Orbit Planning of IKAROS by using Attitude Drift Motion

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Abstract

The world's first small solar power sail IKAROS steadily continues sailing in the deep space. The trajectory of IKAROS can be controlled by changing its spin axis direction, and we accumulate the achievement of the orbit control of the actual solar sail. Moreover, in the future, we plan to control the IKAROS orbit by controlling its spin rate, instead of changing the spin axis direction directly. This is possible when applying the attitude drift motion induced by the solar radiation pressure torque. In this study, we propose the orbit plan by means of this novel orbit control method of the spinning solar sail.

姿勢のドリフト運動を利用した IKAROS の軌道計画

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摘要

世界初の小型ソーラー電力セイル IKAROS は現在も順調に深宇宙を航海中である．IKAROS の軌道は，探査機の姿勢（スピン軸）を変更することにより制御することが可能であり，これまでにスピン軸を制御することによる軌道制御の実績を積み上げてきた．そのため今後は，スピン軸を直接制御するのではなく，光圧による姿勢のドリフト運動を利用し，スピンレートを制御することにより軌道制御を行うという，新たな軌道制御手法を用いて誘導・制御実験を行うことを計画している．本研究では，その軌道制御手法と，それを用いた IKAROS の今後の軌道計画案を提示する．

1. Introduction

IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun, shown in Fig. 1) was launched on 21st of May in 2010[1)] and is still operated at the present time. The orbit of IKAROS is nominally controlled by changing the orientation of the sail membrane by means of the rhumb-line control method[2)]. By utilizing the solar radiation torque, however, we are able to change the direction of the spin-axis only by controlling its spin rate. In the IKAROS operation, the attitude drift motion around Sun direction has been observed. In this motion, the spin-axis direction traces the Sun direction automatically[3)], and we figured out this motion is influenced by the spin rate. This Sun-tracing motion is extremely useful in terms of the power supply, because the spacecraft can obtain the power from sunlight without the attitude maneuver (the solar array panels are mounted on the top plate). We apply this attitude drift motion to several operations (mainly Sun pointing).

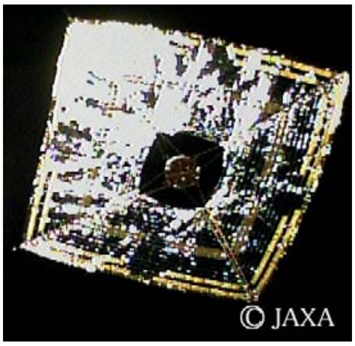

Fig. 1. Solar power sail IKAROS

As one of these operations, we also apply this motion to the orbit control of IKAROS. In the recent operation, we conduct the guidance, navigation and control experiment of IKAROS. In this paper, we introduce to the IKAROS's guidance operation and show the results of the flight experiment.

2. IKAROS Characteristics

The solar sail demonstration spacecraft IKAROS investigated by JAXA has the cylindrical body and the square sail membrane as shown in Fig. 1. This spacecraft was launched on 21st May 2010 as the sub-payload of the PLANET-C; the Venus climate orbiter (which is also developed by JAXA). On 9th June 2010, IKAROS finally succeeded to deploy the membrane in deep space to become the world's first operational solar sail, and at present it is in the optional operation phase after nominal operation phase. The main specifications of IKAROS are summarized in Table 1.

The sail membrane of IKAROS consists of 7.5μm Polyimide and it is evaporated by aluminum in 80 [nm] thickness[4)]. A polyimide has the high thermal, mechanical and chemical resistance properties and is very light.

Although the specular reflectivity of the membrane itself is relatively high due to the reflective properties of aluminum, the averaged specularity is degraded by several devices on the membrane. The main devices are the Flexible Solar Array (FSA)[5] and the Reflectivity Control Device (RCD). The FSA is a thin power collector. If the large power collection system using this FSA can be constructed, it would be possible to load the high power ion engine on a future solar sail spacecraft[6]. The RCD is mounted on the edge of the sail membrane, and it can generate a torque by changing the induced force on each small element's surface[7]. By using this RCD, the spacecraft would not need any propellant to control the attitude. Although the RCD has the capability to become a feasible attitude actuator in the future, it is one of the experimental instruments at the current stage. Therefore, IKAROS uses the gas-liquid equilibrium thrusters[8] as the nominal attitude actuator.

Table 1. Main Specifications of IKAROS

Parameter	Specification
Size of Membrane:	14 x 14 [m]
Material of Membrane:	Polyimide
Total Mass:	< 307 [kg]
Moment of Inertia:	(Ix, Iy, Iz) = (434, 434, 868) [kgm^2]
Specular Reflectivity:	0.719
Diffusive Reflectivity:	0.117
Absorptivity:	0.162
Attitude Control:	Spin
Attitude Actuator:	gas-liquid equilibrium thrusters

Figure 2 shows the orbit of the IKAROS after flyby of Venus on December 8, 2010 in the inertial coordinate system (left side) and the Sun-Earth fixed coordinate system (right side). As illustrated in Fig.2, IKAROS cruises in the elliptic orbit between Venus's and Earth' orbit, and IKAROS steadily go away from the Earth. Thus, the environment of the communication link is degraded as time ticks away, though it also depends to the Earth cone angle. This constraint due to the communication link limits the direction of the spin-axis with respect to the Earth direction, and it means that the trajectory is also limited. Therefore, this degradation of the communication condition critically influences the direction of the attitude maneuver in the actual operation.

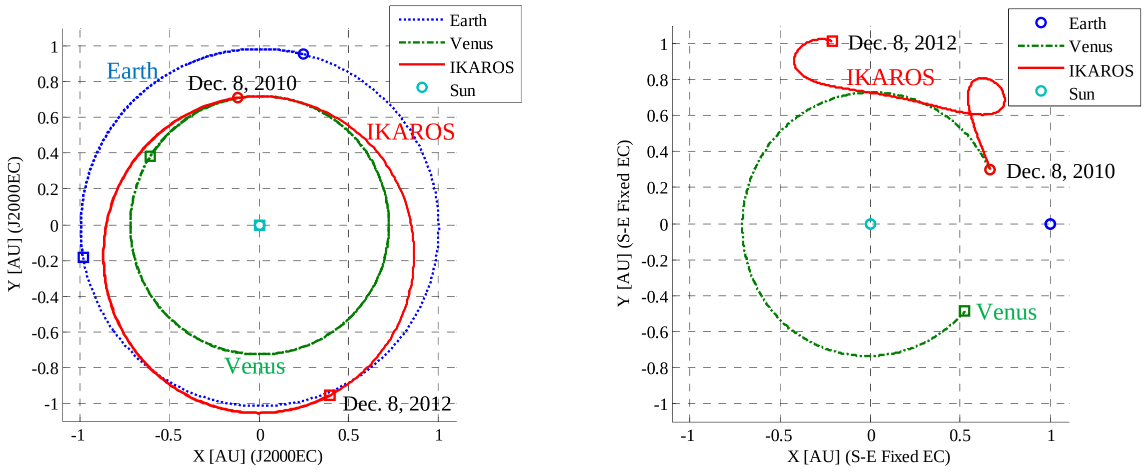

Fig. 2. Trajectory of IKAROS after Venus Flyby on Dec. 8, 2010

3. Definition of Coordinate System

In this paper, we use mainly two coordinate systems. One is the Sun-pointing frame for the attitude expression. The origin of this Sun-pointing frame is the center of the mass of spacecraft. The x-axis lie on the orbit plane, the y-axis is normal to the orbit plane, and z-axis points the Sun-direction. The definition is illustrated on Fig. 3.

The other coordinate system is the virtual B-plane frame. In general, the B-plane is defined with respect to the objective planet. For the IKAROS, however, there is no objective celestial body in the near future. Therefore, we choose a certain time-fixed point on the planed orbit and define this point as the origin of the virtual B-plane. Once we decide the time point, the origin of this frame is determined. The x-axis is defined as the velocity direction at that time point, z-axis is the normal direction to the orbit plane, and y-axis is defined as the right-handed coordinate system.

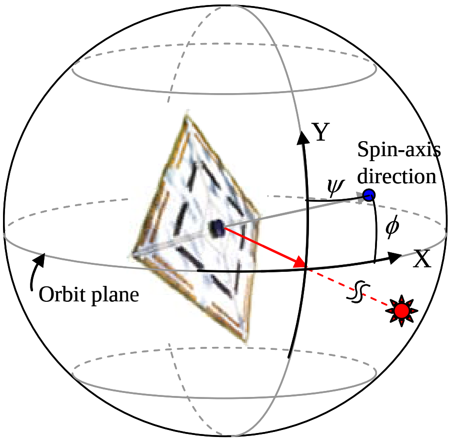

Fig.3 Definition of Sun-pointing frame

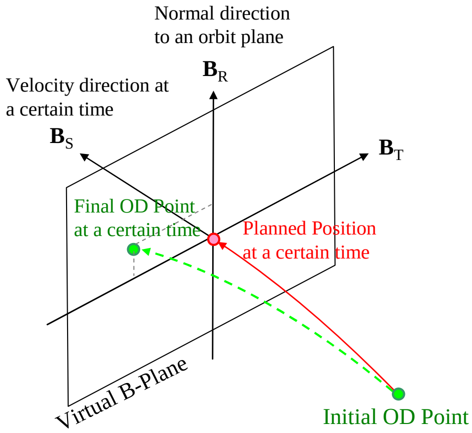

Fig.4 Definition of virtual B-plane frame

3. Relationship between Acceleration and Attitude

The orbit of a solar sail is controlled by the normal pointing direction of the membrane. This is because the acceleration due to the solar radiation pressure (SRP) is a function of the Sun angle β_s and the normal direction vector **n**. The acceleration model is described as follow under the assumption that the normal direction of each membrane segment is aligned with a certain direction in total, and the membrane area is given;

$$\mathbf{a} = -\frac{P_0 A}{mc}\left(\frac{R_0}{r}\right)^2 (\cos\beta_s)\{(c_{abs} + c_{dif})\mathbf{s} + [\frac{2}{3}c_{dif} + 2c_{spe}(\cos\beta_s)]\mathbf{n}\} \qquad (1)$$

where R_0 denotes the distance between Sun and Earth (= 1 [AU]), r denotes the actual distance between the Sun and the spacecraft, c_{abs} denotes the absorptivity, c_{dif} denotes the diffusive reflectivity, c_{spe} denotes the specular reflectivity. The factor 2/3 in front of the c_{dif} is due to the assumed Lambertian diffuse reflection of the front surface, **s** and **n** denote the Sun direction vector and the normal vector, respectively. As described by Eq. (21), the acceleration induced by SRP force depends on the attitude of the spacecraft. Therefore the trajectory of the solar sail can be controlled with this SRP force by varying the spin-axis direction.

Considering the acceleration in the Sun-pointing frame (see Fig. 3), we can describe the components of the acceleration vector in Eq. (21) as follows;

$$\mathbf{a} = \frac{S_0 A}{mc}\left(\frac{R_0}{r}\right)^2 \begin{pmatrix} -(2/3c_{dif}\cos\beta_s + 2c_{spe}\cos^2\beta_s)\cos\phi\sin\psi \\ -(2/3c_{dif}\cos\beta_s + 2c_{spe}\cos^2\beta_s)\sin\phi \\ -(c_{abs} + c_{dif})\cos\beta_s - (2/3c_{dif}\cos\beta_s + 2c_{spe}\cos^2\beta_s)\cos\phi\cos\psi \end{pmatrix} \qquad (2)$$

with the Sun direction vector $\mathbf{s} = (0.0, 0.0, 1.0)^T$, the normal vector of the membrane $\mathbf{n} = (\cos\phi\sin\psi, \sin\phi, \cos\phi\cos\psi)^T$. This equation connects the acceleration with the attitude. More detail information about the orbit control method for the solar sail by applying the attitude drift motion is introduced in Reference 9).

4. Guidance Operation Plan

The guidance and control experiment of the IKAROS was planed twice during September in 2011. In this period, the Earth cone angle become almost 80 [deg] in the case that the spin axis direction is pointing to the Sun direction. Therefore the direction of the attitude maneuver is limited to the decreasing direction of the Earth cone angle. Moreover, we should take into account the attitude drift motion[10)] of IKAROS which has been seen since the sail membrane of IKAROS is deployed. This motion is occurred by the solar radiation pressure, and the spin-axis direction is finally converged into the attitude equilibrium point near the Sun direction (the detail is explained in Reference 10)). Therefore, in order to have a long period in the right side in Fig. 5, the attitude was planned to maneuver to the lower right side rather than just right side. As the result of several considerations, the aim attitude was planned as Fig. 5. In order to maximize the time to keep the attitude in the right side, the spin rate was also planned to increase as Fig. 6. This is because the rate of the attitude drift motion due to the solar radiation pressure is increased or decreased in inversely proportional to the spin rate. Therefore the spin-up was planned just after two large maneuvers. The first maneuver was planned on September 17 and the second maneuver was planned on September 27, and both were conducted as scheduled beforehand.

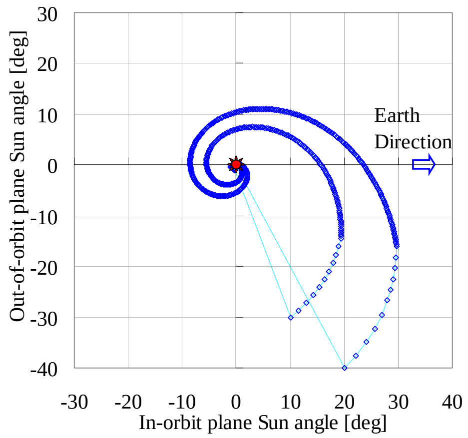

Fig. 5 Planned attitude before experiment

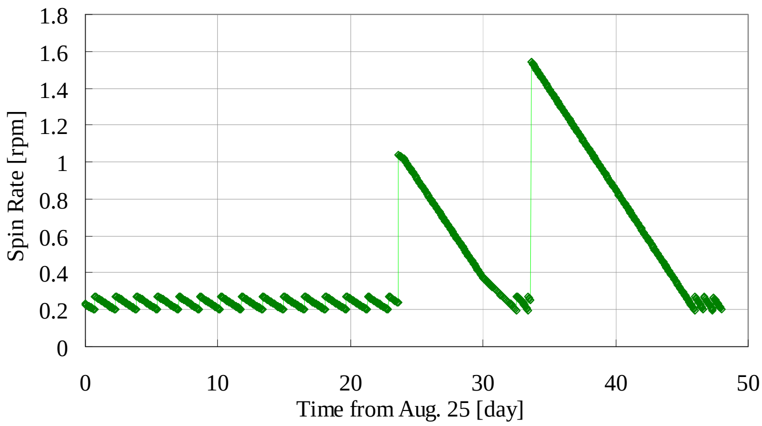

Fig.6 Planned spin rate history before experiment

5. Results of Flight Experiment

The results of flight experiment are shown in this section. The flight experiment for the guidance, navigation and control of the IKAROS was conducted from August 25 to October 11, 2011. The series of each event in the actual operation are summarized in Table 2. In this experiment period, the operations of the orbit determination were conducted four times as shown in Table 2 (but not available for the OD of 2011.09.22). Although the guidance and control were conducted based on these orbit data obtained from each orbit determination, the attitude of sail cannot be chosen arbitrarily under the reason explained in Chapter 4. In order to evaluate the attitude control capability, the training operation for the attitude maneuver was conducted on September 9. During the period from September 14 to 16, the spin-up was executed automatically by the Auto-Macro (ATMC). After the training for the attitude maneuver, the large maneuver operations were conducted on 17^{th} and 27^{th} of September.

Table 2. Operation events during Guidance and Control Experiment

Date	Event	Timing of OD
2011.08.25	Coasting	2011.08.25
2011.08.25 ~ 08.31	Spin-up	---
2011.08.31 ~ 09.03	3-pass Coasting	2011.09.03
2011.09.06	Training 1 for Attitude Maneuver	---
2011.09.10	Spin-up	---
2011.09.13	Small Attitude Maneuver	---
2011.09.14 ~ 09.16	Spin-up by ATMC	---
2011.09.17	Large Attitude Maneuver 1	---
2011.09.20 ~ 09.22	2-pass Coasting	(2011.09.22)
2011.09.24	Spin-up	---
2011.09.27	Large Attitude Maneuver 2	---
2011.09.29 ~ 10.11	4-pass Coasting	2011.09.28

5.1 Results of Attitude Control

The results of the attitude control in the guidance experiments are shown in Figs. 7 and 8. Figure 7 shows the predicted attitude evolution during experiment period. The attitude prediction is based on the estimated torque parameters from the attitude data (Sun cone angle and Earth cone angle). Therefore, this predicted attitude evolution is adequately close to the actual measured attitude within certain accuracy (the difference between determined and predicted data in Fig. 7). From this attitude evolution, it is obvious that the actual attitude stray away from the planned attitude points (purple diamonds at (10, -30) [deg] and (20, -40) [deg]). This is because the attitude maneuver operation was complicated due to several reasons as follows.

In this period, the Earth distance from the spacecraft is already about 0.9 [AU]. IKAROS has two Low Gain

Antennas (LGA), and Middle Gain Antenna (MGA). If we can use the MGA, there is no difficulty to communicate with IKAROS. Nevertheless, the MGA can only be used in the case that the Earth cone angle is within 30 [deg], and the Earth cone angle in this experiment period was from 70 to 80 [deg]. Therefore, we can use LGA only, and the effective bit-rate was 8 [bps] at most (beacon nominally) in the case that the spacecraft is 0.9 [AU] away from the Earth. As the result, the attitude information from the telemetry was hardly obtained online. Therefore, we controlled the spacecraft attitude by based on the coarse Sun cone angle from the beacon, and the Earth cone angle from the Doppler spin modulation[11] with 30 minutes delay. Because of this attitude information delay, the present attitude and the targeted attitude were hardly estimated and predicted in the operation. Therefore, the attitude control accuracy was extremely degraded in this guidance experience period.

Figure 8 shows the predicted spin rate. The rate of the spin rate is also estimated from the Doppler modulation in the every operation pass. As a consequence, the predicted spin rate is also close to the actual measured spin rate within certain accuracy (as shown in Fig. 8). As shown in Fig. 8, the spin rate is decreased naturally (remarkable from 25 to 37 days in Fig. 8). This phenomenon is called as a “windmill effect” and considered to be occurred due to the solar radiation pressure[10]. Because of this decrease of the spin rate, we have to compensate by the spin-up and it can be seen in the Fig. 8 that spin-up operation is conducted several times.

Although the attitude was not able to be controlled to the planned attitude points by two large attitude maneuvers, the attitude was able to change largely from the original points.

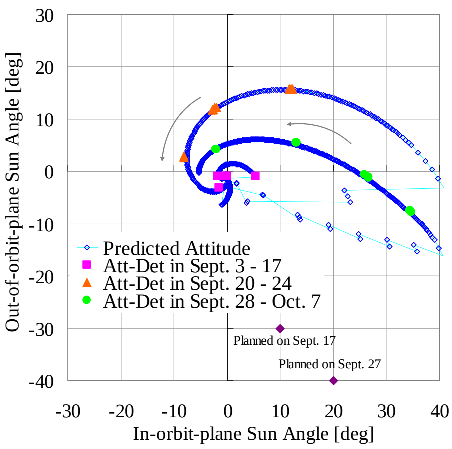

Fig. 7 Predicted attitude evolution

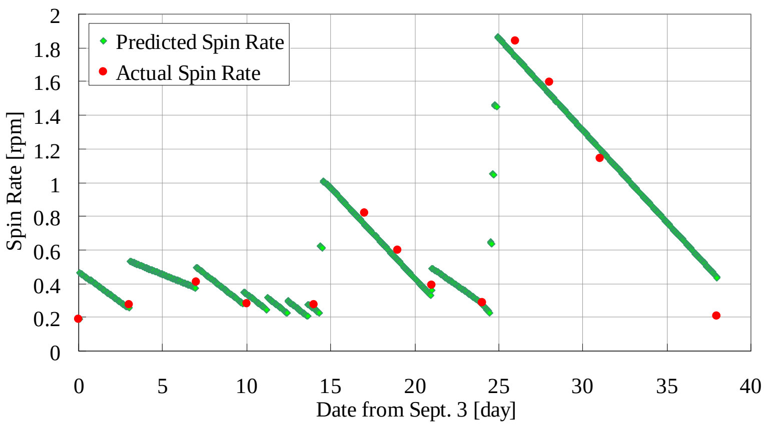

Fig.8 Predicted spin rate history

5.2 Results of Guidance and Navigation

The results of the guidance and navigation experiment are introduced in this section. Figure 9 explains the positions in the virtual B-plane. The positions and error ellipsoids in the virtual B-plane are propagated from each orbit determination point. The error ellipsoids in the virtual B-plane are not only based on the error covariance of the orbit determination, but also considered the parameters error of attitude, specular reflectivity, and the effective area of the sail membrane. The estimated positions in each orbit determination point have the implicit error which is not explicit in the covariance, but in the residual of the measurement. Therefore, we take into account the parameter errors. Because of these errors, although the dynamics model of the propagation and the attitude sequence are almost same in each propagation, the propagated positions are away from each other.

Figure 10 shows the projected positions on the virtual B-plane propagated from each orbit determination point. The origin of the virtual B-plane is defined as the propagated position from the initial orbit determination point (August 25) to October 11, 2011, with the planned attitude sequence. As shown in Fig. 10, the propagated positions are inside of the propagated error ellipsoid from the previous orbit determination point. This means that the navigation and guidance are properly performed within the considered error. In addition, the final orbit determination point (green rectangle) is close to the originally planned position (red circle). Although it seems that the guidance of the spacecraft is adequately performed, it almost accidentally gets close to the targeted position because the error of the attitude maneuver was large (as explained in section 5.1). The reason why the final position is close to the planned position is considered mainly due to the uncounted propulsion beforehand by the RCS. Because there were several attitude and spin rate control operations which are not taken into account when we planned the attitude maneuver. As the total effect of the attitude maneuver error and the uncounted propulsion, the final position get close to the planned position.

As the other information from Fig. 10, the final position of the case when the spacecraft control only the spin rate without attitude maneuver is shown in Fig. 10 (gray triangle). In this case, the attitude almost points to the Sun direction. Therefore, the attitude evolution is dramatically different from the actual operation cases. As the result, however, the final position in the virtual B-plane is close to the planned position and is inside of the error ellipsoid propagated from the initial orbit determination point. This means that the attitude maneuver in this experiment period (two months) is too short to evaluate the orbit control of the solar sail. Therefore, in order to distinguish the control capability and the navigation error more clearly, the guidance results should be evaluated on the (virtual) B-plane in the more future point and promote the orbit determination accuracy in each orbit determination point.

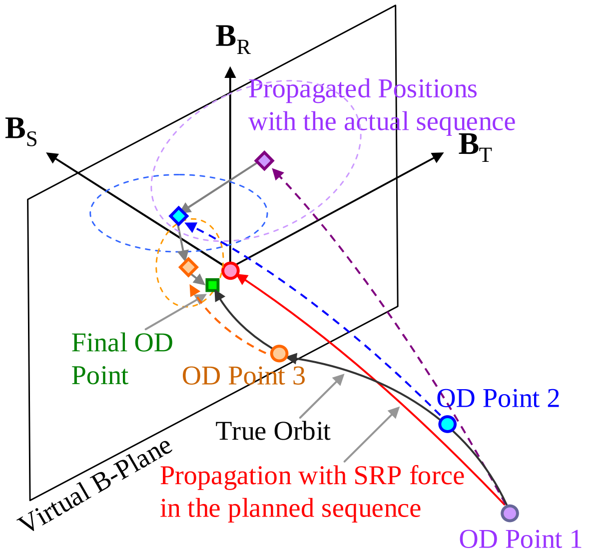

Fig. 9 Image of projected positions in the B-plane

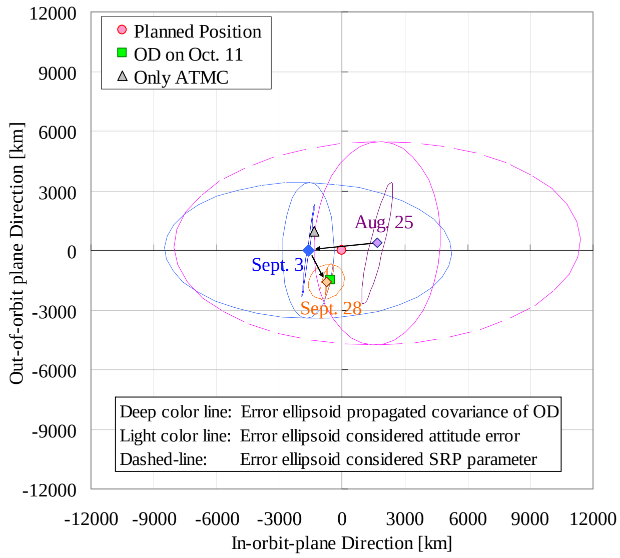

Fig. 10 Propagated positions from each OD point

7. Conclusions

In this paper, we explain the guidance, navigation and control experiment in the actual operation of IKAROS, and show the results of world's first guidance, navigation and control experiment for the operational solar sail spacecraft. As the result of this experiment, it becomes clear to resolve the following issues:

- The attitude maneuver should be conducted under the adequate rapid communication link
- The guidance result should be evaluated in the adequate forward timing
- The sequence of the guidance, navigation and control should be more quickly conducted (This means that the experiment preparation should be started earlier phase)

As above, there are several issues to reflect on the future operation. Nevertheless, we control the IKAROS orbit with the attitude drift motion due to the solar radiation pressure, and obtain the extremely useful knowledge for the future solar sail mission.

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