A study of the Guidance Method for the Small Solar Power Sail Demonstrator, IKAROS

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Abstract: *We present the guidance approach for the Small Solar Power Sail Demonstrator, IKAROS. This approach will be used for future solar sail missions. First, we show the range of orbital controllability, which is severely restricted by the attitude constraint from the power and communication. Second, we also present the adaptive guidance method, in which guidance parameters are updated based on the estimation of the spacecraft's parameters such as the area and reflectivity coefficient of the sail. Finally, we evaluate the guidance approach performance by comparing to flight data of IKAROS.*

Keywords: *Solar Sail, Adaptive Guidance, Parameter Estimation.*

1 Introduction

The Small Solar Power Sail Demonstrator "IKAROS" was launched on May 21st, 2010 by the Japanese H2A rocket from Tanegashima site with the Venus orbiter "Akatsuki" [1]. One objective of the IKAROS mission is acquiring the skills of solar sail's guidance by using the solar radiation pressure actively. This approach will be used for future solar power sail missions.

Although the solar sail generally enable travelling space without propellant, the controllability is restricted because the solar radiation pressure is too small. Moreover, the errors of the parameter estimation of the solar sail are large since the reflectivity of the sail has large uncertainties due to the wrinkles of its thin membrane, and the area of the sail is also uncertain because the membrane is flexible structure. Furthermore, the attitude is constrained from the power and communication requirements severely in the IKAROS mission.

Under above-mentioned conditions, we propose the guidance approach for IKAROS to the target point. First, we show the range of orbital controllability, which is restricted by the attitude constraint. Second, we also show the updating guidance method, which is improved by the estimation accuracy of parameters, such as the area and reflectivity coefficient of the sail. Finally, the actual flight data of IKAROS is also presented.

2. Dynamical Model

2.1 Equations of Motion

In this study, we assume the perturbing force of the eight planets, Pluto and moon for a sail motion because we need a precise propagator to handle with the tiny acceleration by the solar radiation pressure. Supposing that the solar sail is a plane model, the equations of motion in the J2000EQ system are expressed as,

$$\frac{d^2\boldsymbol{r}}{dt^2} = -\frac{\mu}{r^3}\boldsymbol{r} + \sum_{k=1}^{n}\mu_k\left(\frac{\boldsymbol{r}_k - \boldsymbol{r}}{\left|\boldsymbol{r}_k - \boldsymbol{r}\right|^3} - \frac{\boldsymbol{r}_k}{\boldsymbol{r}_k^3}\right) + a_{SRP} \tag{1}$$

$$a_{SRP} = P\frac{1AU^2}{r^2}\frac{A}{m}\cos\alpha\left[(1-\varepsilon)\boldsymbol{e} + (2\varepsilon\cos\alpha + \frac{2}{3}\tau)\boldsymbol{n}\right] \tag{2}$$

where r is a distance between the Sun and the solar sail spacecraft, r_k is the distance between planet k and spacecraft, μ_k is the gravitational parameter of the planet k, P is the solar constant, A is the sail area, m is the mass of S/C, ε and τ are the specular and diffusive coefficients, $\boldsymbol{e}$ is the direction from the spacecraft to the Sun, $\boldsymbol{n}$ is the direction of the sail spin axis, α is the sun angle between $\boldsymbol{n}$ and $\boldsymbol{e}$. Moreover, β_{in} and β_{out} are the sun angle of in-plane and out of plane, respectively (see Fig. 1).

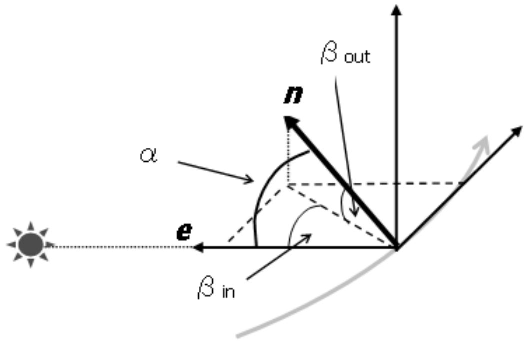

Figure 1. Definition of Angles

2.2. IKAROS Parameters and Mission Constraints

The following are the initial IKAROS parameters obtained by the ground test before launch. These parameters are changed and deteriorated after launch, thus we have to update the value of them by the parameter estimation during mission.

Table 1. IKAROS initial parameters (Plane model)

Mass (*m*)	307 kg
Area (*A*)	184.1 m^2
Specular coefficient (ε)	0.819
Diffusive coefficient (τ)	0.062

3. Definition of the IKAROS Guidance

In the IKAROS mission, we guide the spacecraft to the target point in the B-plane (target plane) of Venus by changing the attitude of the solar sail (β_{in} and β_{out}) using the reaction control system (RCS) [2] and the new thin film reflectivity control device (RCD) [3].

3.1 Equations of Motion

Although the guidance is conducted by changing the attitude of the solar sail, the direction of the attitude is limited due to the power and communication [4]. Figure 2 shows the sun angle between the spin axis and the Sun (to be exact, β_{in}) against the time from launch. The sun angle should be within the two lines of “Power acceptable range”. On the other hand, the contour indicates the Earth angle between the spin axis and the Earth. The region B in Fig. 2 represents the no-link region where we can’t communicate with IKAROS because the antenna causes interference at this time. From the Fig. 2, the no-link region is inevitable during the mission. The central line of “nominal attitude” indicates the nominal .sequence of the sun angle

3.2 Guidance Schedule

For IKAROS mission, we have a normal operation of two-week unit from about one month after the launch to the Venus flyby. The first one week is for the attitude control, and the last one week is for the orbital determination. Thereby, we attempt the IKAROS guidance seven times by dividing the mission duration into seven sections (the numbers in Fig. 2).

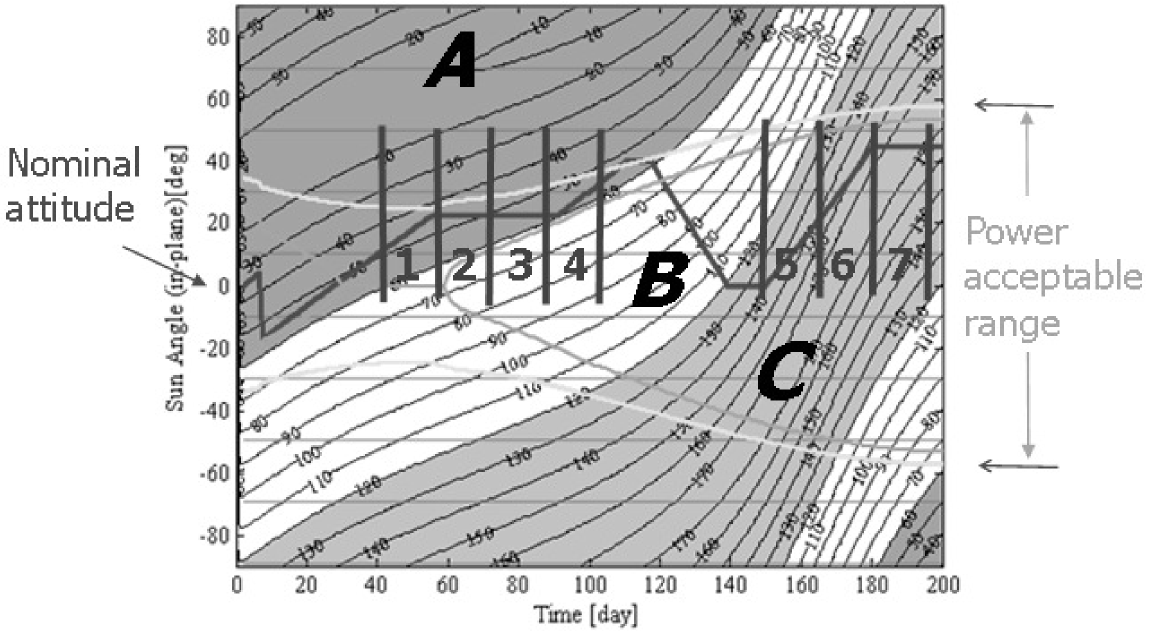

Figure 2. Sail attitude constraint

3.2 G B-plane (Target plane)

The target point is set on the B-plane of Venus in this study (See Fig. 3). The B-plane passes through Venus and is perpendicular to the incoming asymptote of the hyperbolic trajectory (i.e., perpendicular to $\vec{V}_{\infty,in}$). The B-parameter consists of BT and BR direction. The BT direction is parallel to the ecliptic plane, and BR direction is defined by $\vec{V}_{\infty,in} \times \vec{BT}$. The IKAROS spacecraft is guided to the target point on the B-plane by changing its attitude.

Next, to evaluate the guidance approach not only at the final B-plane crossing but also at the each section, here we define the *Estimated point*. The tics in Fig. 3 are points that pass through the B-plane assuming propagating with the solar radiation pressure from the deployment of the IKAROS's membrane to a certain time, and then propagating as the ballistic flight until the B-plane. These points denote the *Estimated point*. (That is, the left upper point is the point assuming ballistic flight whole duration and the right below point is the point assuming the motion considering solar radiation pressure whole duration) The estimated points are plotted every 10 days and every above-mentioned sections in Fig. 3, assuming the nominal sun angle.

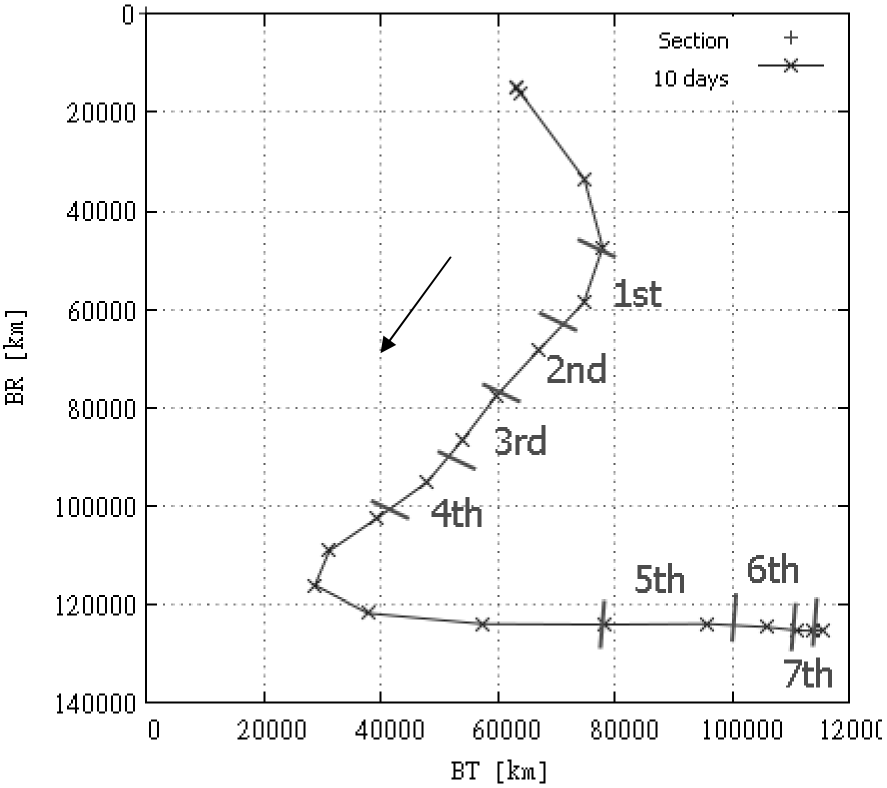

Figure 3. Nominal pass point on the B-plane

4. IKAROS Guidance Strategy

In general, the controllability of the solar sail is tiny compared to the conventional orbital control because the solar radiation pressure is too small. In this chapter, the characteristics of the IKAROS guidance are shown, and the guidance strategy is proposed.

4-1. Controllability on the B-plane

For the guidance, we can change the attitude within the acceptable range of the constraints from the nominal attitude for guidance. According to the Fig. 2, the attitude constraint is severe particularly before the no-link region, but after the no-link region the constraint is relaxed. Therefore, we can change the attitude largely after no-link region relatively. On the basis of these facts, we analyze the range of the orbit control of IKAROS in the B-plane.

Figure 4 shows the sensitivity analysis of the controllability of the B-parameter due to changes of the β_{in} and β_{out} from the nominal angle at every section, in particular the small change of ± 1 deg was applied before the no-link region while the large change of ± 15 deg after the no-link region. We can say that the controllability after the no-link region is larger than that before the no-link region even though it doesn't have enough time to get to the B-plane.

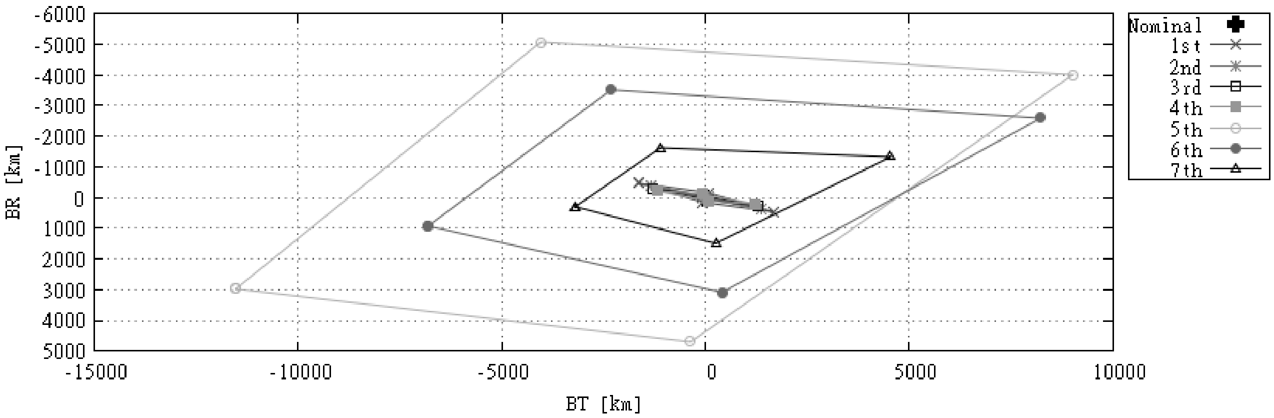

Figure 4. Controllability at each section

4-2. Impact on the uncertainty of IKAROS parameters

Second, we investigate the impact of the parameter errors of the IKAROS's solar sail.

Figures 5 and 6 show the displacements of the B-parameter from the nominal point due to the error of the sail area and specular coefficient, respectively. The numbers in the figures represent each section, and the grey quadrangle in the middle of the figure indicates the controllability of the B-parameter at the first section as mentioned before. It was found that the displacements due to the error of the sail area and specular coefficient are large, especially to the BR direction, compared to the controllability at the first section. Therefore, it is better to guide primarily after improving the accuracy of the parameter estimation in the latter part of the transfer.

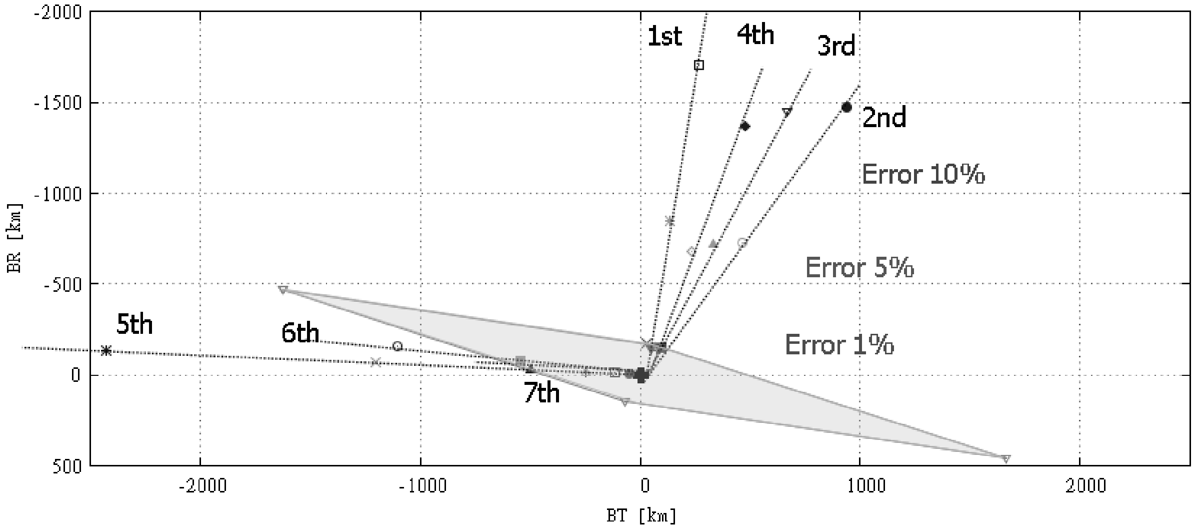

Figure 5. Impact of the error of the sail area

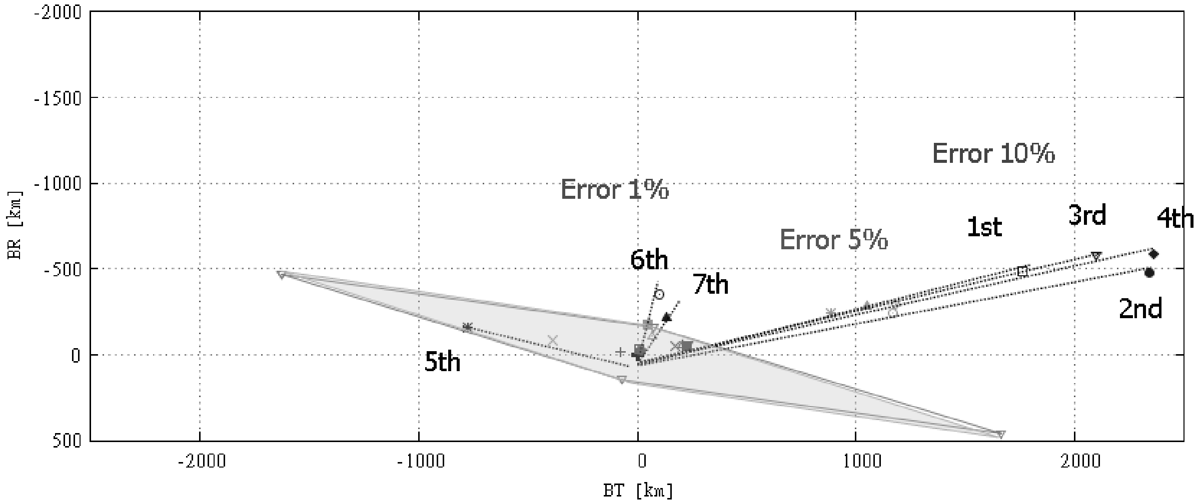

Figure 6. Impact of the error of specular coefficient

4-3. Impact on the IKAROS RCS to Change the Attitude

Next, we investigate the impact of the RCS of the IKAROS. To change the IKAROS attitude, one of ways is to use the RCS (500 mN thruster×2)[2]. However, the translational force Δv_{RCS} is occurred at every maneuver, expressed as,

$$\Delta v_{RCS} = \frac{T \times 2}{\dot{m}} \ln \frac{m}{m - \dot{m}\Delta t} \tag{3}$$

where T is the thrust force per thruster, m is the massof the spacecraft, $\dot{m}$ is the mass of the consumed propellant per maneuver, and Δt is the length of a maneuver.

Figure 7 shows the displacement in the B-plane due to the Δv_{RCS} arising from the 100 times maneuver at each section. The grey quadrangle in the middle of the figure indicates the controllability at the first section again. At a certain time during the mission, we need about 100 times RCS maneuvers to change the attitude of one deg. According to the Fig. 7, the displacement due to the RCS is not small with respect to the controllability of the attitude change. Thereby, we have to take into account the displacement of the RCS for the guidance when changing the attitude by the RCS.

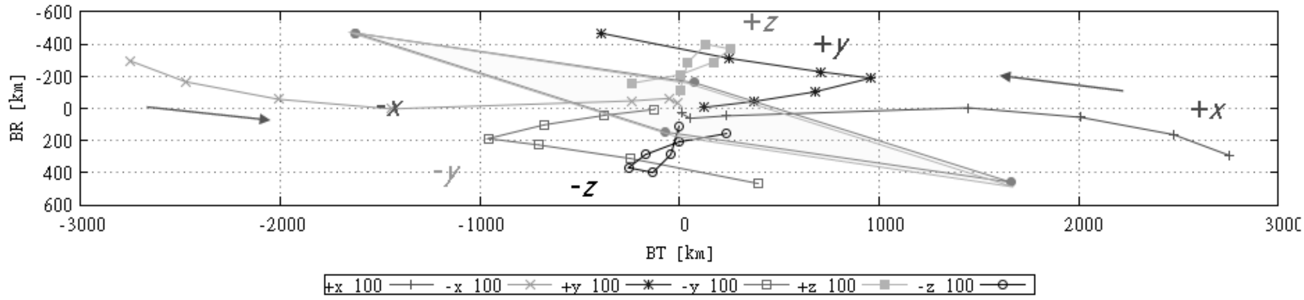

Figure 7. Impact of the RCS

4-4 Guidance Strategy

Based on the above-mentioned investigation, we discuss here the adaptive guidance method for IKAROS mission.

Before launch, the total displacement due to the error of the parameter estimation is greater than the total controllability for IKAROS mission. Thus, we can't set the final target until the uncertainties are reduced by Orbital determination (OD). However, by improving the accuracy of the sail parameter estimation at each section, we refine the guidance accuracy and set the final target at the B-plane (see Fig .8). In this way, we guide the IKAROS to the target point mainly after the no-link region, taking into account the impact of Δv_{RCS}.

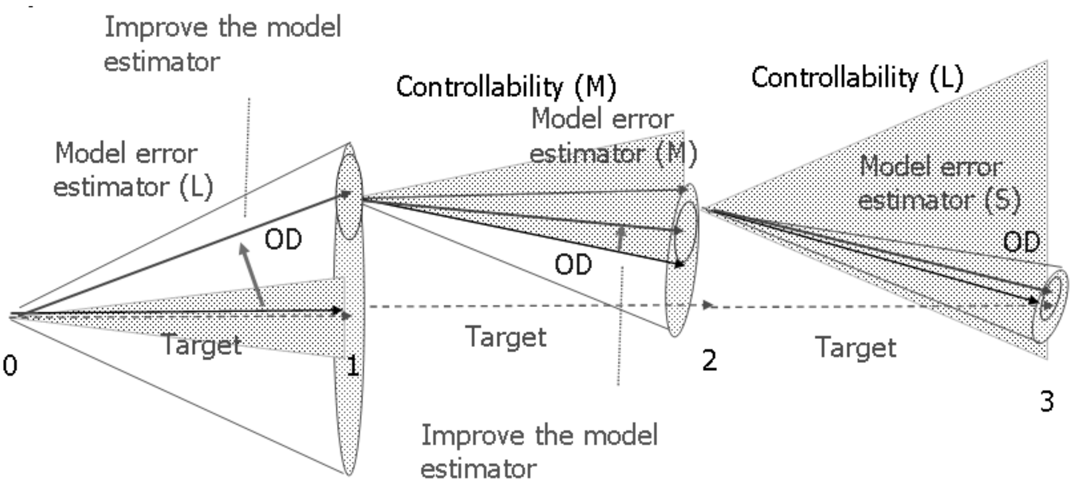

Figure 8. Strategy of the adaptive guidance method

5. Flight Data

In this chapter we evaluate our adaptive guidance approach, compared with the flight data.

The point in the lower right of Fig. 9, *E1,* represents the estimated point in the B-plane on June 13th using the initial IKAROS parameters. On the other hand, the point in the vicinity on the left upper of the *E1*, *OD1*, is the data from the orbital determination. The difference between *E1* and *OD1* is about 2000 km. To improve the parameters, the parameters are changed as the *E1* corresponds to *OD1*. Next, in Fig. 10, the point *E2* is the estimated point on July 5th using the new updating parameters, and *OD2* is the result form the orbital determination. In this case, the difference between *E2* and *OD2* decrease, about 800 km. Thus, we can say that the accuracy of parameter estimation increases. In this way, we refine the parameter estimation gradually.

Next, we discuss the result of the guidance from July 5th to July 17th. In the Fig. 11, the point *N1* is the nominal estimated point, and *T1* is the target point considering the controllability of the SRP and the displacement due to the RCS. To guide the spacecraft to the *T1*, as shown in Fig. 12, the β_{in} and β_{out} are changed from the nominal angle (dot lines) by using the RCS. Table 2 represents the number of the RCS maneuvers to change the IKAROS attitude for the guidance. As a result, *OD3* in Fig. 11 is the data from the orbital determination. As a result, we can say that we could guide the IKAROS to the target point with several thousand kilometers accuracy.

Finally, Fig. 13 shows the guidance results for the six attempts. The points on the line indicate the target points at each time, and the others are data from the orbit determination. In these attempts, we conducted the guidance to an accuracy of several thousand kilometers.

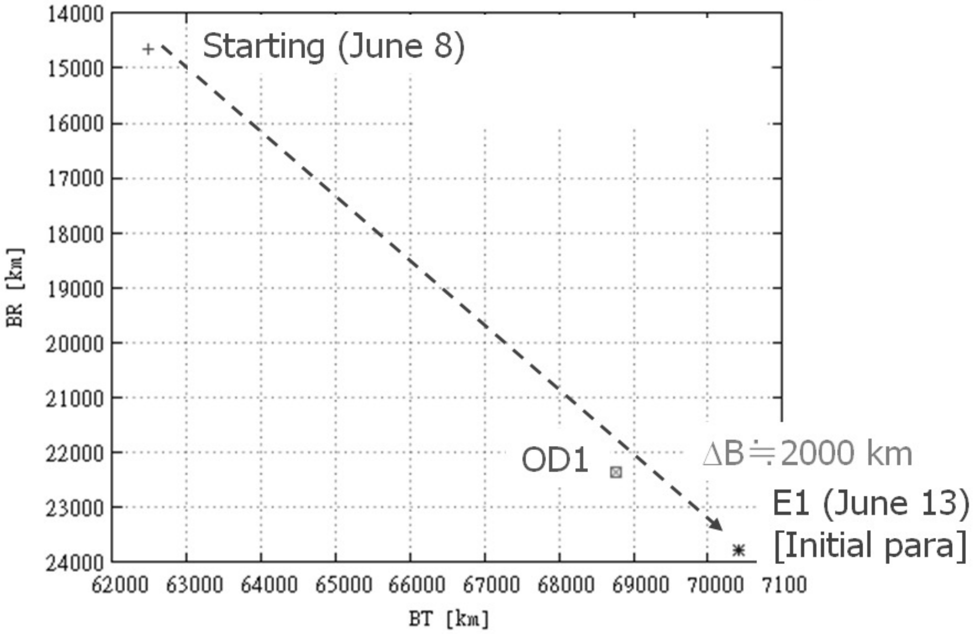

Figure 9. Update the parameters #1

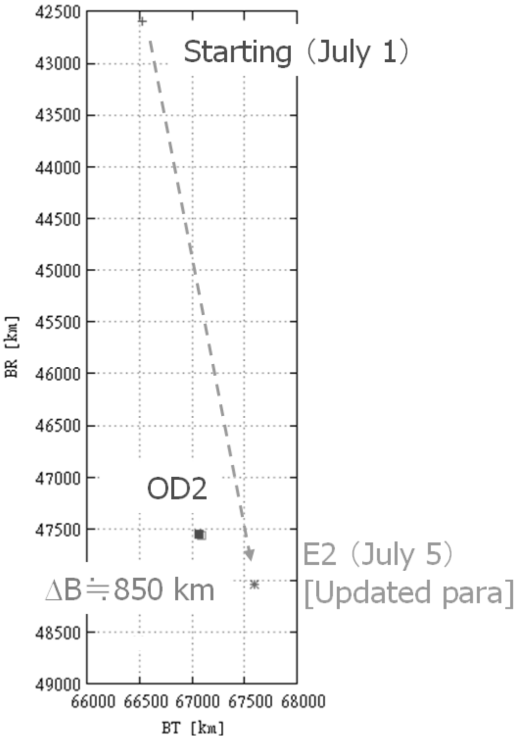

Figure 10. Update the parameters #2

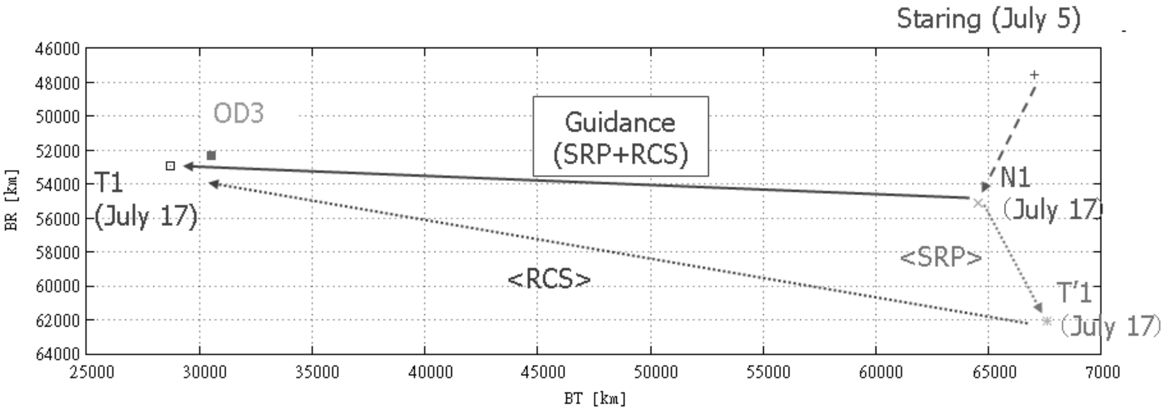

Figure 11. Guidance Results

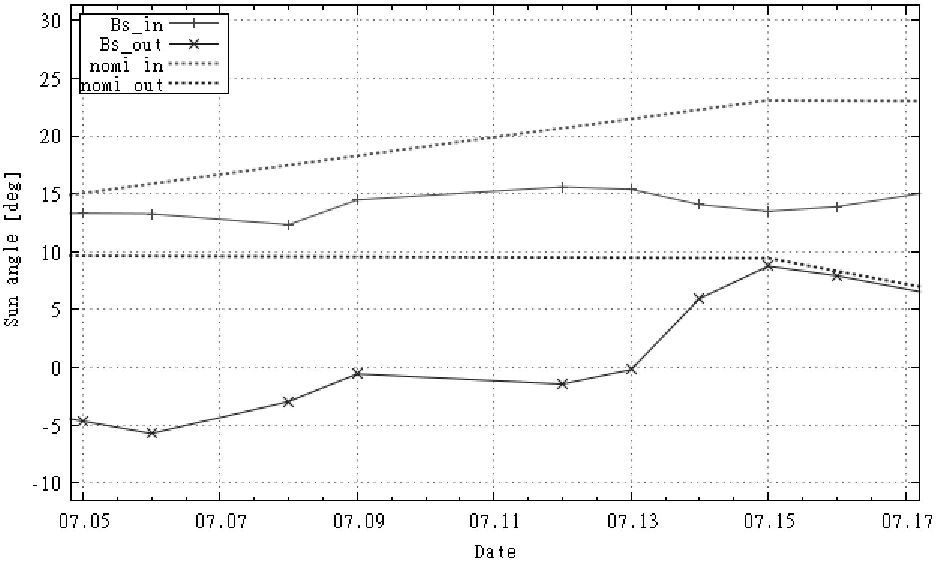

Figure 12. Change of the Sun Angle for the Guidance

Table 2 Number of the RCS Maneuvers

Date	Num of Maneuver
July 7	300
July 8	300
July 9	200
July 12	245
July 14	300
July 15	300

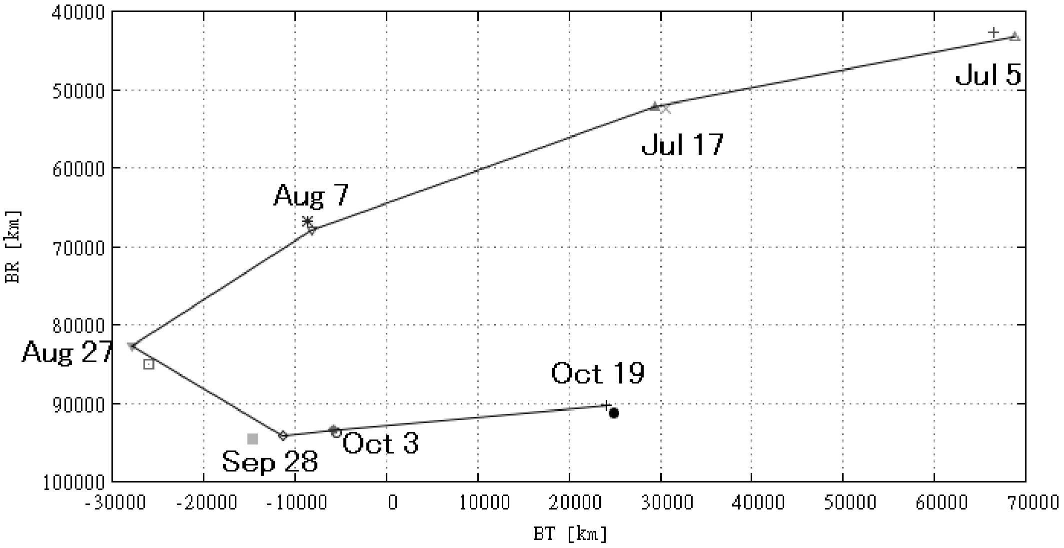

Figure 13. Guidance History

6. Conclusions

In this study, we have discussed the guidance approach for the solar power sail IKAROS mission. First, the range of the orbital controllability on the B-plane, taking account for the attitude constraints, was investigated. As a result, we made a plan to guide the IKAROS spacecraft mainly after the no-link region. Furthermore, according to the analysis of the impact on the uncertainty of the parameters, we should conduct the guidance after improving the accuracy of the parameter estimation. Finally we have evaluated the guidance approach using the flight data. We can conclude that the IKAROS is guide to the target point within several thousands kilometers accuracy.

7. References

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