Solar-C Science Definition Meeting ***Nov. 18, 2008, ISAS***

Mission Design Options for Solar-C Plan-A

Y. Kawakatsu (JAXA)
M. Morimoto (JAXA)
J. A. Atchison (Cornell U.)
J. Kawaguchi (JAXA)

Introduction

Objective of the Study

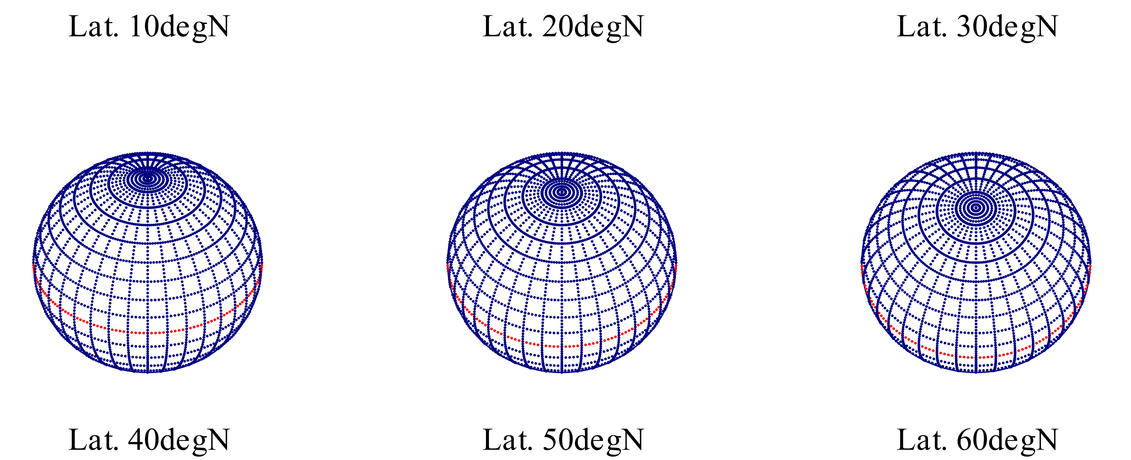
- **Objectives**

  - To show possible trajectory/orbit options which satisfy the mission requirement of Solar-C Plan-A.

  - To provide related information useful for the comparison between the options or mission analysis.

Mission Requirement (tentative)

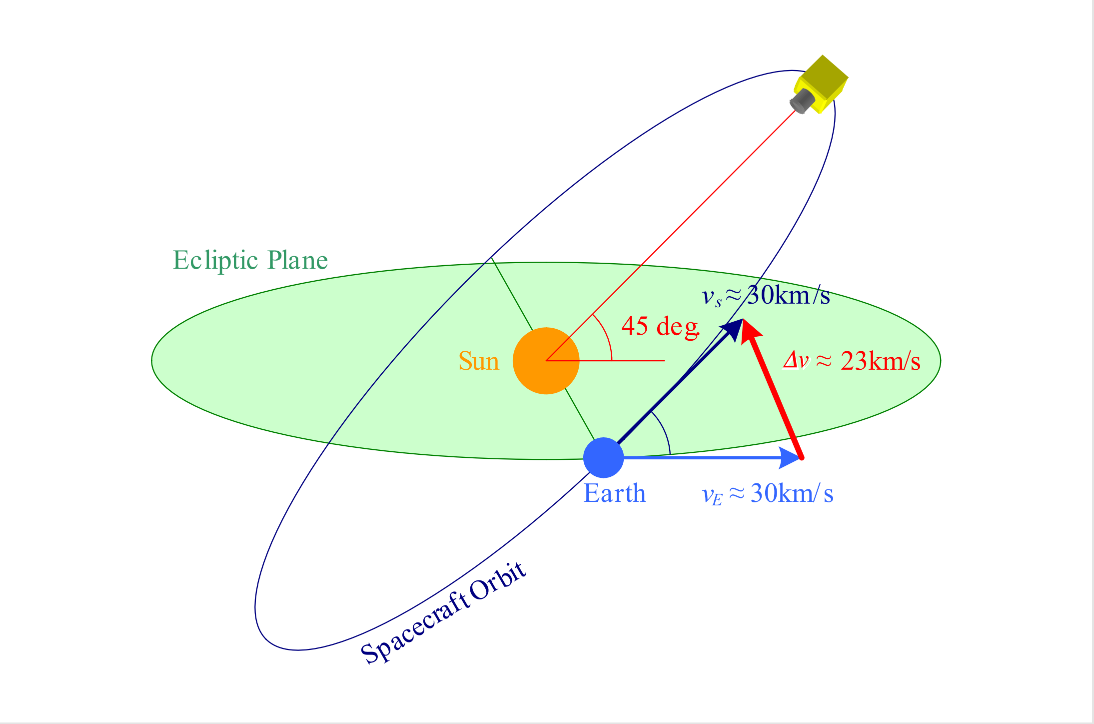
"To reach Lat. 45deg. of the Sun"



View of the Sun from the High Solar Latitude

Challenge to Lat. 45deg.

- **Rough Estimation of the Launch Energy**



$$C_3 = (v_\infty)^2 \approx (23\text{km/s})^2 \approx 530\text{km}^2/\text{s}^2$$

(*cf*. C_3 for the Jupiter Transfer ≈ 80km²/s²)

Techniques to Overcome the Challenge

- **Trajectory Manipulation Techniques Available**

  - Geometric Relation

    Take advantage of the tilt of the Solar equatorial plane against the ecliptic plane (about 7deg.). Choice of the appropriate launch date is important.

  - Launcher Capacity

    Launch energy is still the most contributing part. Launch a small spacecraft with a heavy launcher yields large launch energy.

  - Gravity Assist (Swing-by)

    The most efficient trajectory manipulation method in the interplanetary cruise, which is widely used in various planetary missions.

  - Propulsion

    Usage of high efficiency propulsion system enables large velocity increment with less propellant.

Possible Options of the Trajectory Sequence

● Two Possible Options of the Trajectory Sequence

➢ Usage of the Solar Electric Propulsion (**SEP option**)

Use high ISP ion engine system for orbit maneuver. Spacecraft operates around 1AU. Sub-option includes the usage of the Earth gravity assists to enhance the maneuver efficiency.

➢ Usage of the Jupiter Gravity Assist (**Jupiter option**)

As Ulysses mission, firstly go to the Jupiter and change the orbit plane by the Jupiter gravity assist. Sub-option includes the additional Earth gravity assist to adjust the period of the observation orbit.

● Characteristics of the Options

The following information are to be provided for evaluation/comparison.

- Mass budget.
- Inclination (or Solar latitude).
- Observation profile (start, frequency).
- Impact on the spacecraft system design.

Overview of the Trajectory Sequence

Overview of the Trajectory Sequences

●Usage of the Solar Electric Propulsion (SEP option)

➢Simply increase inclination (SEP-1)

Simply use SEP to increase the inclination. The Earth gravity assist is not used.

➢Combination with the Earth gravity assists (SEP-2)

Use SEP combined with the Earth gravity assists. The method is called Electric Propulsion Delta-v Earth Gravity Assist (EDVEGA).

●Usage of the Jupiter Gravity Assist (Jupiter option)

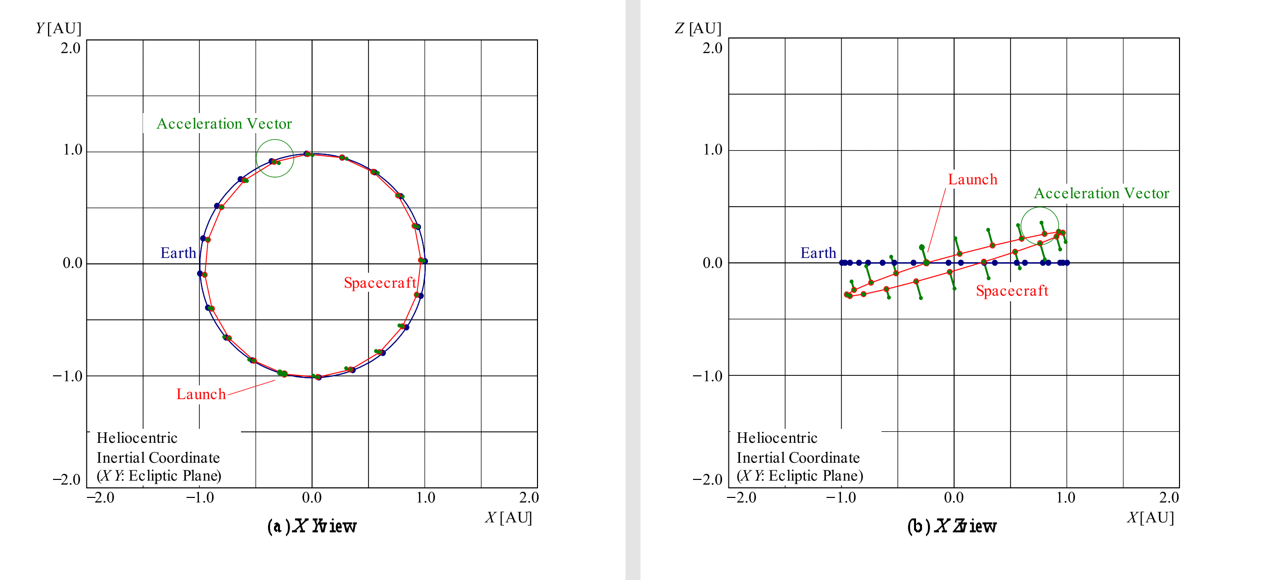
➢Use the Jupiter gravity assist only (Jupiter-1)

Use the Jupiter gravity assist for the orbit plane change. Just as Ulysses mission.

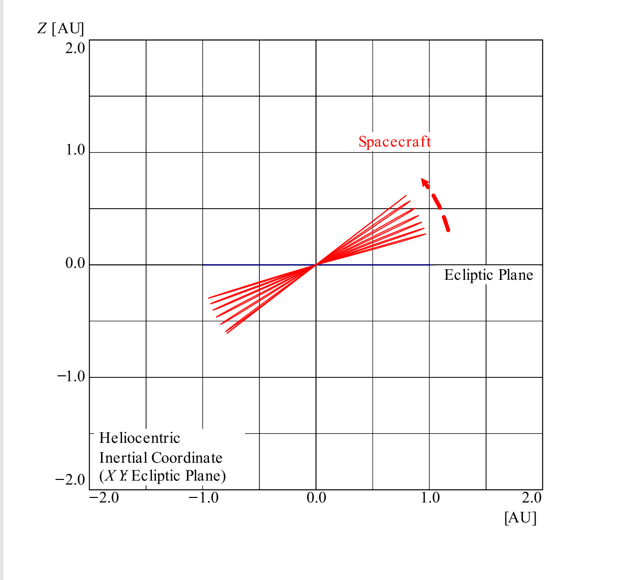
➢Use the additional Earth gravity assist (Jupiter-2)

Add to the Jupiter, use the Earth gravity assist to shorten the period of the observation orbit.

SEP-1 (use SEP, simply increase inclination)



Orbit profile of the 1st cycle



Orbit profile of the sequence

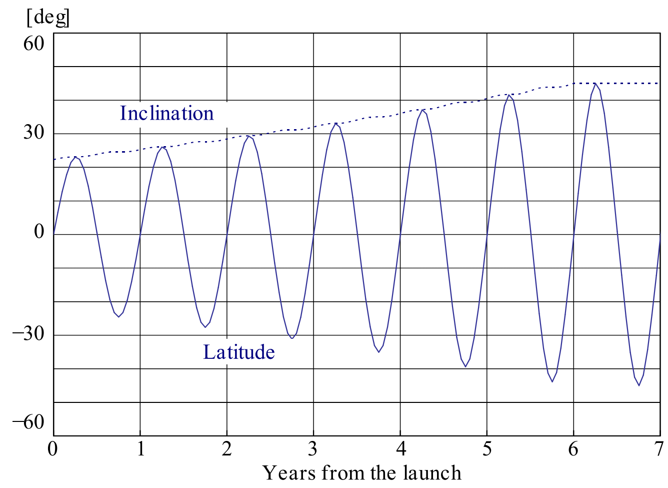
➢Basic Strategy of **SEP-1**

- Any time thrust to increase the inclination as possible.
- Launch v_∞ is in out of ecliptic direction (Practically speaking, modification is required).
- Thrust around the nodes are in the direction approximately normal to the radius & velocity.

SEP-1 (use SEP, simply increase inclination) (cont.)

Summary of the sequence

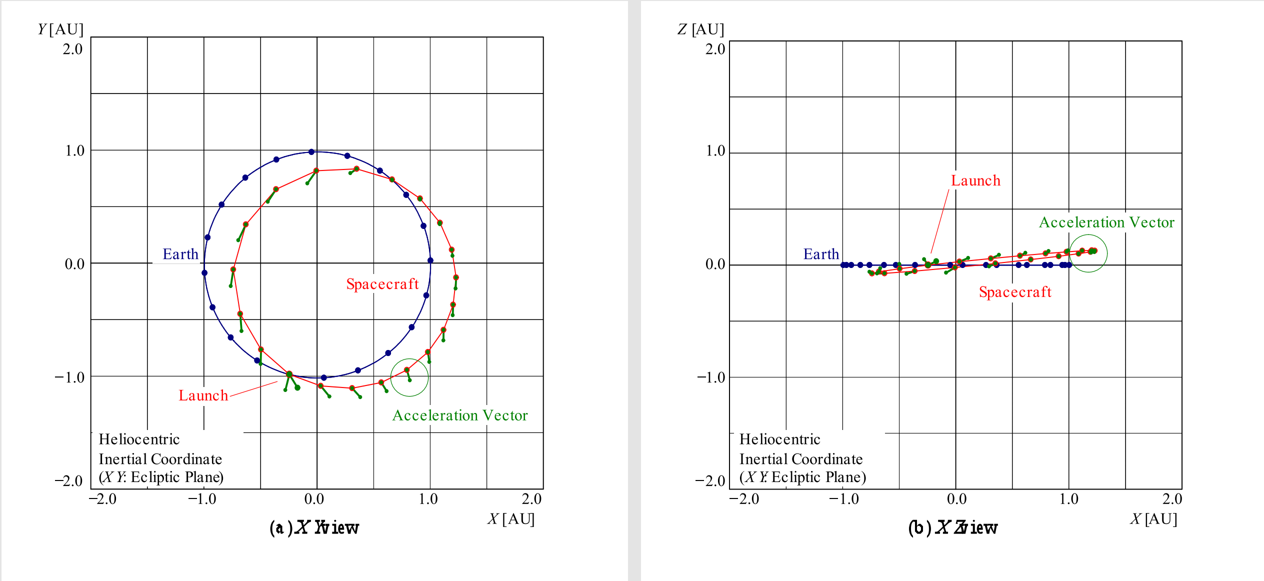
Years from Launch	Event	m	v_∞	i_{SEQ}
0	Launch	1200.0 kg	7.7 km/s	22.3 deg.
1	Earth Encounter #1	1123.0 kg	9.2 km/s	25.3 deg.
2	Earth Encounter #2	1046.1 kg	10.8 km/s	28.5 deg.
3	Earth Encounter #3	962.7 kg	12.6 km/s	32.0 deg.
4	Earth Encounter #4	875.9 kg	14.6 km/s	36.1 deg.
5	Earth Encounter #5	788.5 kg	16.8 km/s	40.5 deg.
6	Earth Encounter #6	713.4 kg	19.0 km/s	45.0 deg.
7	Earth Encounter #7	713.4 kg	19.0 km/s	45.0 deg.



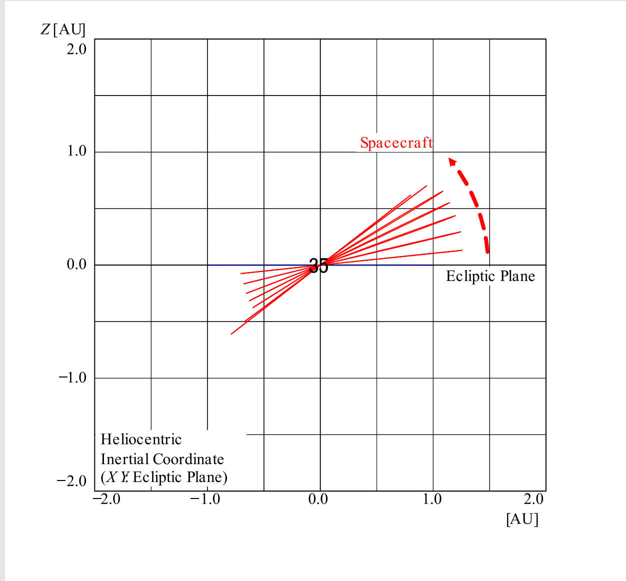
Profile of inclination/latitude

- Advantages
  - Simple strategy.
  - The distance to the Sun is kept to 1AU (Easy for the thermal design).
- Disadvantage
  - Thrust is used not so efficiently to increase the inclination.

SEP-2 (use SEP, combined with the Earth gravity assist)



Orbit profile of the 1st cycle



Orbit profile of the sequence

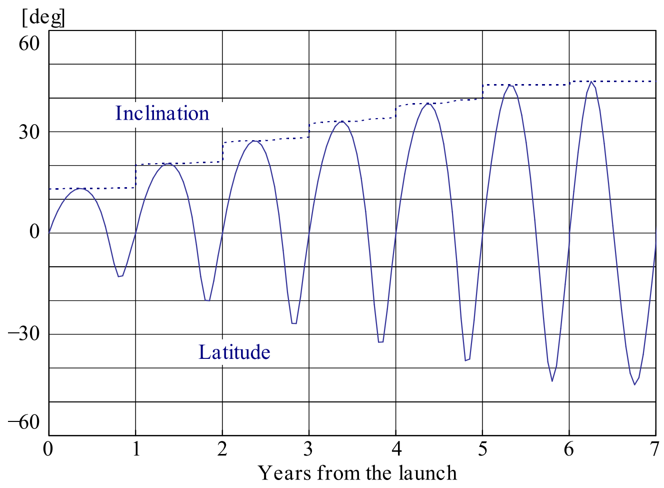
➢Basic Strategy of SEP-2

- Maximize the relative velocity at the Earth encounter.
  (The thrust does not necessarily increase the inclination by itself.)
- Change the direction of the relative velocity to contribute to the inclination increase by the Earth swing-by.
- Keep the orbit eccentricity to hold the efficiency to gain the relative velocity with the Earth.

SEP-2 (use SEP, combined with the Earth gravity assist) (cont.)

Summary of the sequence

Date	Event	m	v_∞	i_{SEQ}
2010/06/07	Launch	1200.0 kg	7.7 km/s	13.0 deg.
2011/06/07	Earth Swing-by #1	1127.3 kg	10.0 km/s	13.5 deg.
				20.2 deg.
2012/06/06	Earth Swing-by #2	1052.0 kg	12.3 km/s	21.2 deg.
				26.7 deg.
2013/06/06	Earth Swing-by #3	974.5 kg	14.6 km/s	28.5 deg.
				32.3 deg.
2014/06/06	Earth Swing-by #4	902.3 kg	16.8 km/s	34.4 deg.
				37.4 deg.
2015/06/07	Earth Swing-by #5	831.3 kg	19.0 km/s	39.9 deg.
				43.9 deg.
2016/06/06	Earth Swing-by #6	831.3 kg	19.0 km/s	43.9 deg.
				45.0 deg.
2017/06/06	Earth Swing-by #7	831.3 kg	19.0 km/s	45.0 deg.



Profile of inclination/latitude

- **Advantage**
  - Thrust is used efficiently to increase the relative velocity with the Earth (but finally, the orbit is circularized by the Earth swing-by with negligible cost).
- **Disadvantage**
  - The distance to the Sun changes due to the orbit eccentricity during the sequence (but finally, the orbit is circularized by the Earth swing-by with negligible cost).

Major Assumptions on SEP Option Study

- **Spacecraft Specification**
  - Initial Mass 1200kg
  - Ion Engine Thrust 120mN
  - Ion Engine Isp 3000sec

Strictly speaking,

$$\begin{cases} 120\text{mN} & (r \le 1\text{AU}) \\ 120\text{mN}/r^2 & (r \ge 1\text{AU}) \end{cases}$$

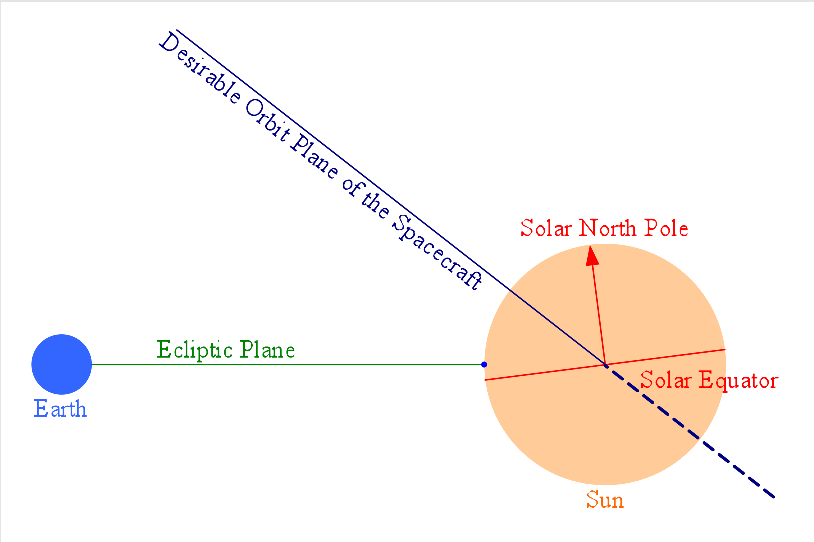
where r is the distance from the Sun. Additionally, degraded in the analysis considering the operation rate.

- **Launcher**
  - H2A202 + upper stage
  - Injection v_∞ 7.7km/s (for 1200kg)

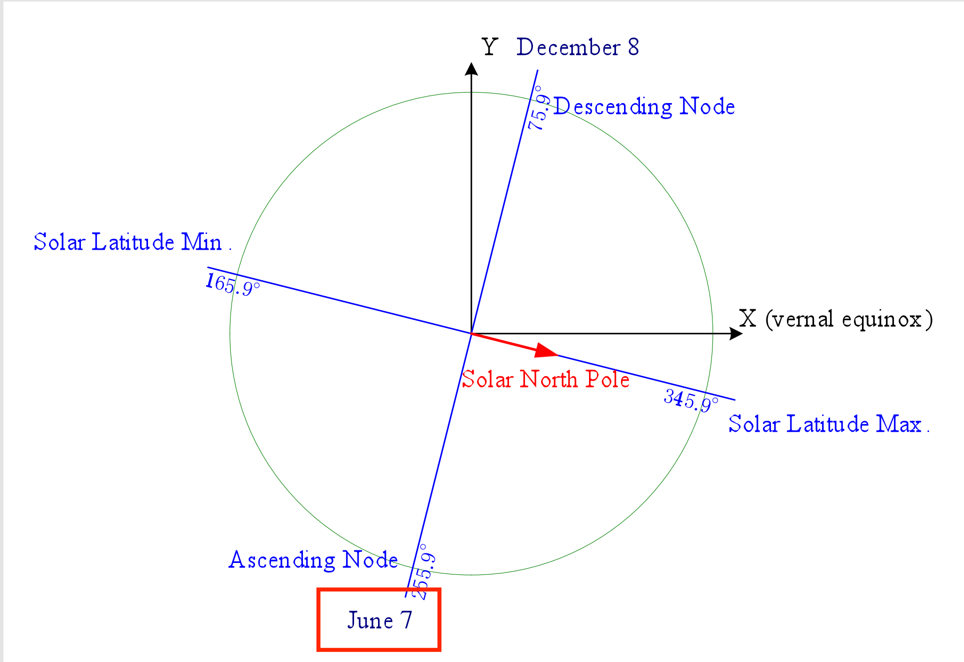
- **Orbit**
  - SEP-1
    - Keep the orbit period approximately to one year (the Earth synchronous orbit), so that the distance to the Earth is kept in limited range.
  - SEP-2
    - Keep the orbit period approximately to one year (the Earth synchronous orbit), so as to enable sequential Earth swing-by.
    - Keep the orbit eccentricity to be smaller than 0.3 from the point of the thermal design.

Major Assumptions on SEP Option Study (Launch Date)

The Solar equatorial plane tilts from the ecliptic plane by 7.25deg (not negligible angle). Launch date is selected considering this geometry.



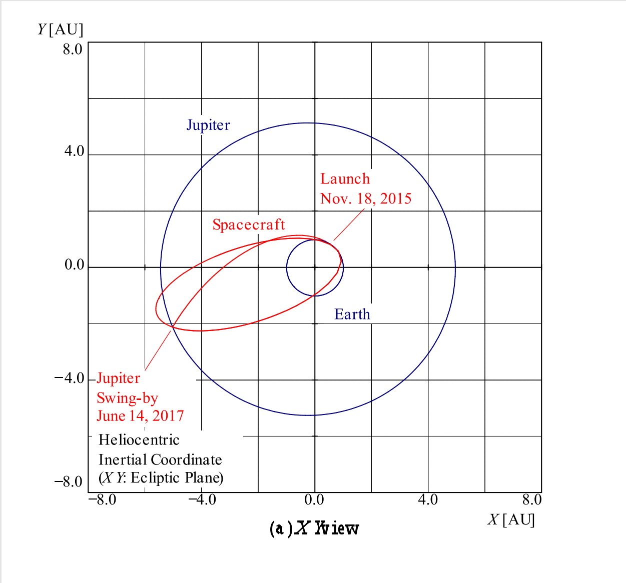
Solar Equatorial Plane and Spacecraft Orbit Plane

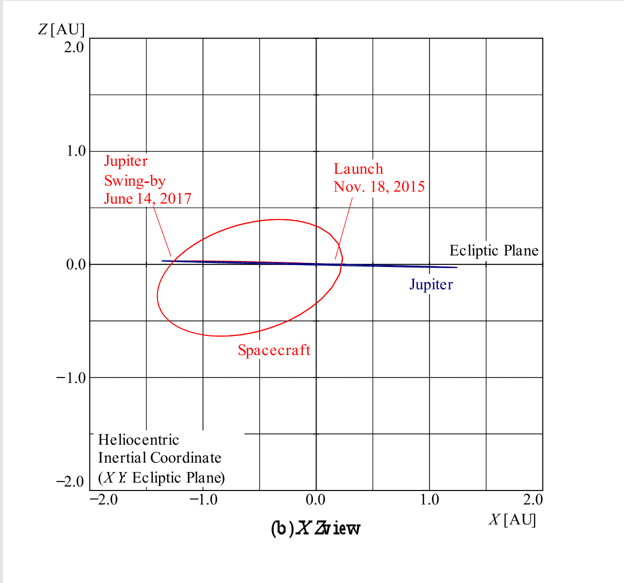


Launch Date Selection

Possible launch dates considering the tilt of the Sun rotation axis are **June 7** and December 8.

Jupiter-1 (use Jupiter gravity assist)

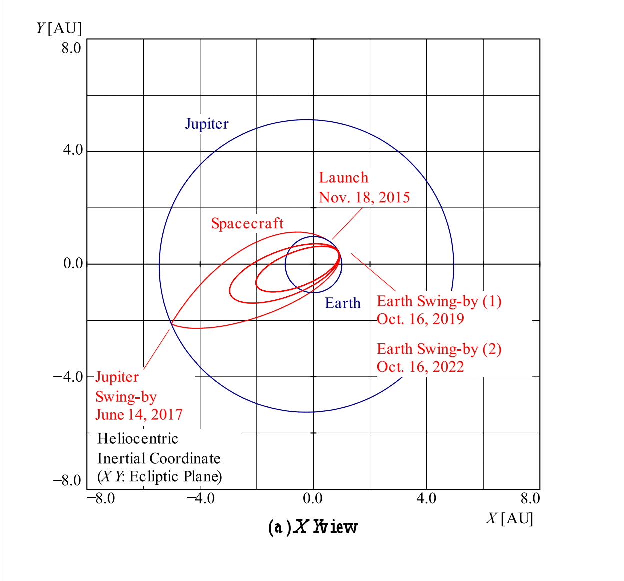


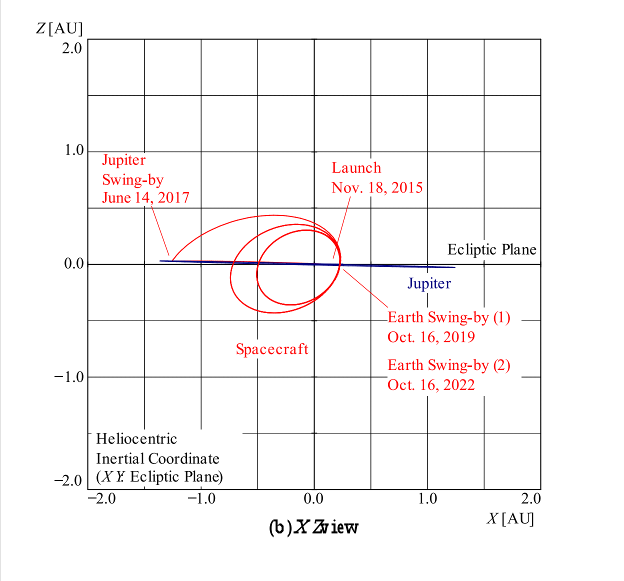


Orbit profile of the sequence

- Basic Strategy of **Jupiter-1**
  - Use the Jupiter gravity assist for the orbit plane change.
  - Just as Ulysses mission.

Jupiter-2 (use the Jupiter gravity assist + the Earth gravity assists)





Orbit profile of the sequence

➢Basic Strategy of **Jupiter-2**

- Use the Jupiter gravity assist for the orbit plane change.
- Use the additional Earth gravity assists to shorten the period of the observation orbit.

Major Assumptions on the Jupiter Option Study

- **Launcher**
  - H2A202 + upper stage
  - Injection v_∞ 10.2km/s (to reach Jupiter)

    (It is not the minimum v_∞ to reach Jupiter, however, to achieve high inclination after the Jupiter swing-by, this v_∞ is required.)

- **Spacecraft Specification**
  - Initial Mass 604kg (for v_∞ of 10.2km/s)

- **Swing-by Condition**
  - Jupiter
    - Minimum distance 6 R_J (equivalent to that of Ulysses)
  - Earth
    - Minimum distance ≈1.2 R_E

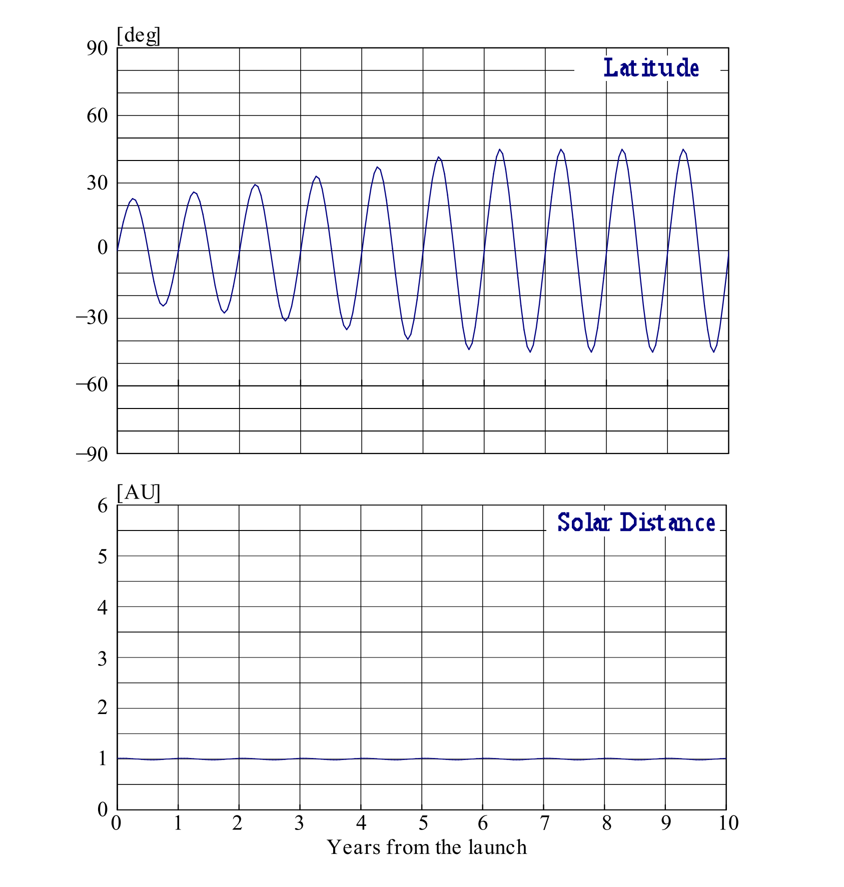
Characteristics of the Options

SEP-1 (use SEP, simply increase inclination)

Mass Budget Example

Item			Mass [kg]	Comments
Total			1200.0	Total Mass
	Dry		737.6	Dry Mass
		Bus	609.0	Bus System
		Mission	100.0	Mission Instruments
	Propellant		516.6	Propellant
	Margin		-54.2	Margin

- Problems (to be solved)
  - Minus margin in the mass budget.
  - Launch constraints not yet considered.
    (The consideration may degrade the performance)
  - Long operation time of the ion engine.
- Options (to enhance the feasibility)
  - Usage of the larger launcher.
  - Lower the target latitude.
    (Reduction to Lat. 30deg. yields 250kg plus margin.)
  - Tuning of the ion engine specification.



Latitude & Solar Distance Profile

SEP-2 (use SEP, combined with the Earth gravity assist)

Mass Budget Example

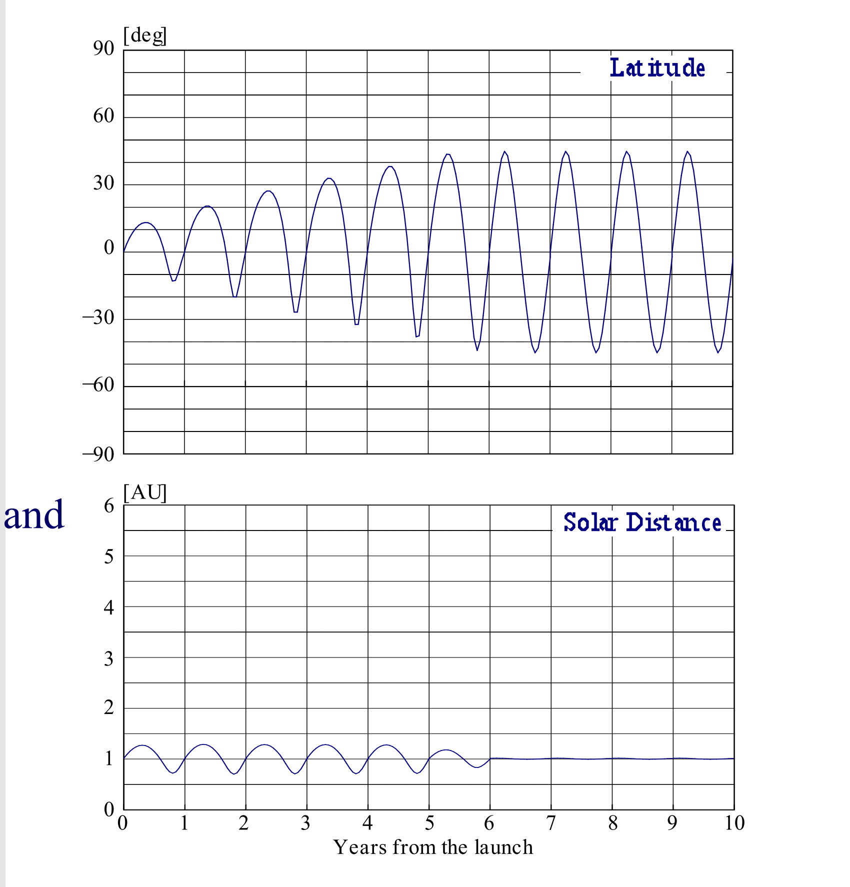
Item	Mass [kg]	Comments
Total	**1200.0**	Total Mass
Dry	708.2	Dry Mass
Bus	608.2	Bus System
Mission	100.0	Mission Instruments
Propellant	398.7	Propellant
Margin	**93.1**	Margin

➢Problems (to be solved)

- Spacecraft system design.
  (Geometrical relation between the Sun, the Earth, and the probe changes largely.)

➢Options (to enhance the feasibility)

- Usage of the larger launcher.
- Tuning of the ion engine specification.
- Tuning of the trajectory design condition.
  (e.g. constraints as to the thrust direction)
- Usage of the Venus swing-by.
  (Instead, the launch opportunity is restricted.)



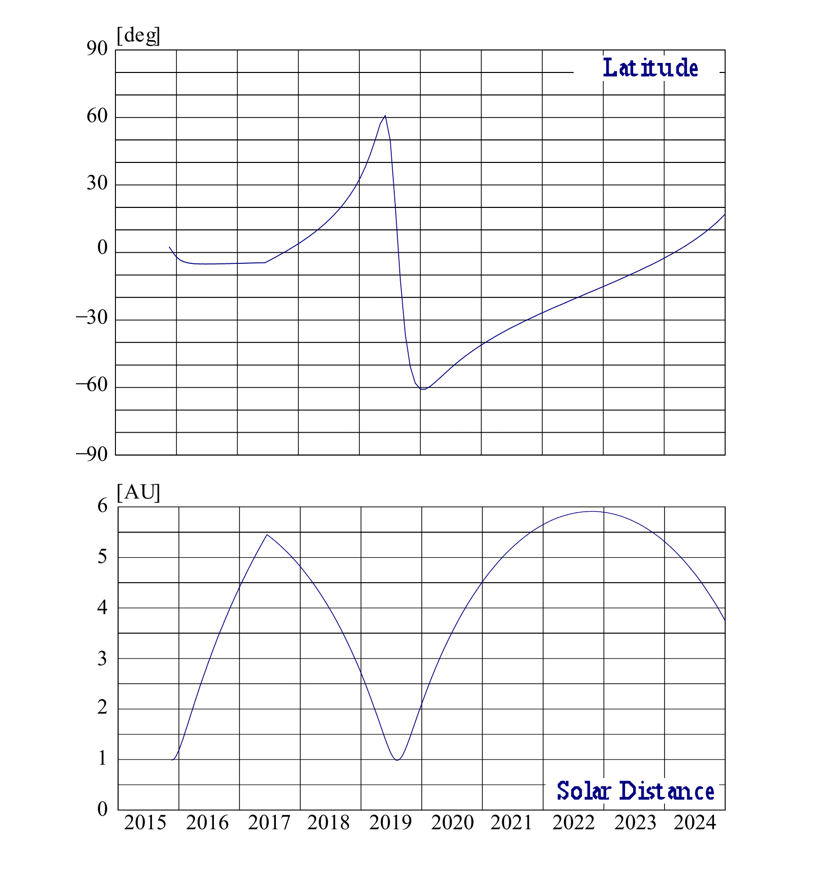
Latitude & Solar Distance Profile

Jupiter-1 (use Jupiter gravity assist)

Mass Budget Example

Item	Mass [kg]	Comments
Total	**604.0**	Total Mass
Dry	573.2	Dry Mass
Bus	473.2	Bus System
Mission	100.0	Mission Instruments
Propellant	30.0	Propellant
Margin	**0.8**	Margin

- **Problems** (to be solved)
  - Zero margin in the mass budget.
  - Radiation environment at the Jupiter swing-by.
  - Long observation interval.
- **Options** (to enhance the feasibility)
  - Usage of the larger launcher.
  - Tuning of the trajectory design condition.
- **Note**
  - Launch opportunity is once / 1.3year.
    (Synodic period between the Jupiter and the Earth is about 400days.)



Latitude & Solar Distance Profile

Jupiter-2 (use the Jupiter gravity assist + the Earth gravity assists)

Mass Budget Example

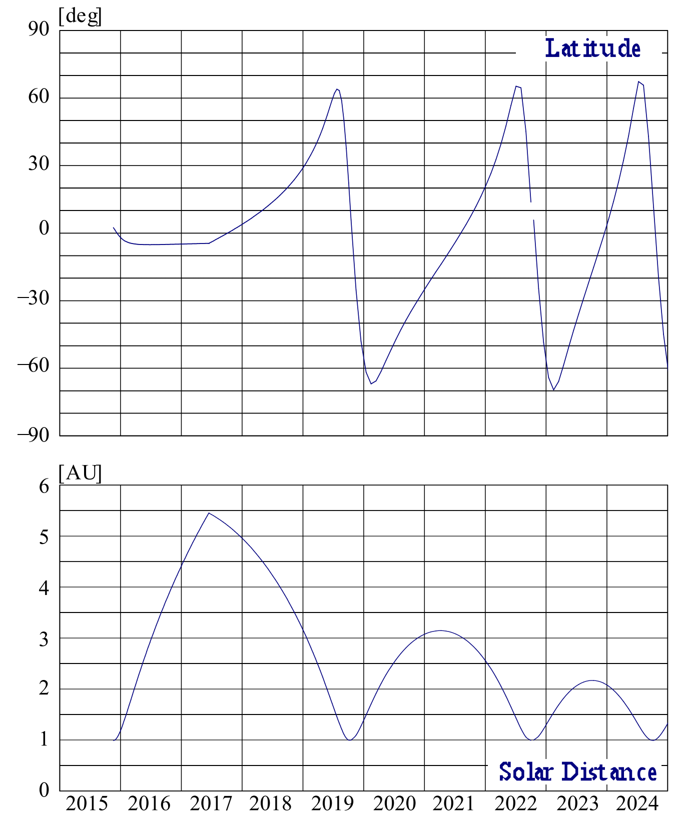
Item			Mass [kg]	Comments
Total			**604.0**	Total Mass
	Dry		573.2	Dry Mass
		Bus	473.2	Bus System
		Mission	100.0	Mission Instruments
	Propellant		30.0	Propellant
	Margin		**0.8**	Margin

➢Problems (to be solved)

- Zero margin in the mass budget.
- Radiation environment at the Jupiter swing-by.
- Trajectory correction after the Earth/Jupiter swing-by may be severe.

➢Options (to enhance the feasibility)

- Usage of the larger launcher.
- Tuning of the trajectory design condition.



Latitude & Solar Distance Profile

Observations and Discussions

- Usage of the Solar Electric Propulsion (SEP option)
  - Two options (**SEP-1**, **SEP-2**) have their own problems, and their feasibility is not clear at this stage.
  - However, it seems to be a feasible solution between these options, if it is combined with the careful tuning of the spacecraft design, the operation plan, and the mission requirement.
  - To be conservative, at least Lat. 30deg. seems to be achievable.

- Usage of the Jupiter Gravity Assist (Jupiter option)
  - Basically, **Jupiter option** has a disadvantage of the "long observation interval" compared to **SEP option**. The usage of the Earth swing-by (**Jupiter-2**) may relax this problem.
  - If it is acceptable, further study should be done focusing on the spacecraft design to survival around the Jupiter (power supply, radiation environment).
  - There may be a feasible solution, if it is combined with the adoption of the larger launcher.

Summary

- Possible trajectory/orbit options are studied which satisfy the mission requirement of Solar-C Plan-A. The requirement assumed is "To reach Lat. 45deg. of the Sun".

- Two possible options of the trajectory sequence are proposed. They are,
  - Usage of the Solar Electric Propulsion (**SEP option**)
  - Usage of the Jupiter Gravity Assist (**Jupiter option**)

- Examples of the trajectory design results are provided with the related information for the comparison between the options.

- Observations on the results and the points of the discussion are provided (in the previous slide).

End