Orbit Determination for Long-term Prediction of Solar Power Sail Demonstrator IKAROS

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The world's first solar sail IKAROS (Interplanetary Kite-craft Accelerated by Radiation of the Sun) was launched along with the Venus Climate Orbiter Akatsuki in May 2010. IKAROS was full successful of missions that have been planned for first half year. After the Venus flyby in Dec 2010, it was carried out an extended mission. IKAROS has succeeded many additional engineering and scientific missions.

We are obtained many orbit determination skill[1)] in nominal and extended phase. However, the IKAROS was almost run out the fuel in Dec 2011, so attitude and spin rate was out of control .As a result, lost communication with the ground station due to the power shortage on December 24, 2011. After this operation IKAROS began to repeat the hibernation of the 10-month period by substantially fixed attitude in inertial coordinate while maintaining the spin rate between 5rpm and 6rpm without fuel. End of a hibernation, it is necessary to difficult orbit determination and 10 months or more of the long-term trajectory prediction for antenna tracking at USUDA deep space tracking station. In order to perform the orbit determination of long-term arc, an optical model[2)] of the solar sail back surface was constructed. Also we constructed attitude motion model[3)] to predict attitude of spin axis motion due to solar radiation pressure (SRP) torque.

After Dec 2011, we couldn't get normal range data, only obtained range rate data which using FFT analysis[4)] at offline data from open loop receiver. Also azimuth and elevation data when we observed IKAROS at beacon mode were obtained. In a very difficult situation, we study to estimate the uncertainty orbit determination error. And we try to considered search operation using USUDA deep space tracking station and Yamaguchi University tracking station for VLBI.

In this paper, we present orbit and attitude determination using few year long-term data and how to search a large area for antenna tracking to find out IKAROS.

Key Words: Orbit determination, IKAROS, Long-Term prediction, Attitude motion

1. Introduction

The IKAROS (Interplanetary Kite-craft Accelerated by Radiation Of the Sun) was launched along with the Venus Climate Orbiter Akatsuki in May 2010. Fig. 1.1 shows IKAROS's mission sequence. IKAROS was successful missions that have been planned for first half year. In this phase, we were able to operate a stable orbit determination. And we acquired the skills to consider polarization bias and to eliminate spin modulation. These were required for orbit determination of the spin solar sail.

After the Venus flyby in Dec 2010, it was carried out at extended mission that IKAROS had achieved a variety of results. One of the results was necessary to correspond to changes in spin rate in orbit determination arc at low spin rate.

IKAROS was performed a reverse spin operation in order to solve the problem of spin rate uncontrolled by the fuel depletion in Oct 2011. After this operation IKAROS began to repeat the hibernation of the 10-month period by substantially fixed attitude in inertial coordinate while maintaining the spin rate between 5rpm and 6rpm without fuel. After wake up from hibernation, it is necessary to difficult orbit determination for 10 months or more the long-term trajectory prediction. In order to perform the orbit determination of long-term arc to construct an optical model of the solar sail back surface. And we study to estimate the uncertainty orbit determination error.

For the long-term prediction we have to study attitude motion and spin rate motion dynamics. Attitude motion is strongly related to spin rate, especially at low spin rate. Recently we have find out signs that the spin rate is changing in deceleration in the telemetry data at 2014 and 2015.

2. Overview of IKAROS

IKAROS is constructed to maintain the shape of a huge 14 m x 14m square by spinning, and the square of the quadrilateral have a mass attached. Spin rate and attitude are controlled through the tether by thruster of the main body in the center. An outline of IKAROS is shown in Fig 2.1.

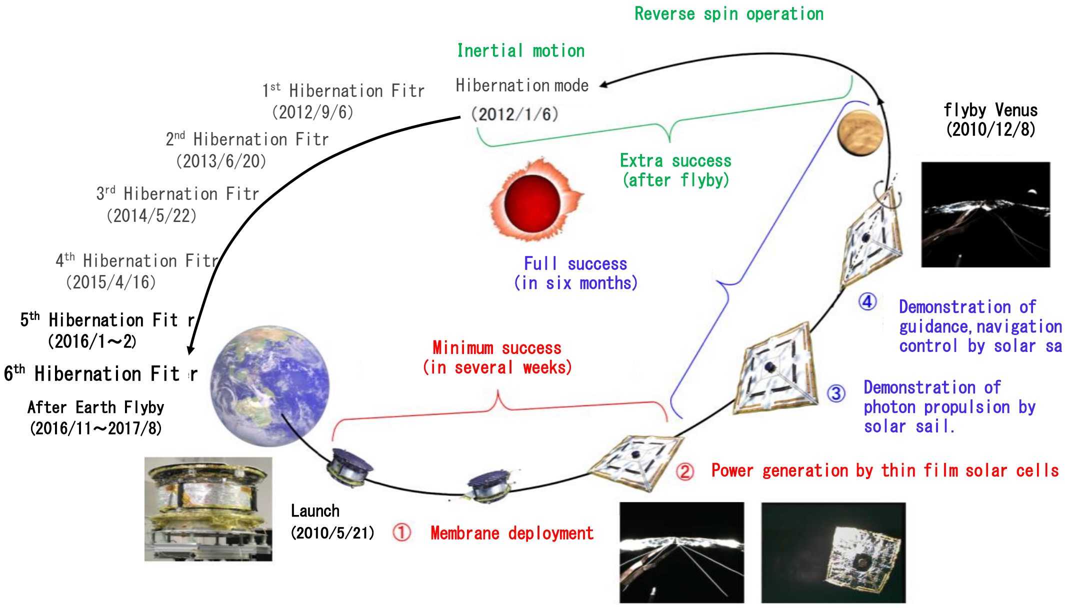

Fig. 1.1 Mission sequence

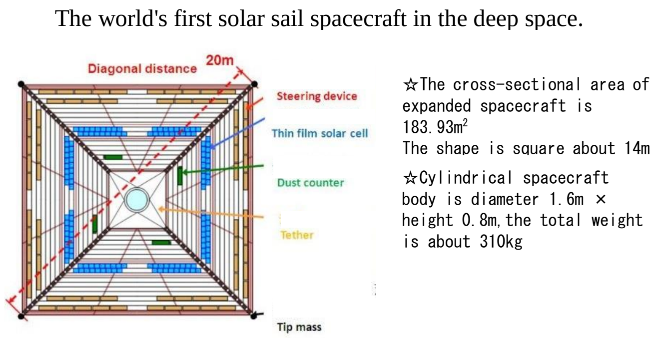

Fig. 2.1 Overview of IKAROS

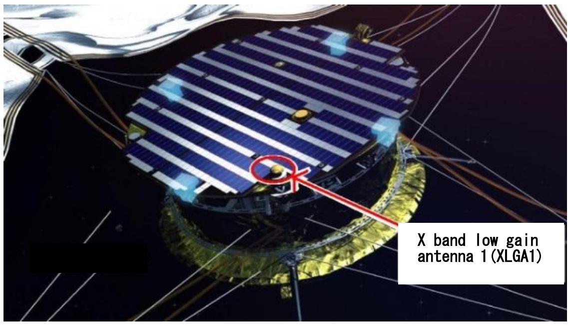

Fig. 2.2 XLGA1 antenna position

As a characteristic of IKAROS, rotational torque called the wind turbine effect occurred due to unbalance of solar radiation pressure caused by unevenness of the large film.

Since this torque worked in the direction of gradually decreasing the spin, nominal operation phase from launch to Venus swing-by had to spin up by thruster periodically.

It was possible to maintain spin rate without consuming fuel due to changing direction of spin rate and rotational torque by solar radiation pressure after reverse spin operation carried out.

The attitude of IKAROS is determined by the earth angle using the amplitude of Doppler modulation by spin and the sun angle by the sun sensor. The spin rate was known by telemetry. Therefore, the earth angle is obtained using the amplitude magnitude. Fig 2.2 show position of X band Low Gain Antenna (XLGA). XLGA is located about 715 mm away from the spin axis. This location makes Doppler modulation and the Earth angle changes amplitude magnitude.

The acceleration due to solar radiation pressure is about 100 m / sec in a half year. In search operation after wake up from hibernation, it was necessary that a long-term prediction orbital trajectory more than 10 months which considering the solar radiation pressure.

For that purpose, we are constructing an attitude dynamics model [3] to predict attitude in the future, making it possible to create a future trajectory over several years.

3. Orbit determination for nominal phase

In the nominal phase, it was necessary to remove the spin rate modulation and perform orbit determination. There was a polarization bias due to the spin rate and it was necessary to consider it in the orbit determination.

The equation of Doppler bias due to polarization is shown in (1).

$$f_{bias} = C\left(\frac{1}{f_T} + \frac{1}{f_R}\right)\omega \quad (1)$$

Table 3.1 shows the definition of variables.

Table 3.1 Doppler bias due to polarization

C:	Speed of light(m/sec)
f_T:	transmit frequency(Hz)
f_R:	Receive frequency(Hz)
ω :	Spin rate(round/sec)
f_{bias}:	Doppler bias due to polarization(m/sec)

The solar radiation pressure model used is shown in Table 3.2. A huge thin film of solar sail is thought to emit absorbed sunlight with almost no time delay. Therefore, a model considering the thermal radiation was needed. Fig 3.2 shows a conceptual view of the model considering the thermal radiation.

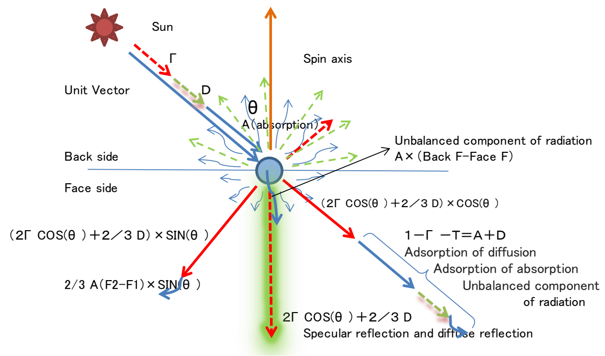

Fig. 3.1 Conceptual diagram of solar radiation pressure model of IKAROS

The solar radiation pressure acceleration for a plane perpendicular to the spin axis Zs is given as follows;

$$\ddot{\mathbf{r}}_{srp\perp} = \frac{S_0 R_0^2}{c}\frac{S}{m_s}\frac{1}{r^2}\left(\left((1-\Gamma-T)\cos\theta_s + \left(2\Gamma\cos\theta_s + \frac{2}{3}D + \frac{2}{3}A(F_2-F_1)\right)\cos^2\theta_s\right)\frac{\mathbf{r}}{r} + \left(2\Gamma\cos\theta_s + \frac{2}{3}D + \frac{2}{3}A(F_2-F_1)\right)\cos\theta_s\left(\mathbf{z}_s \times \frac{\mathbf{r}}{r}\right)\times\frac{\mathbf{r}}{r}\right) \qquad (2)$$

The definition of the solar radiation pressure model is shown in Table 3.2.

Table 3.2 IKAROS solar radiation presser model

S_0:	Solar constant (= 1.35 × 10^3 [W/m ^{2}])
R_0:	1A.U.(=1.4959787×10^8[km])
c:	Speed of light
m_s:	S / C mass
S:	Area of the plane
Γ:	Reflection coefficient
D:	Diffusion coefficient
T:	Transmittance
r:	S / C position vector of the sun center
$\mathbf{z_s}$:	Unit vector in the inertial space of the S / C spin axis
θ_s	Solar orientation angle (cos θ s = (- r / r) ・ Z s)
A	Absorption rate A =1 - D - Γ - T: T = 0
F_1	The emissivity ratio of the surface
F_2	Emissivity ratio on the back side

The estimated value of the solar radiation model was gradually changing in nominal phase. Fig. 3.2 shows the trend of estimation value of solar radiation presser model.

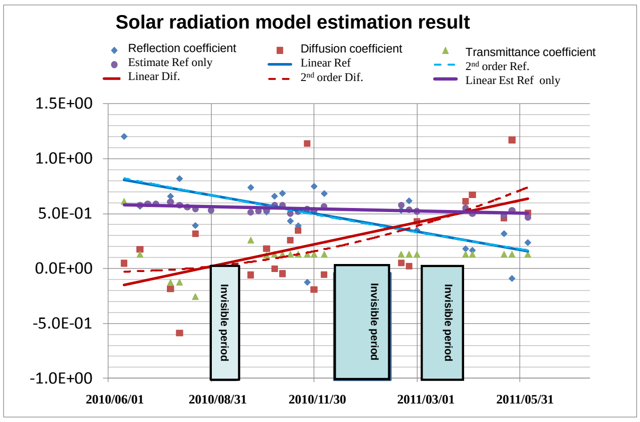

Fig. 3.2 The trend of estimation value of solar radiation presser model.

The red line and the blue line are the trends when both specular reflection and diffuse reflection parameters are estimated at the same time. The purple line is the trend when only reflection parameters estimated. The invisible period are the earth angle became about 80 degrees or more. So in this period, telemetry's link became quite difficult.

Fig. 3.3 shows the flight data of the spin rate and the sun angle. Spin rates are roughly decelerating from 2010 to May 2011. Along with this deceleration, the red line and the blue line change while having a correlation. This difference is fairly large, if the estimation result is correct, it may be caused by state of wrinkles changed by decreases centrifugal force.

The purple line decreases very slowly, but this is thought to be caused by a change in physical properties due to sunlight.

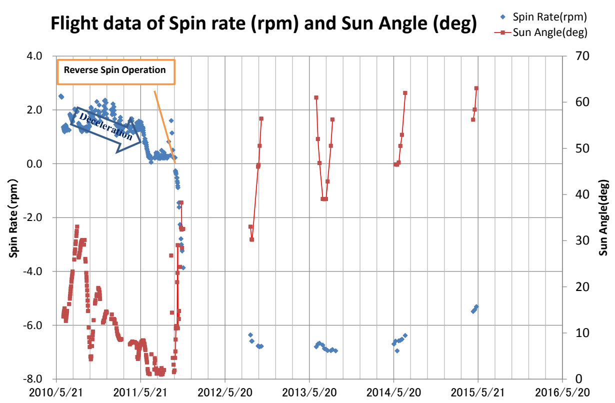

Fig. 3.3 Flights data of spin rate and sun angle

4. Orbit determination for extended phase

In extended operation, we mainly operated with low spin rate. We conducted a number of experiments, such as operation and guidance control where the attitude of the spin axis was largely changed. In anticipation of depletion of fuel, reverse spin operation was carried out to stabilize the spin rate without fuel. As a result, the spin rate gradually increased without fuel and the moment of inertia increased gradually, so the attitude changed from solar tracking to inertial fixation. In the end, IKAROS could not maintain the power and hibernated.

In this phase, the spin rate/rate in the trajectory determination arc became large and spin modulation could not be removed with fixed parameters. In addition, the quality of tracking data worsened as the distance to the earth gradually increased. The uncertainty of attitude by low spin rate has also appeared. The accuracy of orbit determination worsened than the previous phase.

Therefore we have constructed a system that simultaneously performs attitude motion and orbit determination. We were able to achieve highly accurate orbit determination.

5. Orbit determination for Long-term prediction and search operation

IKAROS hibernated because the spin rate increased and the inertial directivity increased. After that, the search operation became necessary.

The problem of this phase was the long-term orbit prediction, highly reliable trajectory determination and prediction of attitude motion model was necessary. The initial attitude motion model was roughly classified into three models[3]. As a result, it was discovered using a model with strong inertial orientation.

5.1 First search operation

In the first recapture[1], the radiation pressure parameter[2] on the back side was also studied, and the orbital error was propagated after considering the thermal radiation model from the large film.

In this operation, totally four Doppler data by off line FFT analysis from Open Loop receiver and AZ, EL data when it was successfully received signals were newly added for observation data.

5.2 Second search operation

In the second search operation[1], we had predicted that the search area due to propagation 3 sigma errors were about 10 times the half beam-width of Usuda, but it was able to be found in the initial search operation. In this operation, 7 Doppler data created by post processing from Open Loop receiver and AZ EL data when it was receiving signals were added as observation data.

5.3 Third search operation

In the third search operation[1], at the first search was conducted on April 22, 2014 and succeeded in the third search. We succeeded in searching using forecast values improved on the back and surface optical parameters by observation data acquired in 2012 and 2013.

Fig. 5.1 shows the transition of the assumed error ellipse 3σ of the search operation from the first search operation to the third. Although the axes are Right Accession (RA) and Declination (DEC), the scale in the Dec direction is enlarged twice the RA direction.

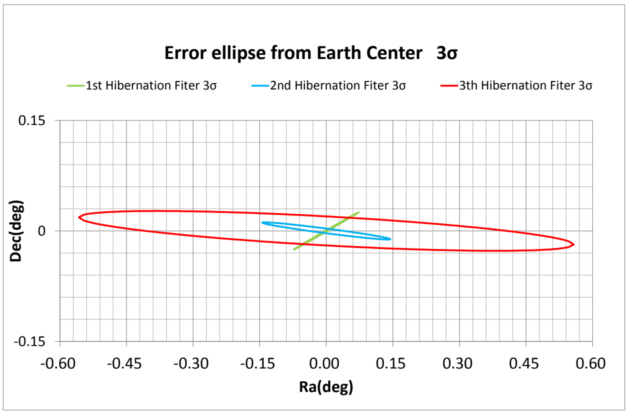

Fig. 5.1 1st～3rd Error Ellipse from Earth Center

In addition, in the third search operation after hibernation, not only the conventional time offset search but also the offset search in the RA DEC direction converting to the AZ EL offset using the instantaneous azimuth / latitude gradient by the predicted value was also performed.

5.4 Fourth search operation

The fourth search operation[1] started searching on March 5, 2015 and spent a period of one and a half months until discovery. We have succeeded in searching by applying a new search method [4] such as post-processing analysis using 1-way data with open loop receiver.

In this search operation, since the distance between the satellite and the earth was close, three Doppler data could be obtained with a normal Doppler receiver, but the range data could not be acquired.

5.5 Fifth search operation

In the 5th search operation, a program was created so that a search in a wide range can be automatically carried out by adding an offset of the search area planned in advance to the antenna prediction value. It is possible to detect weak received data by FFT analyzing the received frequency data at offline. The 5th search is very close in terms of distance but IKAROS's transmitting and receiving antennas are facing the back side and could not be found. Perhaps it seems that radio waves were weaker than assumed, or it was hibernating rather than being as expected. The search area is shown in Fig. 5.2. It was searched that about 1.5 deg. x 0.5 deg. range.

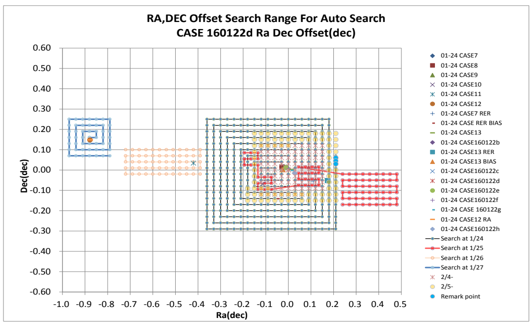

Fig. 5.2 RA DEC Offset Search Area

5.6 Sixth search operation

In the sixth search operation, the range data was created pseudo by using at the timing when the frequency sweep ended. It was possible to create one point pseudo range data for each period at 2013 and 2015. It was formulating spin modulation and statistically processing, we were able to reduce the error of each data to 8000 km and 1000 km respectively. As a result of orbital determination while assigning parameters using these data, the search area could be reduced as shown in Fig. 5.3. In January 2016, the search area when sweep timing pseudo range data is used is indicated by red solid line. The search area when sweep timing pseudo range data is not used is indicated by a pink dashed line.

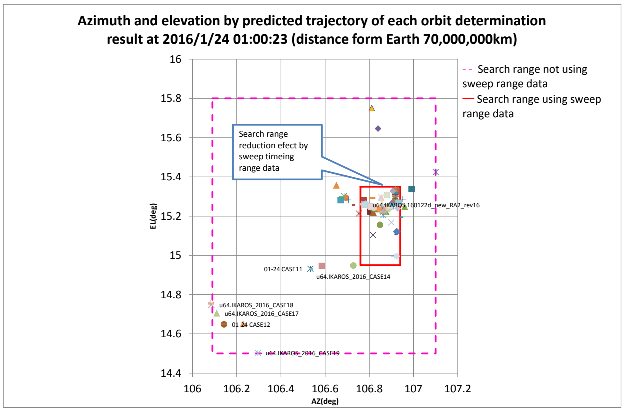

Fig. 5.3 Search area for IKAROS in 2016/1/24

In the sixth search, it can be considered that the transmitting / receiving antenna is facing the earth, so it is an assumption that stronger radio waves can be received than the fifth search.

For this reason, it is possible to search an area wider than the 5th search area. Fig. 5.4 shows the search area up to the present.

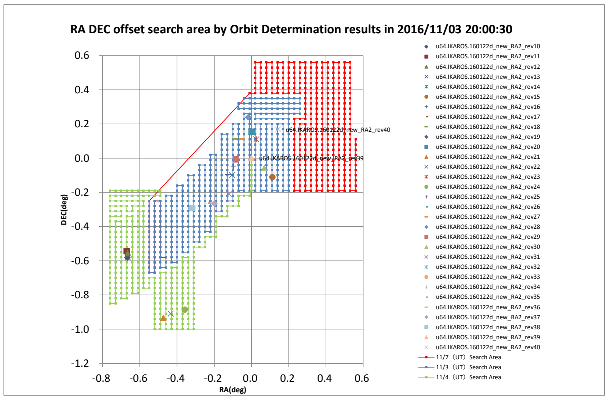

Fig. 5.4 Search area by Usuda deep space station for 3 days

At the same time, the search operation was also carried out using Yamaguchi Univ.'s 32m antenna. Fig. 5.5 shows the search area by Ra. Dec. It was used when the Earth's distance is relatively close. A line of each color is search area for a day.

I expect it to analyze offline, but it has not been discovered as of Fabray 2017. It seems that the spin torque force is reversed by the observed spin rate data in Fig. 3.3. Therefore, we constructed the spin torque motion model at section 6.

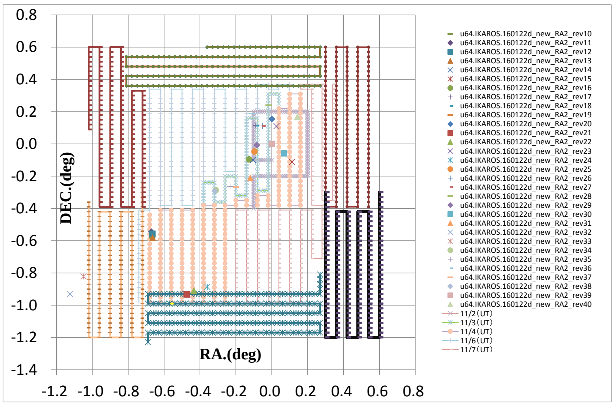

Fig. 5.5 Search area by Yamaguchi Univ.'s 32m antenna

6. Consideration of spin motion

The model of the spin rate motion[3,5] was formulated by fitting the motion model to the rate of spin rate acquired from the flight data. However, this model was formulated as fixed for distortion angle ξ indicating the windmill effect and the deflection angle η as like as the shape of the umbrella. In this paper, ξ and η are divided and formulated as in Eq. 6.1 so that it can be adapted to long-term spin motion.

Spin rate is from 0 to 1.2 rpm

$$\xi = \xi_1(c + b\Omega + a\Omega^2)$$
$$\eta = \eta_1 \tag{3}$$

Spin rate from 1.2 rpm to 2.7 rpm

$$\xi = \xi_1、\ \eta = \eta_1 \tag{4}$$

Spin rate from 2.7 rpm to 7 rpm

$$\xi = \xi_1\xi_2/(m_s m_c\Omega^2 + (C_1 + \xi_2))$$
$$\eta = \eta_1\eta_2/(m_s m_c\Omega^2 + (C_2 + \eta_2)) \tag{5}$$

Table 6.1 spin motion model

Values name	Values mean
ξ	Distortion angle indicating the windmill effect
ξ_1	Windmill effect coefficient 1
ξ_2	Windmill effect coefficient 2
η	Deflection angle
η_1	Deflection angle coefficient 1
η_2	Deflection angle coefficient 2
a	Polynomial second order coefficient
b	Polynomial first order coefficient
c	Polynomial zero order coefficient
C1	Continuity securing coefficient for ξ
C2	Continuity securing coefficient for ξ
m_s	Sail membrane total weight
m_c	Sail membrane center radius

Here ξ and η are divided into three sections and formulated so that fitting can be made based on the flight data obtained during the hibernation mode.

Here, it differentiates into three sections of formula (5) where centrifugal force and wrinkle elastic force dominate, formula (4) treated as a constant value, and formula (3) fitted to actual data. The division of these equations made it possible to match the spin rate and the sun angle to the actual flight data as shown in Fig. 6.1 and 6.2. Especially assuming that the windmill effect of ξ is reversed at about -7 rpm because the spin rate is decelerating from the spin rate flight data in 2014 and 2015.

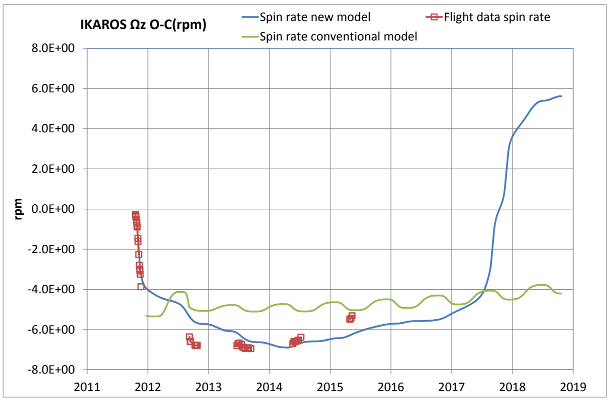

Fig. 6.1 Spin rate by observation data and motion model

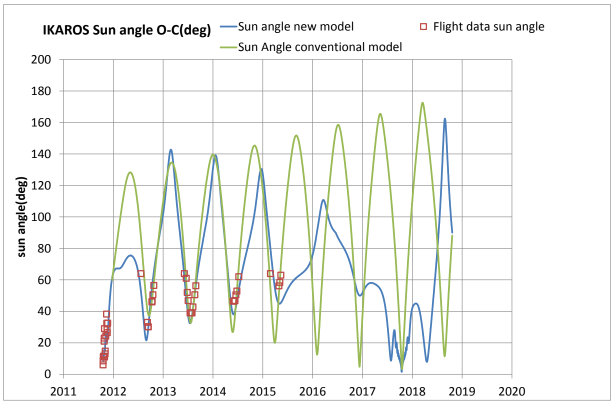

Fig. 6.2 Sun angle by observation data and motion model

The structure constituting the windmill effect of the sail membrane would had been eventually destroyed by the centrifugal force becoming larger as the spin rate increases. Perhaps, as a result of multiple breakdowns of it, we believe that the windmill effect was reversed.

Parameters surveys were performed with these formulated models and the parameters were estimated to minimum values. At the same time, we simultaneously estimated the attitude and the orbit using observation data of Doppler, azimuth and pseudo range from 2011 to 2015.

The attitude motion shows chaotic dynamics when the spin rate through around 0 rpm. In the orbit determination, the estimation of the tracking data has a greater influence on the search range than the change of attitude model. However, the attitude motion changes greatly like chaos, the period of wake up from hibernation changes. Therefore, the search time changes greatly. The solar angle related to orbital propagation almost same as the conventional model until 2015, but after 2016 the chaotic behavior becomes stronger. Therefore we will be regularly operating the search operation once per a month.

7. Summary

Search operation of IKAROS due to hibernation has been successful as a result of trial and error in the past 4 times. In the fifth time, there was a possibility of receiving signal but we could not catch the signal from the IKAROS's antenna.

In the sixth search operation, automatic offset program makes search area larger, offline FFT analysis made it possible to pick up weak signal. Pseudo-created range greatly reduced search area. As these results, the search area is considered to be no problem. We are extending the attitude motion model. It is the spin motion model changes possible to deal with all direction from handling the angle around the sun orientation. As a result, it is possible to predict a more precise period of wake up from hibernation.

8. Conclusion

IKAROS's orbit determination requires technical elements that are not ordinary operation such as construction of attitude motion model and long - term prediction due to hibernation. These technical elements to be useful in next solar power sail spacecraft.

References

1) ShoTaniguchi, Takafumi Ohnishi , Osamu Mori , Hideki Kato, Hiroshi Takeuchi, Atsushi Tomiki, Yuya Mimasu, Naoko Ogawa, Tsutomu Ichikawa, MakotoYoshikawa, and Shota Kikuchi, Orbit determination of Interplanetary Kite-craft Accelerated By Radiation of the Sun (IKAROS), *The Fourth International symposium on Solar Sailing in Kyoto Japan(2016).*

2) Sho Taniguchi, Takafumi Ohnishi, Yuya Mimasu, Yuji Shirasawa, Katsuhide Yonekura, Mori Osamu, Hiroshi Takeuchi, Tsutomu Ichikawa, and Makoto Yoshikawa, Orbit Determination and Evaluation of Prediction Error to Acquire IKAROS, *57th Space Science and Technology Conference. (2013).*

3) Yuya Mimasu, Sho Taniguchi, Hiroshi Takeuchi, Yuji Shirasawa, Katsuhide Yonekura, Osamu Mori, Ryu Funase, Takano Saiki and Yuichi Tsuda, LONG-TERM ATTITUDE AND ORBIT PREDICTIN OF SOLAR SAILING IKAROS WHILE BEING LOST IN SPACE, *ASS 13-406 (23rd AAS/AIAA Spaceflight Mechanics Meeting, Kauai, Hawaii in 2013)*

4) Shota Kikuchi, Hiroshi Takeuchi, Osamu Mori, Yuya Mimasu, Yoji Shirasawa, Hideki Kato, Naoko Ogawa and Sho taniguchi, Progress of Search Operation for IKAROS by means of Open-loop Tracking Data, *30th International Symposium on Space Technology and Science, (2015).*

5) Yuichi Tsuda, Takano Saiki, Yuya Mimasu, Ryu Funase, Modeling of Attitude Dynamics for IKAROS Solar Sail Demonstrator, *ASS 11-112 (The 21rd AAS/AIAA Spaceflight Mechanics Meeting, New Orleans, Louisiana, USA, Feb.13-17,2011)*