move to the end of that maneuver
	Hopping (a spinner)	Specify the count to multiply integration interval when you click the [<<] button or the [>>] button

Table 12　Information displayed on the Review Throughout window

Item group	Explanation
Time	S. Time (start time), C. Time (current time), and DT (elapsed time) are displayed in this area. The start time is the time the probe left the space base, and the current time is the time corresponds to the position of the object to be displayed
Relative Position of Target	Position of the target relative to the probe. You will find explanations about phi and elv in Orbital local coordinate system
Relative Velocity of Target	Velocity of the target relative to the probe. You will find explanations about phi and elv in Orbital local coordinate system
Line of Sight Velocity (departing)	Line of sight velocity of the target from the probe. When the value is positive, the target is departing from the probe

Maneuver Editor window

On the Maneuver Editor window, you can edit each maneuver of the Flight Plan. The following table shows types of maneuvers in SSVG.

Table 13　Types of maneuvers in SSVG

Type	Explanation
START	Make the probe leave the space base. This maneuver specifies start time and velocity relative to the space base
CP	Make the probe change the orbit by the chemical propulsion engine. This maneuver specifies delta-V
EP_ON	Make the probe set the status of the electric propulsion engine to ON. This maneuver specifies delta-V per day
EP_OFF	Make the probe set the status of the electric propulsion engine to OFF.
SS_ON	Make the probe set the status of the solar sail to ON. This maneuver specifies area of the sail and orientation of the sail
SS_OFF	Make the probe set the status of the solar sail to OFF.
FLYTO	Make the probe fly until specified time. The trajectory of the probe will be computed using gravitational attractions of every planet and accelerations from the electric propulsion engine and the solar sail. This maneuver specifies the time when the flight ends.

You can use full functions of the Maneuver Editor window only when you edit the Next Line. When you edit the Next Line, the Show Orbit window will appear and you can see predicted orbit and/or predicted position of the probe. Following explanations are for cases when you edit a Next Line.

Table 14 Operations of the Maneuver Editor window

Item	Relating Maneuver type	Operation
Maneuver Type	any type	Change the maneuver type of the maneuver. Select appropriate type on the drop-down list and click adjacent [Apply] button
Start Time - ISOT End Time - ISOT	START FLYTO	Specify start time in ISO format (START) Specify end time of the flight in ISO format (FLYTO) †
Start Time - JD End Time - JD	START FLYTO	Specify start time in Julian date (START) Specify end time of the flight in Julian date (FLYTO) †
Flight Duration	FLYTO	Specify the flight duration in days. When you click adjacent [Apply] button, the value will be applied to the End Time †
[Show Orbit] button	any type	When clicked, SSVG computes position and orbit of the probe using specified time and/or delta-V, and displays them on the 3D Orbit window. SSVG perform this computation using a two body model, so the position and orbit do not contain effects of gravitational attraction of planets including the target, and does not contain acceleration from the electric propulsion engine or the solar sail.
[FTA] button	START CP	When clicked, SSVG invokes FTA function, and opens the FTA Setting window. Please consult FTA Setting window
[Optimize] button	START CP	When clicked, SSVG invokes Optimize Assistant to assist user to fined preferable start time or maneuver time, and flight duration. Please consult Start Optimize Assistant window or CP Optimize Assistant window
Parameters (a table)	any type	You need specify parameters of the maneuver on this table. Explanations of parameters are in the next table
[Finish and Exec] button	any type	Finish editing of the maneuver and execute it
[Finish] button	any type	Finish editing of the maneuver
[Cancel] button	any type	Cancel editing of the maneuver

† When the Show Orbit window is active, operations on the Prediction Time Manipulator and/or DT will be applied to End Time and Flight Duration of the Maneuver Editor. On the contrary, operations of End Time and/or Flight Duration of the Maneuver Editor window will be applied to the Show Orbit window and the 3D Orbit window only when you click the [Show Orbit] button on the Maneuver Editor window.

Table 15 Parameter items on the Maneuver Editor window

Parameter item	Relating Maneuver type	Explanation
dv	START CP	Specify absolute value of the delta-V. The value should be in meters per second
dvpd	EP_ON	Specify absolute value of the delta-V for one day operation of the electric propulsion engine. The value should be in meters per second
phi	START CP EP_ON	Specify the angle phi (stands for a Greek character) to indicate direction of the delta-V. The value should be in degrees. Consult Orbital local coordinate system for the definition of phi
elv	START CP EP_ON SS_ON	Specify the angle elv (stands for "elevation") to indicate direction of the delta-V or orientation of the solar sail. The value should be in degrees. Consult Orbital local coordinate system and Solar sail coordinate system for the definition of elv
aria	SS_ON	Specify area of the solar sail. The value should be in square meters.
theta	SS_ON	Specify the angle theta (stands for a Greek character) to indicate orientation of the solar sail. The value should be in degrees. Consult Solar sail coordinate system for the definition of theta
inter	FLYTO	Specify the length of one step of numerical integration for computation of trajectory of the probe. The value should be in days.

New Flight Plan window

On the New Flight Plan window, you can specify properties of the new Flight Plan.

For the new probe, you need to specify name and mass, and need to select a space base from which the probe starts the voyage. SSVG provides sixteen space bases to start your probe from; each base is placed on a Lagrangian point L1 or L2 of a planet. For example, the space base "EarthL2" is placed on the Lagrangian point L2 of the Sol-Earth system. It means that this space base is about 1.5 million kilometers from the Earth, opposite to the sun.

You need to specify a celestial object as a target, the destination of the voyage. When you select one of the planets, dwarf planet Pluto, or the Moon, check the Planet/Moon radio button and you can select the object on the drop-down list.

If you want to fly the probe toward another small body, check the Small Body radio button and enter name and SPKID of the body. For the SPK file, click adjacent [...] button, and select SPK file of the body. If you don't have SPK file and/or SPKID of the body, please consult Get SPK file for the small body and get them prior to generate the new Flight Plan.

FTA Setting window

On the FTA Setting window, you can specify parameters for FTA.

FTA stands for Fixed Time Arrival Guidance. In SSVG, it's a function to compute delta-V which makes the probe arrive at the target on the specified time. SSVG assumes the use case of FTA as follows:

- On the Maneuver Editor window which editing a Next Line,
- In case that type of the maneuver is START or CP,
- Specify the arriving time as prediction time of the Show Orbit widow,
- Invoke FTA function by clicking [FTA] button.

If you follow this use case, select "Get Prediction Time from Show Orbit Window" radio button for the "Time to Arrival," but you may select "Specify Time to Arrival" and enter flight duration to the arrival into the "Time to Arrival (days)" field.

Sometimes you want to guide the probe toward an adjacent place of the target, not center of the target. In that case, you can specify the place on the "Set Probe's Sight on" area with three parameters, range, angle phi, and angle elv from the center of the target. Please consult Orbital local coordinate system for definitions of phi and elv.

Start Optimize Assistant window

This is a window which assists you to select parameters of the START maneuver of the probe.

This window assists you when your probe flies directly from the space base to the target, and assists you selecting preferable start time and length of the flight (flight duration). Start time and flight duration give large effect to the efficiency of the voyage, and there are many aspects to select the best orbit. Start Optimize Assistant window allows you try any start time and flight duration, and show you each orbit graphically, delta-V of the probe to leave the space base, and relative velocity of the target when the probe arrives. You may pick up convenient orbit easily.

Defining the orbit, you can use the arrival time of the probe to the target in replacement of the flight duration.

Because predicted orbit on Optimize Assistant is a Kepler orbit (a conic section computed as a two-body problem), the actual trajectory of the probe will be a little different one.

Table 16 Operations of the Start Optimize Assistant window

Item group	Item	Operation
Look at	SSB	The SSB, Solar System Barycenter, is placed at the center of the figure displayed on the 3D Orbit window
	Probe	N/A
	Target	N/A
Show Orbit	Space Base	When checked, the trajectory of the space base is displayed on the 3D Orbit window as a red curved line
	Target	When checked, the Kepler orbit of the target is displayed on the 3D Orbit window as a green curved line
	Probe Predicted	When checked, the predicted orbit of the probe is displayed on the 3D Orbit window as a cyan curved line
Flight Duration is Arranged by	Flight Duration	When checked, you can directly define flight duration
	Arrival Time	When checked, you can define arrival time of the probe to the target in replacement of the flight duration
Arrange Start Time	[<<] button	Move the center time of the slider with one step (†1) to past
	[>>] button	Move the center time of the slider with one step (†1) to future
	Wide	When checked, the range of the slider is ±250 days
	Narrow	When checked, the range of the slider is ±50 days
	slider	When moved, the Start Time will change. You can move it with arrow keys or wheel of mouse also
	Deviation	The deviation of the slider from center
	Start Time	The time when the probe leaves the space base
Arrange Flight Duration (†2)	[<<] button	Change the center value of the slider with one step (†1) to lower
	[>>] button	Change the center value of the slider with one step (†1) to higher
	Wide	When checked, the range of the slider is ±250 days
	Narrow	When checked, the range of the slider is ±50 days
	slider	When moved, the Flight Duration will change. You can move it with arrow keys or wheel of mouse also
	Flight Duration	The length of the flight in days
	Arrival Time	The time when the probe arrives the target
other buttons	Clear Statistics	Clear minimum value (Min.) and maximum value (Max.)
	Finish and Apply	Apply current start time and delta-V to the Maneuver Editor, and close Optimize Assistant
	Cancel	Discard current parameters and close Optimize Assistant

(†1) One step is 250 days (when Wide) or 50 days (when Narrow).

(†2) This portion of the table shows operations when you select "Flight Duration" for "Flight Duration is Arranged by." For operations when you select "Arrival Time," please consult the portion for Arrange Start Time.

Table 17　Information displayed on the Start Optimize Assistant window

Item group	Explanation
Initial Delta-V (m/s)	Delta-V to start the probe. The absolute value of current delta-V, its minimum, and its maximum value† are displayed. For current delta-V, parameters phi and elv are displayed also. About phi and elv, please consult Orbital local coordinate system
Terminal Relative Velocity (m/s)	Relative velocity of the target when probe arrives. The absolute value of current relative velocity, its minimum, and its maximum value† are displayed
Total DV (IDV + TRV)	The summation of delta-V to start the probe and relative velocity of the target when probe arrives. The current value, its minimum, and its maximum value† are displayed

† You can clear the minimum and the maximum value by clicking [Clear Statistics] button.

CP Optimize Assistant window

This is a window which assists you to select parameters of the CP maneuver (changing the orbit by chemical propulsion engine) of the probe.

This window assists you when your probe is on flight and you want to change the orbit to the one which guide the probe to the target. It assists you to select preferable maneuver time and length of the flight (flight duration) after the maneuver. Maneuver time and flight duration give large effect to the efficiency of the voyage, and there are many aspects to select the best orbit. CP Optimize Assistant window allows you try any maneuver time and flight duration, and show you each orbit graphically, delta-V of the CP maneuver, and relative velocity of the target when the probe arrives. You may pick up convenient orbit easily.

Defining the orbit, you can use the arrival time of the probe to the target in replacement of the flight duration.

Because predicted orbit on Optimize Assistant is a Kepler orbit (a conic section computed as a two-body problem), the actual trajectory of the probe will be a little different one.

Table 18 Operations of the CP Optimize Assistant window

Item group	Item	Operation
Look at	SSB	The SSB, Solar System Barycenter, is placed at the center of the figure displayed on the 3D Orbit window
	Probe	N/A
	Target	N/A
Show Orbit	Space Base	When checked, the trajectory of the space base is displayed on the 3D Orbit window as a red curved line
	Target	When checked, the Kepler orbit of the target is displayed on the 3D Orbit window as a green curved line
	Probe Predicted	When checked, the predicted orbit of the probe is displayed on the 3D Orbit window as a cyan curved line
	Probe Trajectory	When checked, the trajectory of the probe is displayed on the 3D Orbit window as a blue curved line
Flight Duration is Arranged by	Flight Duration	When checked, you can directly define flight duration
	Arrival Time	When checked, you can define arrival time of the probe to the target in replacement of the flight duration
Maneuver Time is	Fixed to Current Time	When checked, the maneuver time is fixed to the current time (end time of the preceding maneuver)
Arrange Maneuver Time	[<<] button	Move the center time of the slider with one step (†1) to past
	[>>] button	Move the center time of the slider with one step (†1) to future
	Wide	When checked, the range of the slider is ±250 days
	Narrow	When checked, the range of the slider is ±50 days
	slider	When moved, the Maneuver Time will change. You can move it with arrow keys or wheel of the mouse also
	Deviation	The deviation of the slider from center
	Maneuver Time	The time when the CP maneuver will be executed
Arrange Flight Duration (†2)	[<<] button	Change the center value of the slider with one step (†1) to higher
	[>>] button	Change the center value of the slider with one step (†1) to lower
	Wide	When checked, the range of the slider is ±250 days
	Narrow	When checked, the range of the slider is ±50 days
	slider	When moved, the Flight Duration will change. You can move it with arrow keys or wheel of the mouse also
	Flight Duration	The length of the flight in days
	Arrival Time	The time when the probe arrives the target
other buttons	Clear Statistics	Clear minimum value (Min.) and maximum value (Max.)
	Finish and Apply	Apply delta-V to the Maneuver Editor, and close Optimize Assistant (†3: Important)
	Cancel	Discard current parameters and close Optimize Assistant

(†1) One step is 250 days (when Wide) or 50 days (when Narrow).

(†2) This portion of the table shows operations when you select "Flight Duration" for "Flight Duration is Arranged by." For operations when you select "Arrival Time," please consult the portion for Arrange Maneuver Time.

(†3: Important) The maneuver time is not applied to the Maneuver Editor or other maneuver(s).

When you applied parameters with arranged maneuver time, you should adjust preceding maneuver(s) before execution of this maneuver. This maneuver (which is applied parameters) should be executed at the arranged maneuver time. You can use current maneuver time which is saved to system clipboard.

Table 19 Information displayed on the CP Optimize Assistant window

Item group	Explanation
Initial Delta-V (m/s)	Delta-V to start the probe. The absolute value of current delta-V, its minimum, and its maximum value† are displayed. For current delta-V, parameters phi and elv are displayed also. About phi and elv, please consult Orbital local coordinate system
Terminal Relative Velocity (m/s)	Relative velocity of the target when probe arrives. The absolute value of current relative velocity, its minimum, and its maximum value† are displayed
Total DV (IDV + TRV)	The summation of delta-V to start the probe and relative velocity of the target when probe arrives. The current value, its minimum, and its maximum value† are displayed

† You can clear the minimum and the maximum value by clicking [Clear Statistics] button.

Coordinate systems

Ecliptic coordinate system

Ecliptic coordinate system uses the ecliptic plane and the orbital plane of the Earth as the fundamental plane. The X axis direct to the vernal equinox, the Z axis is perpendicular to the ecliptic plane and direct northward, and the Y axis completes the right-handed rectangular system with X and Z axes. SSVG uses J2000 system for the ecliptic plane and the vernal equinox.

Orbital local coordinate system

This is a coordinate system based on orbit of the object which revolves around the sun.　It uses the orbital plane of the object as the fundamental plane, the X axis is parallel to the relative velocity vector of the object for the sun, the Z axis is parallel to the angular momentum vector of the object, which is perpendicular to the orbital plane of the object, the Y axis completes the right-handed rectangular system with X and Z axes.

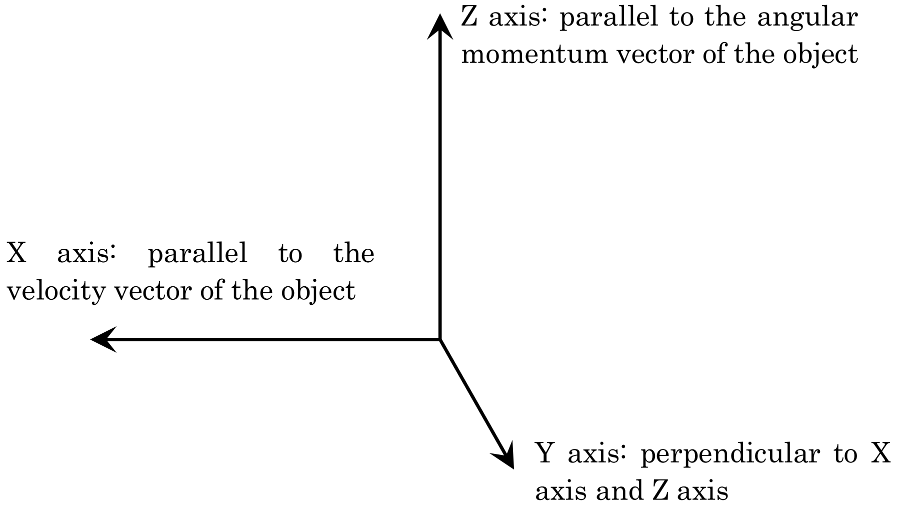

Figure 1　Orbital local coordinate system

Polar coordinate representations on the orbital local coordinate system

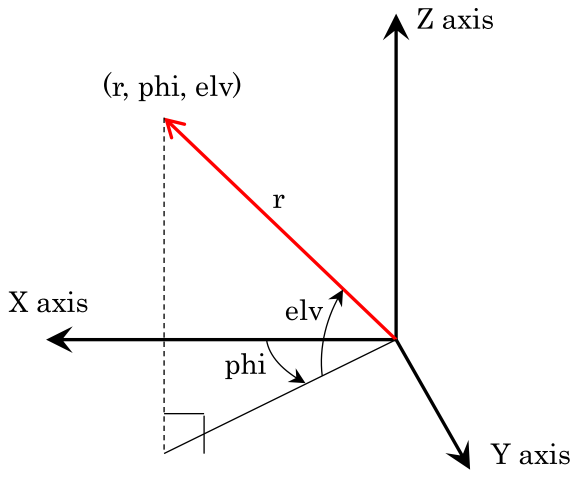

Figure 2　Polar coordinate representations on the orbital local coordinate system

Solar sail coordinate system

This is a coordinate system based on orbit of the object which revolves around the sun, and it is used to specify the direction (orientation) of the solar sail in SSVG. It uses the orbital plane of the object as the fundamental plane, the X axis is parallel to the position vector of the object from the sun, the Z axis is parallel to the angular momentum vector of the object, which is perpendicular to the orbital plane of the object, the Y axis completes the right-handed rectangular system with X and Z axes.

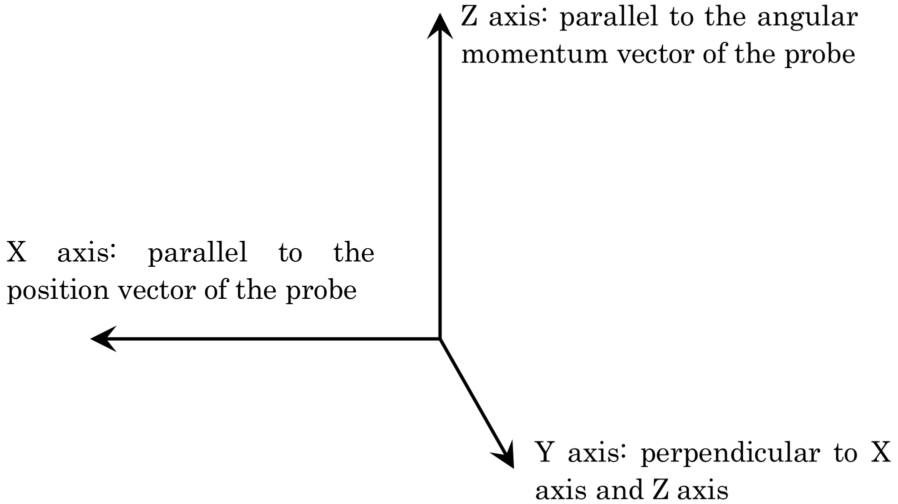

Figure 3 Solar sail coordinate system

Polar coordinate representations on the solar sail coordinate system

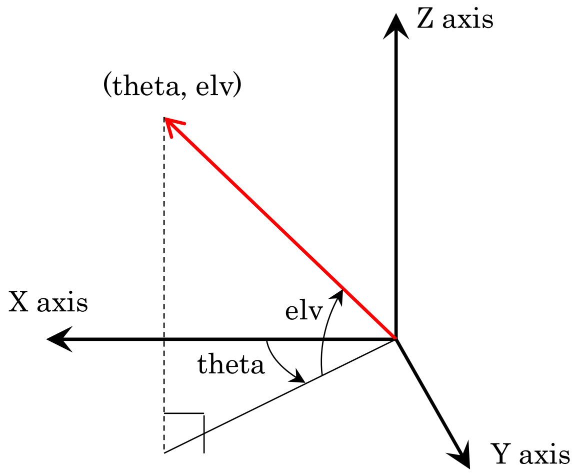

Figure 4 Polar coordinate representations on the solar sail coordinate system

In SSVG, we specify the orientation of the solar sail by these theta and elv of the normal vector of the sail plane. The sail plane has two normal vectors opposite to each other; we use the one departing from the sun.

Time

In SSVG the time is represented by Barycentric Dynamical Time (TDB). SSVG uses Julian date for expressing date and time internally, but sometimes display date and time in ISO 8601 extended format, with no time zone designators.

Chemical propulsion engine

We made some simplifications about chemical propulsion engine. In SSVG, chemical propulsion engine changes the velocity of the probe at an instant; it requires no time to operate. SSVG does not consider about the consumption of the fuel and/or oxidizer. SSVG does not consider errors correspond to the propulsion; errors about absolute delta-V and/or errors about direction of delta-V.

Electric propulsion engine

Electric propulsion engine in SSVG accelerate the probe continuously with specified rate during a FLYTO maneuver when the status is on. We made some simplifications about it also. SSVG does not consider about the consumption of the propellant. SSVG does not consider the limitation of the electric power which can be used to accelerate the probe. SSVG does not consider errors correspond to the propulsion; errors about absolute delta-V rate and/or errors about direction of delta-V.

Solar sail

Solar sail is modeled as a perfect plane mirror in SSVG. The area can be specified freely, and the sail can be moved to any orientation instantly. SSVG does not consider errors correspond to the propulsion; errors about area of the sail and/or errors about orientation of the sail.

Numerical integration of position and velocity of the probe

During a FLYTO maneuver, SSVG computes trajectory of the probe using numerical integration of forces which affects motion of the probe. SSVG considers following forces and neglects others:

Gravitational attraction of the sun
Gravitational attraction of the eight planets and the Moon
Propulsive force of the electric propulsion engine and the solar sail