Solar Sail Acceleration Modeling and its Estimation for IKAROS Spacecraft

Tomohiro Yamaguchi[1)], Yuya Mimasu[2)], Yuichi Tsuda[2)],
Sho Taniguchi[3)], Hitoshi Ikeda[2)] and Makoto Yoshikawa[2)]

[1)] *The Graduate University for Advanced Studies, Sagamihara, Japan*

[2)] *Japan Aerospace Exploration Agency, Sagamihara, Japan*

[3)] *Fujitsu Ltd., Sagamihara, Japan*

This paper investigates the modeling of the solar sail acceleration for the solar sail demonstrator IKAROS. The modeling of solar sail acceleration is a key element for future deep space exploration using solar sail because it impacts the fuel budget and flexibility of the operation. Estimation of the solar sail acceleration model in space is required because the solar sail have large uncertainty due to the flexible membrane. Since the solar sail wrinkles after the deployment and reorientations, it is difficult to configure the model before the launch. This research concentrates on the estimation of solar sail acceleration model using the radiometric tracking data from nominal phase of IKAROS spacecraft. The estimation is evaluated using the normalized SRP acceleration, and the 90 % of the expected performance is confirmed.

小型ソーラー電力セイル実証機IKAROSの加速度モデルとその推定について

本研究では，小型ソーラー電力セイル実証機 IKAROS の太陽輻射圧加速度とそのモデル化を評価した．IKAROS は 2010 年 6 月 9 日にソーラーセイルを軌道上で展開し，太陽輻射圧による本格的な加速を開始した．このようなソーラーセイルの航法・誘導には精密なソーラーセイルの加速度モデルが必要である．しかし，ソーラーセイルの膜面は柔軟な構造物であるため，展開や姿勢変更後の形状や表面の状態を正確に予測するのは困難である．そのため，地上実験の結果だけでは，その加速度モデルを構築することが困難であり，軌道上でソーラーセイルの加速度モデルを推定することが重要である．本発表ではノミナルフェーズにおけるトラッキングデータを用い，軌道情報からソーラーセイルの加速度モデルを推定し，その有効性を明らかにする．推定結果を規格化した太陽輻射圧加速度を用いて評価し，想定の約 90%の太陽輻射圧加速度を確認した．

1. Introduction

Recently, the target of space explorations become further and further from the Earth. For instance, the interest in small celestial bodies are going to move on main-belt and Trojan asteroids from near Earth objects. Since these space explorations require huge energy to achieve their objectives, high efficient propulsion system (i.e. electric propulsion, solar sail, etc.) have developed. Hayabusa[1)] and Dawn spacecraft are now cruising deep space with electric propulsion system. Although more efficient propulsion system are required to expand deep space explorations.

Solar sail have a capability to receive solar photon momentum and obtain acceleration without fuel. Many application for the innovative space mission are investigated and planned using solar sail.[2)–5)] Also several concept and project are going on. UrtraSail is the solar sail concept which has several “brades” of solar sail firm material with a microsattellite on the tip.[6)] This system uses a solar sail firm of densities approaching 1 g/m^2 for a very large, and high acceleration due to 1 km^2 solar sail areas. Cosmos 1 was a project to test the solar sail technology, funded by Planetary Society.[7)] Although, the 600 m^2 mylar sail was planed to launch into the Earth orbit with inclination of 80 deg by converted missile, the launch was failed and the spacecraft failed to reach the orbit.

The Japan Aerospace Exploration Agency (JAXA) is planning a “solar power sail” mission, which are a hybrid system using ion-propulsion engines as well as a solar sail. JAXA have launched a small solar sail demonstration spacecraft called IKAROS (Figure 1) in May 2010, as a precursor mission of the medium size solar power sail for the Jupiter-Trojan system exploration. The minimum success criteria of this spacecraft are the demonstration of the solar sail deployment system and the power supply from the thin-film solar cell. The full

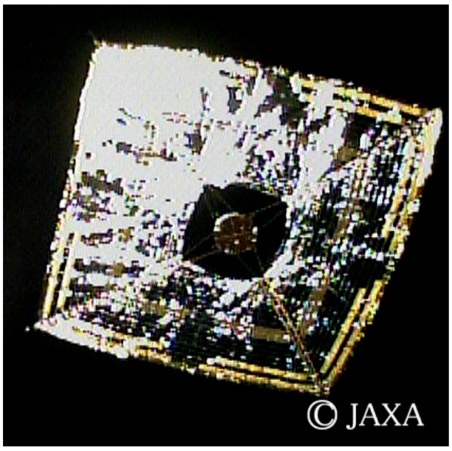


Figure 1. Solar sail demonstration spacecraft IKAROS.

success criteria of the spacecraft are the acceleration and navigation using the solar sail in the interplanetary trajectory. IKAROS spacecraft succeeded its solar sail deployment on the transfer orbit to the Venus and confirmed the electronic power generation by the solar cell on the solar sail. The minimum success criteria have achieved, and IKAROS spacecraft concentrates on the collection of the tracking data for the analysis of the solar sail dynamics. To achieve the full success criteria, it is necessary to model the solar sail force with consistent parameters. This modeling will allow us to mitigate the navigation cost and become a useful heritage for future solar sail missions.

A precise solar sail force model is the key factor of successful navigation for the solar sail spacecraft. Many prelaunch experiments have held to confirm the performance of solar sail deployment and stability.[8),9)] Although conventional spacecraft model can be based on ground-based measurements, solar sail force model needs to be refined after launch. Since a practical solar sail requires large area to obtain a force from solar radiation pressure, a sail needs to be deployed in space. The deployment may occur some wrinkles and deformation from nominal shape that expected before launch. Also the uncertainty becomes much larger since the sail surface will suffer from degradation. There is some studies about the on-orbit calibration of solar sail model. Whorton and Hoot shows the technique of astronomical observation for solar sail orbit determination, thrust performance verification, and optical model validation.[10),11)] Heaton and Brinckerhoff present the solar sail model validation from NASA historic Echo balloons trajectories.[12)] The Echo balloons are comprised of aluminized Mylar, were in low Earth orbits. However, these method is available if the spacecraft orbits around Earth and this strategy cannot adapt for IKAROS spacecraft. Rios-Reyes and Scheeres investigated a methodology for estimating the force and moment generated by arbitrary shape using generalized sail model based on in-flight data.[13)] However they assumed ideal in-flight data measured using inertial measuring units.

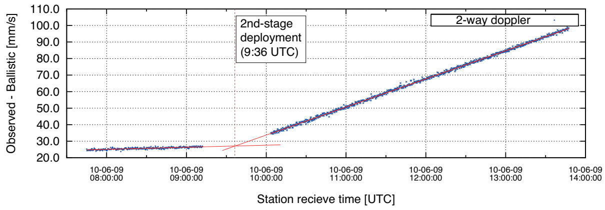


Figure 2. Doppler signal in solar sail deployment

This paper investigates the solar sail force estimation using real tracking data from the nominal phase of the IKAROS operation. The radiometric tracking data is available for the conventional spacecrafts and it doesn't require any special equipment. Chapter 2 describes the trajectory and attitude of the IKAROS spacecraft. Chapter 3 investigates the estimation approach for the SRP force acting on the solar sail. Chapter 4 summarizes the results.

2. Trajectory and attitude of IKAROS spacecraft

The IKAROS spacecraft was launched together with JAXA's Venus climate orbiter Akatsuki on May 21, 2010. After the separation from H2A launch vehicle, the solar sail was successfully deployed on June 9, 2010, and now it is cruising with solar sail acceleration in an interplanetary space. The spacecraft wet mass is 307 kg including the square-shaped solar sail of 16 kg. The solar sail was deployed and kept the shape by centrifugal force of the spacecraft spinning. Thus it does not have any rigid structure to support the extension of the sail, enabling to achieve very light and simple sail support mechanism.

IKAROS spacecraft have deployed its flexible membrane in June 9th, 2010. The continuous Doppler signal have been received at Usuda Deep Space Center of JAXA. The Doppler signal are evaluated as observed value minus ballistic value (Figure 2). The inclination of the 2-way Doppler signal in the figure shows the solar sail force acting on the IKAROS spacecraft. The time which spacecraft operated with 1-way Doppler mode is blank. The Doppler signal suddenly inclined after the scheduled deployment time of the solar sail. The solar sail deployment is confirmed from this fact.

The spacecraft continues its flight and it approached Venus on December 8, 2010, one day after the Akatsuki's Venus orbit insertion maneuver. This delay is the consequence of the solar sailing. During the interplanetary flight, JAXA ground station collected the radiometric data not only for the tracking, but also for the investigation of the solar sail dynamics.

Figure 4 illustrates the attitude history of coasting arcs of the IKAROS since sail deployment until Venus flyby. The upper figure is the history of solar cone angle and the bottom figure is the history of the Earth

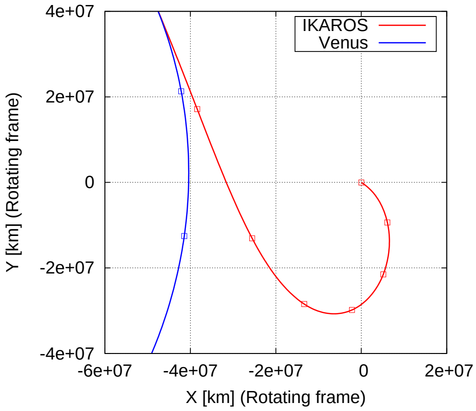


Figure 3. Interplanetary trajectory of IKAROS (Sun-Earth fixed rotating frame)

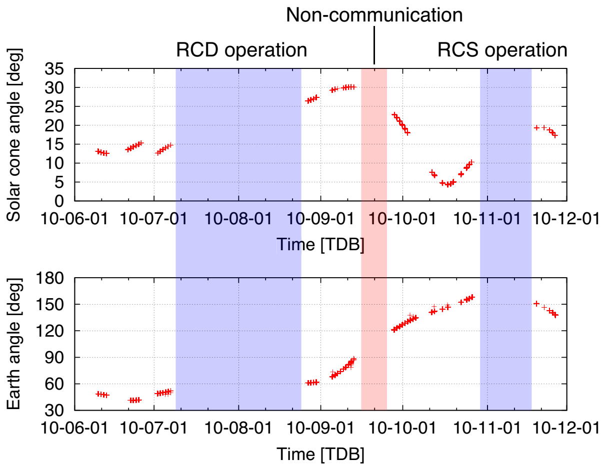


Figure 4. IKAROS attitude history for coasting arcs (since sail deployment until Venus flyby)

angle. The Earth angle is the angle between the spin axis and the Earth direction from the spacecraft. Three blank region is shown in the figure. The first blank is the region with RCD (reflectivity control devise) operation. RCD is the devise equipped on the edge of the sail and can control the attitude with changing the surface reflectivity. The RCD operation becomes a perturbation from the aspect of SRP estimation with radiometric observable, because the operation make the attitude determination inaccurate. The second blank is the non-communication due to the conflict between radio signal and sail surface. This conflict occurs when the Earth angle is 90 deg. The third blank is the frequent RCS operation for the Venus flyby preparation. As mention before, RCS operation is the perturbation impacts the SRP estimation. This period had frequent RCS operation to adjust the trajectory and attitude for the Venus flyby.

3. Solar Sail Model Estimation

Estimation of solar sail force means a parameter estimation of solar sail model. Since IKAROS's solar sail is composed by flexible membrane, the sail may have a large uncertainty due to the deployment after the launch. In this section, SRP modeling of the IKAROS spacecraft is investigated. Firstly, flat plate model is introduced as a SRP model. Next the condition of the SRP estimation is explained. And the last, the result of the SRP estimation is evaluated with the normalized SRP acceleration.

3.1. Flat Plate Model

A flat plate solar sail model is implemented to estimate solar sail force with relatively short period orbit determination. This model assumes a solar sail as a plane composed by a unique material. The force is modeled as following equation, considering absorbing and reflecting component of solar radiation pressure (SRP).[14)]

$$\boldsymbol{F} = -P\left(r_s\right) A \cos\alpha \left\{a_1 \hat{\boldsymbol{r}}_s + \left(2a_3\cos\alpha + a_2\right)\hat{\boldsymbol{n}}\right\} \qquad (1)$$

where $P\left(r_s\right)$ is the solar radiation pressure at sun-spacecraft distance r_s, A is the sail's area. $\hat{\boldsymbol{n}}$ is the normal vector of the solar sail and $\hat{\boldsymbol{r}}_s$ is the sun insertion vector, α is called as solar cone angle and calculated by $\cos\alpha = \hat{\boldsymbol{n}}^T\hat{\boldsymbol{r}}_s$, and those vectors are described in Fig. 5. a_1, a_2, a_3 are the optical parameter of the sail surface and they are defined as follows;

$$a_1 = 1 - \rho s \qquad (2)$$

$$a_2 = B_f\left(1-s\right)\rho + \left(1-\rho\right)\frac{\epsilon_f B_f - \epsilon_b B_b}{\epsilon_f + \epsilon_b} \qquad (3)$$

$$a_3 = \rho s \qquad (4)$$

where B_f, B_b are the sail front and back surface Lambertian coefficients, ϵ_f, ϵ_b are the sail front and back surface emissivity, ρ is the sum of the reflectivity, s is the fraction of specular reflection.

3.2. Conditions

The condition of arc parameter estimation is summarized in Table 1. The orbit determination and SRP estimation is calculated using batch weight least square. The observable are X/X band 2-way Doppler and range, and those weights are 0.5 mm/s and 2 m, respectively. These weights are compatible with the Doppler and range accuracy which are observed on the post-fit residual of those observable. The uncertainty of the range bias are considered as 10 m. The range bias is hardly observed in the IKAROS tracking data. It is because the IKAROS is operated by the single tracking station (Usuda Deep Space Center : UDSC) and the bias is usually observed with the operation with the multiple tracking station. The bias of the UDSC is confirmed by the operation of the Akatsuki, which is operated by the UDSC and the NASA's Deep Space Network (DSN).[15)] The orbit

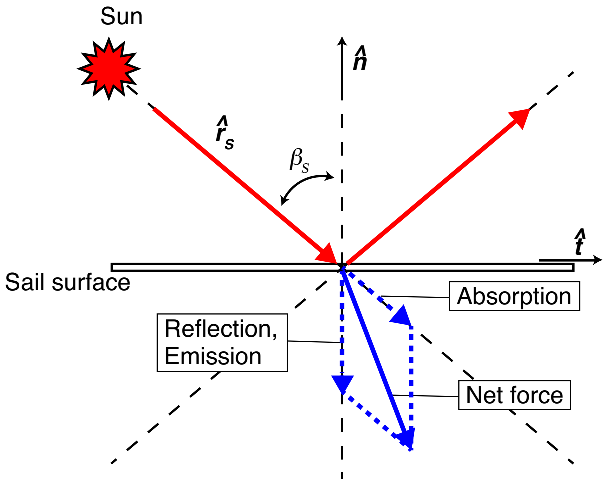


Figure 5. Flat plate model

are propagated using the given state vector at epoch with planetary perturbation and solar radiation pressure. The planetary perturbation is calculated using JPL ephemeris DE423.[16] DE423 is one of the latest ephemerides which intended for the MESSENGER mission to Mercury. As mentioned in chapter 2, FPM SRP model is implemented for the estimation of arc parameters. The attitude is estimated by the attitude group of the IKAROS. It is estimated with the solar cone angle measurement from the sun sensor on the bus cylinder and the Earth angle from the spin modulation on the Doppler signal. The Earth orientation model is compatible with IERS conventions 2003.[17] The orientation model consists of three transformational rotations, bias-precession-nutation, sidereal-rotation and polar motion. The Earth orientation model is implemented for the transformation between GCRF (Geocentric Celestial Reference Frame) and ITRF (International Terrestrial Reference Frame). The coordinate transformation is CIO-based (Celestial Intermediate Origin based) based approach with IAU 200A precession-nutation. Several method is recommended in IERS and its comparison is investigated by Vallado.[18] The media correction is implemented according the recommendation of IERS conventions 2010.[19] The media correction consists of two major correction, tropospheric delay and ionospheric delay. The tropospheric delay is implemented using the estimated zenith path delay from IGS (International GNSS Service[1]) database and Global Mapping Function.[20] The ionosphere delay is implemented using the total electron content database of IGS and ionosphere mapping function.[19]

The estimation parameter selection is important for the SRP estimation because the parameters need to be sensitive to the tracking data and fulfill the correction of the SRP force. The candidate of the estimate parameters are the optical parameters of FPM (a_1, a_2, a_3) and sail effective area A. A priori value of those parameters

[1] http://igscb.jpl.nasa.gov/

Table 1. Condition of SRP estimation

Estimation filter	Weighted least square
Observable	X/X band 2-way Doppler and range
Propagate model	DE423 planetary perturbation model Solar radiation pressure
Attitude	Estimated value using solar cone angle and the Earth angle
Observable weight	Doppler : 0.5 mm/s, Range : 2 m
Consider uncertainty	Range bias : 10 m
Ground station	Usuda 64 m antenna
Earth orientation model	Compatible with IERS conventions 2003
Media correction model	Compatible with IERS conventions 2010

is the measurements of the ground-based experiments for the devices on the sail. Adding the measured value to FPM parameters, the parameters (a_1, a_2, a_3, A) become 0.28, -0.02, 0.72, 184 m^2, respectively. a_3 and area is implemented as estimated parameters because those parameter have large impact to the SRP force.

The estimation results are evaluated with two factor. One is the residuals of the observables, and another is the normalized SRP (NSRP). The residuals shows the how the estimation data fits to the flight data. The residuals need to be distributed as zero mean and gaussian. NSRP is the SRP acceleration normalized with 1 AU and 0 deg solar cone angle. NSRP should be a constant value if there is no big deformation nor drastic surface condition change. The NSRP is given as follows;

$$NSRP = P_0 A \left(a_1 + a_2 + 2a_3\right) \qquad (5)$$

where P_0 is the solar radiation pressure at 1 AU and the value is 4.56×10^{-6} N/m^2. The estimated NSRP is 4.65×10^{-6} m/s^2.

3.3. Results

The SRP acceleration of solar sail IKAROS is evaluated by 11 coasting arcs since solar sail deployment at June 2010 until Venus flyby at December 2010. The residual in the first coasting arc after the sail deployment is described in Figure 6. It is observed that the residuals distributed properly. The NSRP is 4.196×10^{-6} m/s^2 and it is found that the value is about 90 % of the expected value. The NSRP are summarized in Figure 7. Most of the NSRP are distributed about the 90 % of the expected value. However, some of the coasting

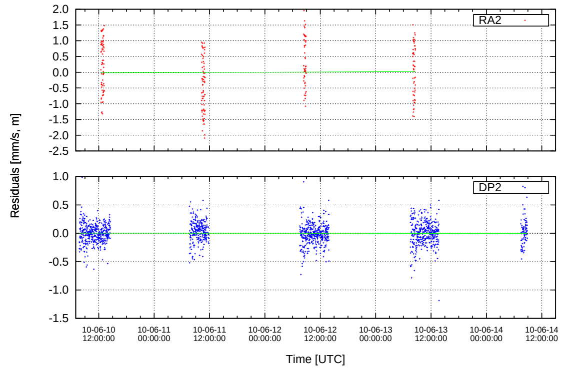


Figure 6. Range and Doppler residuals on June 10 - 14 (Doppler RMS : 0.21 mm/s)

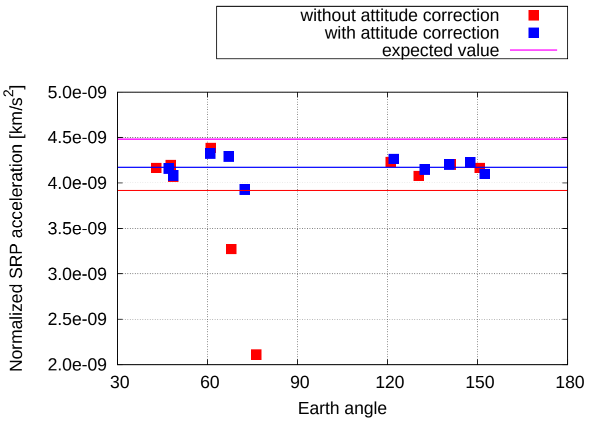


Figure 7. Normalized SRP

arcs present irregular values. The irregular values is obtained if the coasting arcs have a large Earth angles or solar cone angles. Also it is observed that some of the coasting arc shows the irregular Doppler residuals even if the NSRP have the regular value.

There is several reasons to have those anomaly. Four possible error sources are investigated. Planetary ephemeris affects Doppler through the planetary perturbation. The planetary ephemeris are estimated using optical observation and spacecraft range and VLBI operations. The largest perturbation for IKAROS trajectory is the Earth or Venus and those position uncertainties are less than 10 km. Considering this error, the Doppler may have the error with 10^{-3} mm/s, which is negligible. Secondary, the Earth orientation model may have an error. The model is used for the transformation to/from GCRF and ITRF. Considering 1 m error in the GCRF position the Doppler error could up to 10^{-2} mm/s, which is still negligible. Next, the media correction may have an error. The model error could impact the radio signal propagation and make an uncertainty with the order of 1 nsec. The Doppler error will be about 10^{-2} mm/s

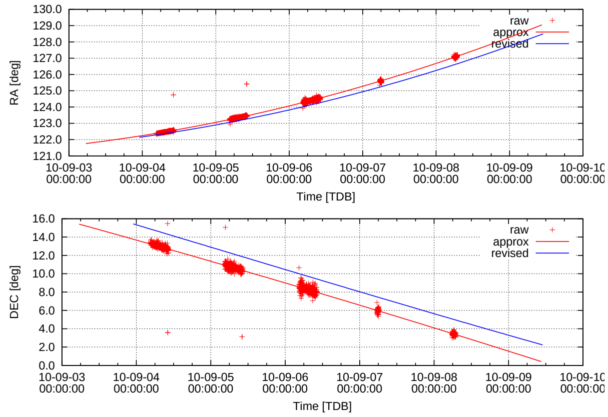


Figure 8. Attitude correction with the orbit determination

and it is negligible. The last consideration is attitude. The attitude determination have some error and it may have 1 deg level. Then the uncertainty on the Doppler becomes 10 mm/s level and it impact the estimation dramatically.

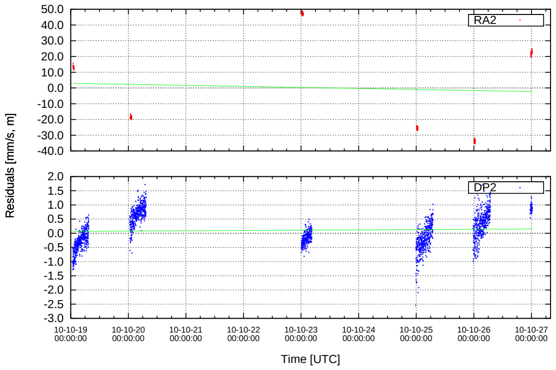
In order to correct the attitude, the SRP characterization with estimating both orbit and attitude is proposed. This hybrid method makes best use of the sensitivity of the radiometric tracking data with respect to the attitude through the SRP acceleration. This is possible because a solar sail have a high sensitivity with respect to the attitude due to a large area to mass ratio. Taking the high sensitivity of Doppler signal with respect to the attitude through the SRP acceleration, the both orbit and attitude propagation parameters are estimated. We decide to use the dynamical attitude model of the solar sail. This method can describe the attitude without the measurements. By estimating the dynamical parameters of the attitude model, we can obtain the best-fit attitude of the sail independent from the sensors attached on the bus cylinder. To construct this method, the reliable dynamical attitude model is required.

The spiral attitude model is introduced by the IKAROS attitude team to solve the attitude motion of the spinning solar sail. The model considers an arbitrary-distributed optical property and an arbitrary axis symmetry deformation. Using this model, the linearized form of the SRP torque $\boldsymbol{T}$ for spin axis motion α, δ are given by;

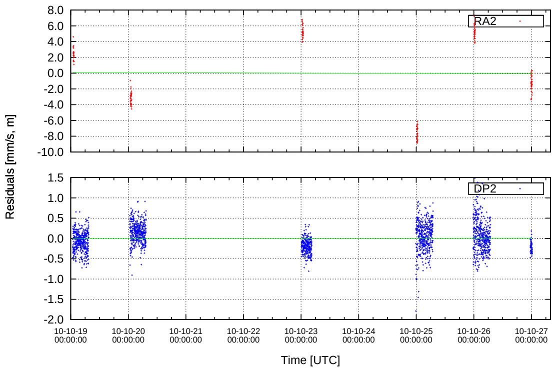
$$\boldsymbol{T} = P\frac{\pi R^3}{3}\begin{pmatrix} A & -B \\ B & A \end{pmatrix}\begin{pmatrix} \cos(\delta-\delta_S)\sin(\alpha-\alpha_S) \\ \sin(\delta-\delta_S) \end{pmatrix} \tag{6}$$

where α_S, δ_S are the Sun direction and P is the solar radiation pressure. The A, B would be the estimate parameter for the attitude correction method.

Figure 8 illustrates the attitude correction for the coasting at early September 2010. It is seen that the attitude is slightly corrected from the original attitude history. The blue plots in Figure 7 described the revised



(a) without attitude estimation (Doppler RMS : 0.56 mm/s)



(b) with attitude estimation (Doppler RMS : 0.32 mm/s)

Figure 9. Range and Doppler residual with and without the attitude estimation

NSRP with the attitude correction. It is described Figure 9 that the residuals are becomes regular with the attitude estimation. Both Doppler and range residuals becomes small. The root mean square (RMS) of the Doppler residuals becomes 0.32 mm/s from 0.56 mm/s. It is found that the attitude correction method works properly.

4. Conclusion

The solar sail force estimation was investigated using the tracking data of IKAROS nominal phase. The solar sail acceleration was estimated with new attitude correction method and the reliable solar sail acceleration was confirmed by the normalized acceleration. According to the estimation, about 90 % of the expected performance is confirmed.

Reference

1) Kawaguchi, J., Fujiwara, A., and Uesugi, T., "Hayabusa-Its technology and science accomplishment summary and Hayabusa-2," *Acta Astronautica*, Vol. 62, No. 10-11, 2008, pp. 639–647.

2) Leipold, M., Seboldt, W., Lingner, S., Borg, E., Herrmann, A., Pabsch, A., Wagner, O., and Brueckner, J., "Mercury sun-synchronous polar orbiter with a solar sail," *Acta Astronautica*, Vol. 39, No. 1-4, 1996, pp. 143 – 151.

3) Macdonald, M. and McInnes, C. R., "Realistic earth escape strategies for solar sailing," *Journal of Guidance, Control, and Dynamics*, Vol. 28, No. 2, 2005, pp. 315–323.

4) Morrow, E., Scheeres, D. J., and Lubin, D., "Solar sail orbit operations at asteroids," *Journal of Spacecraft and Rockets*, Vol. 38, No. 2, 2001, pp. 279–286.

5) Dachwald, B., "Optimal solar-sail trajectories for missions to the outer solar system," *Journal of Guidance, Control, and Dynamics*, Vol. 28, No. 6, 2005, pp. 1187–1193.

6) Hargens-Rysanek, J., Coverstone, V. L., and Burton, R. L., "Orbital precession via cyclic pitch for the ultrasail system," *Advances in the Astronautical Sciences*, Vol. 127, 2007, pp. 1009–1028.

7) Reichhardt, T., "Setting sail for history," *Nature*, Vol. 433, No. 7027, 2005, pp. 678–679.

8) Tsuda, Y., Mori, O., Takeuchi, S., and Kawaguchi, J., "Flight result and analysis of solar sail deployment experiment using S-310 sounding rocket," *Space Technology*, Vol. 26, No. 1-2, 2006, pp. 33–39.

9) Mori, O., Shida, M., Kawaguchi, J., Nishimaki, S., Matsumoto, M., Shibasaki, Y., Hanaoka, F., Arakawa, M., and Sugita, M., "Static deployment of large membrane of spinning solar sail using a balloon," *Advances in the Astronautical Sciences*, Vol. 127, 2007, pp. 1029–1040.

10) Whorton, M. S., "Solar Sail Orbit Determination from Ground Observations: A Proposed Professional - Amateur Collaboration," *Society for Astronomical Sciences Annual Symposium*, Vol. 24, May 2005, pp. 97–100.

11) Hoot, J. E. and Whorton, M. S., "Ground Imaging for Solar Sail Orbit Determination: A Proof of Concept," *Society for Astronomical Sciences Annual Symposium*, Vol. 25, May 2006, pp. 157–163.

12) Heaton, A. F. and Brinckerhoff, A. T., "Solar sail model validation from echo trajectories," *Advances in the Astronautical Sciences*, Vol. 127, 2007, pp. 999–1008.

13) Rios-Reyes, L. and Scheeres, D. J., "Solar-sail navigation: Estimation of force, moments, and optical parameters," *Journal of Guidance, Control, and Dynamics*, Vol. 30, No. 3, 2007, pp. 660–668.

14) Montenbruck, O. and Gill, E., *Satellite Orbits: Models, Methods and Applications*, Springer, 2005.

15) Ryne, M. S., Mottinger, N. A., Broschart, S. B., You, T.-H., Higa, E., Helfrich, C., and Berry, D., "NAVIGATION SUPPORT AT JPL FOR THE JAXA AKATSUKI (PLANET-C) VENUS ORBITER MISSION," *Advances in the Astronautical Sciences*, Vol. 140, 2011.

16) Konopliv, A. S., Asmar, S. W., Folkner, W. M., Karatekin, Ö., Nunes, D. C., Smrekar, S. E., Yoder, C. F., and Zuber, M. T., "Mars high resolution gravity fields from MRO, Mars seasonal gravity, and other dynamical parameters," *Icarus*, Vol. 211, Jan. 2011, pp. 401–428.

17) McCarthy, D. D. and Petit, G., "IERS Conventions (2003)," Tech. rep., International Earth Rotation and Reference Systems Service, 2004, IERS Technical Note No. 32.

18) Vallado, D. A., Seago, J. H., and Seidelmann, P. K., "Implementation issues surrounding the new IAU reference systems for astrodynamics," *Advances in the Astronautical Sciences*, Vol. 124 I, Tampa, FL, United States, 2006, pp. 515 – 534, Terrestrial reference systems;Reference systems;Summary equations;.

19) Petit, G. and Luzum, B., "IERS Conventions (2010)," Tech. rep., International Earth Rotation and Reference Systems Service, 2010, IERS Technical Note No. 36.

20) Boehm, J., Heinkelmann, R., and Schuh, H., "Short note: A global model of pressure and temperature for geodetic applications," *Journal of Geodesy*, Vol. 81, No. 10, 2007, pp. 679–683.