Photon Acceleration Model of Flexible Spinning Solar Sail

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(Received July 22nd, 2009)

The solar sailing spacecraft is one of the promising propulsion systems for the future deep space exploration mission. Japan Aerospace Exploration Agency (JAXA) has been studying the spin solar sail spacecraft which has a squared-shape type solar sail. One of the most significant objective to control the satellite orbit of the spacecraft is to estimate the thrust force induced by the photon, namely to establish the acceleration model before the launch. In a viewpoint to use this model in orbit, the calibration of the acceleration model and evaluation of the dynamics on orbit are also important issue. This paper presents the way to construct the acceleration model of the Solar Radiation Pressure (SRP) on ground, and the calibration and evaluation strategy for this model by using the on-orbit data.

Key Words: Solar Sail, Solar Radiation Pressure, Acceleration Model, Spinning Spacecraft

Nomenclature

- $R_0$: distance between Sun and Earth
- $r$: distance between Sun and spacecraft
- $s$: Sun direction vector
- $n$: nodal vector of each element
- $\theta$: angle between vectors $s$ and $n$
- $S_0$: solar constant (i.e. 1367 [W])
- $\rho_s$: specular reflectivity
- $\sigma$: absorptivity
- $\sigma_d$: diffuse reflectivity
- $\kappa$: thermal emissive parameter

1. Introduction

The propulsion system which uses the solar radiation pressure force is called the solar sailing system. In this system, the propellant is not needed to obtain the thrust force. In other words, there is a big advantage in terms of the cost for the propellant. This feature has motivated people to research this propulsion system and it has been thought to widely spread the space exploration. Although a lot of research about the solar sail spacecraft had been studied all over the world, it has never been launched in the history of space development. The space agencies including NASA and the Planetary Society tried to launch the solar sail spacecraft, and all of those approaches were failed. Japan Aerospace Exploration Agency (JAXA) plan to launch the demonstration solar sail satellite, which named Interplanetary Kite-craft Accelerated by Radiation Of the Sun (IKAROS) as shown in Fig. 1. This spacecraft aims at the technical demonstration to generate the acceleration induced by the Solar Radiation Pressure (SRP). One of the most significant tasks to achieve the solar sail mission in terms of a navigation, is to estimate the thrust force induced by the photon, namely to establish the precise SRP model. The IKAROS project team decided to estimate the SRP coefficients in the 2-stage estimation algorithm, and already validate the adequacy of the 1st stage estimation. This paper presents the method to model the SRP and the preliminary analysis of the 2nd estimation method for the photon acceleration.

2. Configuration of IKAROS

The solar sail demonstration satellite IKAROS investigated in JAXA has the cylindrical body and the square sail membrane as shown in Fig. 2. The specification of this spacecraft is described in Table 1. This satellite will be launched in 2010 as the piggy bag satellite of the PLANET-C which is also developed in JAXA and the Venus observation spacecraft.

The sail membrane of IKAROS consist of the 7.5mm Polyimide evaporated 80 [nm] aluminum. A polyimide has the high thermal, mechanical and chemical resistance properties and the mass is very light. It is not an exaggeration to say that this material enables to make real the solar sail. In the IKAROS case, by receiving the sunlight to the aluminum side, the thrust force can be generated by its high reflectivity. There
are various devices on the sail membrane. The main devices are the Flexible Solar Array (FSA), the Reflectivity Control Device (RCD), and the PolyVinylidene DiFluoride (PVDF) dust collector. The FSA is a thin power collector by sunlight. If the large power collection system by this FSA can be constructed, it is possible to load the high power ion engine on the spacecraft. This propulsion system like a hybrid of the ion engine and the large size sail solar loading on a number of FSA makes the capability of deep space mission wider. The RCD is used to control the attitude of spacecraft. This device is mainly made by the liquid crystal, and it can translate the ratio of reflectivity on each element’s surface. This device is mainly made by the polyimide membrane evaporated thin aluminum. The Each device has a different optical feature. To be precise, although the all elements on the membrane must be taken into account, we consider the optical properties only of the sail membrane, the FSA, and the RCD in terms of the dominance of the area. The portion of the area on the membrane and the nominal optical parameters are shown in Table 2.

Table 2. Portion & nominal optical parameters of each component.

<table>
<thead>
<tr>
<th>Property</th>
<th>Membrane</th>
<th>FSA</th>
<th>RCD</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A       )</td>
<td>149.5 [m²]</td>
<td>10.3 [m²]</td>
<td>18 [m²]</td>
</tr>
<tr>
<td>( \rho_1 )</td>
<td>0.819</td>
<td>0.035</td>
<td>0.01</td>
</tr>
<tr>
<td>( \sigma_1 )</td>
<td>0.119</td>
<td>0.866</td>
<td>0.44</td>
</tr>
<tr>
<td>( \sigma_0 )</td>
<td>0.062</td>
<td>0.099</td>
<td>0.55</td>
</tr>
</tbody>
</table>

The optical parameters are dealt as the constant parameter for the general materials in modeling the solar radiation pressure. The membrane’s optical feature is almost same as the aluminum, because its surface faced to the Sun is evaporated by the aluminum. Therefore, its optical parameters can be dealt as the constant. For the object which has a laminate structure such as the FSA, however, we should better take into account the effect of the refraction. It is because especially the specular reflectivity has an angular dependency, which means the thrust power is changed by the change of the angle of incidence (macroscopically equal to the attitude). This angular dependency in the laminate structure can be explained in the thin-film optics field\(^1\). Fig. 3. shows the angular dependency of the laminate structure of FSA, calculated by the equation of the thin-film optics theory.

This calculation is based on the complex index of refraction, and this value should be confirmed by the experiment. In the simulation of this acceleration model, this angle dependency of the FSA is taken into account. Although there is also the wavelength dependency for the reflection and should be taken into account, it is not considered in this study.

3.2. Thermal radiation

The effect of the thermal radiation is taken into account in Eq. (1) as the emissive parameter \( \kappa \). In the general spacecraft, this emissive parameter can be expressed as Eq. (2) under the approximation that the emission follows Lambertian reflectance.

\[
\kappa = (\varepsilon_f \cdot T_f^4 - \varepsilon_b \cdot T_b^4)/(\varepsilon_f \cdot T_f^4 + \varepsilon_b \cdot T_b^4) \tag{2}
\]

where, \( \varepsilon_f \) and \( \varepsilon_b \) denotes the emissivity of the front side and the backside against the sunlight, \( T_f \) and \( T_b \) denotes the

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Table 1. Specification of IKAROS.

<table>
<thead>
<tr>
<th>Property</th>
<th>Sail membrane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body structure</td>
<td>Cylinder Square</td>
</tr>
<tr>
<td>Shape</td>
<td>Cylinder Square</td>
</tr>
<tr>
<td>Size</td>
<td>( \phi 500 \times h 400 ) [mm] 14 x 14 [m]</td>
</tr>
<tr>
<td>Mass</td>
<td>(-300) [kg] (-15) [kg]</td>
</tr>
<tr>
<td>Material</td>
<td>Al7075, Al6061, CFRP, SUS304 Polyimide</td>
</tr>
</tbody>
</table>

3. Photon Acceleration Model

In general, the acceleration model by the solar radiation pressure can be expressed as Eq. (1).

\[
a = -\frac{S}{mc} \left( \frac{R_0}{r} \right)^2 \int_0^\pi \int_0^{2\pi} \int_0^\pi \left( \sigma_1 + \sigma_2 \right) n \cdot \left[ \left( B_1 \sigma_1 + \sigma_1 \kappa + 2 \rho_1 \cos \theta \right) \right] m dA dA dA
\]

where, \( m \) denotes the mass of the spacecraft, \( c \) denotes the light speed, \( A \) denotes the area of element. From this equation, we can see the necessary parameters, and need to consider about each parameter can be from what factor.

3.1. Optical properties

The specular reflectivity \( \rho \), absorptivity \( \sigma \), and diffuse reflectivity \( \sigma \) are named as the optical parameters on the whole. In the sail membrane of IKAROS, there are several devices including the FSA’s and the RCD’s in addition to the

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Fig. 2. Configuration of IKAROS.

Fig. 3. Angular dependency of FSA.
The solar parameter 3.3. Distance from the Sun

The emissivity is relatively small compared to the backside. The range from 300[K] to 500[K], because the front side emissive parameter defined as Eq. (3).

\[ \kappa = (\varepsilon_f B_f - \varepsilon_b B_b) / (\varepsilon_f + \varepsilon_b) \]  

(3)

Although there seems no effect of the surface temperature in this equation, the emissivity of a certain material has the temperature dependency. It means eventually the emissive parameter follows to Eq. (4).

\[ \kappa = (\varepsilon_f(T) - \varepsilon_b(T)) / (\varepsilon_f(T) + \varepsilon_b(T)) \]  

(4)

This temperature dependency is calculated by the appropriate way and should be evaluated by the proper experiment. In this study, however, this dependency is referred to the experiment data in Ref. 3) as the primitive consideration. Fig. 4. shows the temperature dependency of the emissivity of the polyimide film evaporated thin aluminum (Kapton-H/Al) and the emissive parameter calculated by using this temperature dependent emissivity for the backside of the sunlight and the constant emissivity for the front side.

From this orbit, the distance of the spacecraft from the Sun can be known and the solar parameter is calculated. Accompanying the input power by the sunlight increases with the distance, the temperature of the sail membrane also increases. The temperature can be obtained from Eq. (5) with the absorptivity of the front side and the emissivity of front and back side.

\[ T = \sqrt[\sigma P_e / \sigma (\varepsilon_f + \varepsilon_b)} \]  

(5)

where \(\sigma\) denotes the Stefan-Boltzmann constant (i.e. 5.67 \times 10^{-8} [W/m^2K^4]). Fig. 6. shows the temperature of the sail membrane and the distance of the spacecraft from the Sun.

By using this temperature variation, we can obtain the emissive parameter at each temperature from Fig. 4.

\[ 3.4. \text{Configuration of sail membrane} \]

The shape of the membrane is not a just flat plate. It is bent by the radiation pressure. Although the exact configuration must be simulated by the Finite Element Method (FEM), it takes time to construct the software and also calculate. In this study, only simple shape model for the deformation of the out plane is used by calculating from the elastic dynamics equation. The displacement of the sail membrane can be calculated as follow under the assumption that there is no tip mass on the edge of the membrane:

\[ z = k \log \left( \sqrt{x^2 + y^2} / r_e \right) \]  

(6)

with the parameter \(k\) defined by the solar constant, and the parameter \(\eta\) consist of area density of the membrane and the spin rate, and Poisson ratio as described in Eqs. (7) and (8).

\[ k = P_e / 2\eta, \quad \eta = (3 + \nu)\mu \Omega^2 / 8 \]  

(7) - (8)

where, \(\nu\) denotes the Poisson ratio (= 0.3), \(\mu\) denotes the area density (= 0.075 [kg/m^2]), and \(\Omega\) denotes the spin rate around z-axis in body fixed frame (= 1 [rpm]). Fig. 7. shows the variation of displacement at several distances from the Sun (0.713 [AU] ~ 1 [AU]).
The displacement increases proportional to the solar parameter. The normal direction of this membrane surface can be expressed as follow;

\[ n = \frac{1}{\sqrt{1 + k^2 (x^2 + y^2)}} \left( \frac{kx (x^2 + y^2)}{ky (x^2 + y^2)} \right) \]  

(9)

Finally the acceleration can be calculated by this normal vector of each element of the sail membrane.

4. Comparison with Simple SRP Model

In order to evaluate the contribution to the acceleration by each factor mentioned above, we compare the full modeled acceleration with the simple acceleration model expressed as follow;

\[ a = \frac{S A (b^2)}{mc} \left( \cos \theta \right) \left( 1 - \rho \right) \left( \sin \left( \frac{2}{3} \sigma_1 + 2 \rho \cos \theta \right) \right) \]  

(10)

The optical parameters of the whole sail are assumed to be equal to the membrane. The result of this comparison is shown as the difference of accelerations (full model – simple model) with elapsed time from the launch to 200 days later in Fig. 8. The attitude is assumed to be varied through the nominal sequence in the orbit plane shown as the black line in Fig. 8.

![Fig. 8. Comparison of acceleration between full model and simple single plane model.](image)

The acceleration of full model is smaller than that of the simple model. The main reasons of this difference are due to the segmentation of the optical properties and the thermal radiation force. The contribution to this difference of the photon acceleration induced by each factor is summarized in Table 3.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Max Diff a [km/s²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Parameters</td>
<td></td>
</tr>
<tr>
<td>Segmentation</td>
<td>3.4 × 10⁻⁸</td>
</tr>
<tr>
<td>Angular Dependency</td>
<td>3.7 × 10⁻¹²</td>
</tr>
<tr>
<td>Thermal Radiation</td>
<td></td>
</tr>
<tr>
<td>Nominal</td>
<td>1.8 × 10⁻¹⁰</td>
</tr>
<tr>
<td>Temperature Dependency</td>
<td>4.1 × 10⁻¹²</td>
</tr>
<tr>
<td>Sail Configuration</td>
<td></td>
</tr>
<tr>
<td>Nominal</td>
<td>2.2 × 10⁻¹⁰</td>
</tr>
<tr>
<td>Distance Dependency</td>
<td>5.0 × 10⁻¹⁴</td>
</tr>
<tr>
<td>Angular Dependency</td>
<td>2.4 × 10⁻¹⁷</td>
</tr>
</tbody>
</table>

*1 the nominal value of the thermal radiation is the case that thermal radiation is considered without temperature dependency, *2 the nominal value of sail configuration is the case that the solar parameter contributed to sail shape is constant despite the distance or Sun angle

This is because the optical parameter especially the specular reflectivity of the FSA and the RCD is smaller than the membrane. This feature indicates it is difficult to estimate acceleration properly for whole attitude range by the simple single plane model.

5. On-orbit Calibration of Model

The photon acceleration model should be calibrated by the on-orbit data to use for the navigation of the future solar sail. The acceleration of the spacecraft in orbit mainly is given by the Orbit Determination (OD) process with estimating the position and the velocity. In general, the optical parameter (or parameters) of the acceleration is estimated in the OD process, then the acceleration model is constructed by this parameter (or these parameters). In the IKAROS case, however, we plan to propose a slightly different approach to obtain the photon acceleration model, which is separated two-stage estimation; the nominal 3-pass OD and the long term estimation. On the first stage, the acceleration is estimated as the single plane sail for several attitude orientations. After that, the acceleration at each point is combined as the detail model as shown in Fig. 9.

![Fig. 9. Image of 2-stage acceleration estimation.](image)

There are two main reasons for this approach; one is that we should know the photon acceleration in the several attitude orientations, the other is that the number of parameters for the acceleration is more than the general SRP model. The first reason indicates the OD is preferred to be performed during whole period of the spacecraft’s life time without any disturbance force. In the IKAROS operation sequence, however, it is impossible not to use the Reaction Control System (RCS) to change the attitude during so long time (several days). That is why, as the first stage estimation, the nominal OD is performed by using the 3-pass coasting range and range rate data during the interval of the RCS operating periods as shown in Fig. 10. In this process, the configuration of the membrane is assumed to be the single flat plane. Therefore, there exists the difference of the acceleration induced by the difference of the configuration model such as mentioned in section 3.4. Nevertheless, even in this 3-pass coasting OD process, it is confirmed that the acceleration is estimated within the adequate accuracy (See Ref [1]).

On the other hand, the second reason is supposed to be caused by this small difference of the acceleration which is un-modeled by the single plane model used in the first stage estimation process. Therefore, we plan to take into account this un-modeled effect in the second stage estimation. In the
second stage estimation, the photon acceleration is modeled by the Generalized Sail Model (GSM).

\[
\mathbf{F} = \frac{S \sigma \lambda}{c} \int \mathbf{A}(\hat{r}) \mathbf{J} \mathbf{J}^T \mathbf{r} - 2 \hat{r} \cdot \mathbf{J}^T \mathbf{r} - (\mathbf{J}^T \mathbf{r})^2 \, dA
\]

(11)

where \( \hat{r} \) denotes the Sun direction unit vector \( \mathbf{A}(\hat{r}) \) denotes the attitude matrix which consists of the components of \( \hat{r} \), and \( \mathbf{J} \) is the coefficient matrix composed by three tensors \( \mathbf{J}_1 \), \( \mathbf{J}_2 \) and \( \mathbf{J}_3 \) expanded as:

\[
\mathbf{J}_1 = \frac{1}{A} \int \mathbf{a}_1 \hat{n} \, dA; \quad \mathbf{J}_2 = \frac{1}{A} \int \mathbf{a}_2 \hat{n} \, dA; \quad \mathbf{J}_3 = \frac{1}{A} \int \mathbf{a}_3 \hat{n} \, dA
\]

(12)

where \( \mathbf{a}_1 = B, \mathbf{a}_2 = \sigma, \mathbf{a}_3 = \kappa \) and \( \hat{n} \) is the normal vector to the surface of a certain location on the sail and this vector can be expressed as a function of location of each point of the surface. The components of these tensors have the symmetry in all their indices, hence the number of the coefficients for the force in GSM can be reduced to 19 parameters. In order to estimate these full coefficients, GSM paper suggests the need of dozens of measurements. In practice, however, it is difficult to achieve to get so many measurements in the continuous state such as IKAROS case.

In addition to symmetric reduction for the number of parameter, we can reduce that under some assumptions for the shape of the sail. Especially the rotational spacecraft case which has the axis symmetry, GSM proposed only 5 coefficients can construct the force model. In this case, these 5 parameters are expanded as follows:

\[
\mathbf{J}_1 = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}; \quad \mathbf{J}_2 = \begin{bmatrix} J_{11}^1 \\ 0 \\ 0 \end{bmatrix}; \quad \mathbf{J}_3 = \begin{bmatrix} J_{11}^3 \\ 0 \\ 0 \end{bmatrix}
\]

(13)

with the equality between some coefficients: \( J_{11}^2 = J_{21}^2, J_{11}^3 = J_{21}^3, J_{11}^1 = J_{21}^1 = J_{11}^1 = J_{21}^2 \). If we assume that the configuration of the membrane is expressed as Eq. (6), each coefficient can be determined to be follows:

\[
J_1^1 = (1 - \rho_c) \pi (R_s^2 - R_2^2) / A
\]

\[
J_1^2 = J_2^2 = a_3 \pi \lambda^2 / A \left( R_0 + \sqrt{k^2 + R_2^2} \right) / R_0 \left( R_0 + \sqrt{k^2 + R_2^2} \right)
\]

\[
J_1^3 = \frac{a_3 \pi}{A} \left( R_0 \sqrt{k^2 + R_2^2} - R_0 \sqrt{k^2 + R_2^2} - k^2 \log \left( \frac{R_0 + \sqrt{k^2 + R_2^2}}{R_0 + \sqrt{k^2 + R_2^2}} \right) \right)
\]

\[
J_3^1 = J_3^2 = J_3^3 = \rho_2 \pi \lambda^2 / 2A \left( k^2 + R_2^2 \right)
\]

(14) - (18)

In these equations, there is a dependency between equations. Especially, Eq. (18) can be expressed as the sum of Eq. (14), Eq. (17) and a constant parameter as follow:

\[
J_3^{133} = \pi (R_s^2 - R_2^2) / (k^2 + R_2^2)
\]

(19)

By using this translation, finally, we can reduce the number of coefficients to 4 parameters.

5.2. 2nd Estimation of acceleration

In order to construct the photon acceleration by using the on-orbit data, we estimate the \( \mathbf{J} \) coefficients. As we discussed in the previous section, finally the photon acceleration model can be expressed with 4 coefficients as follow:

\[
\mathbf{F} = P(\mathbf{r}) \mathbf{A} \begin{bmatrix} \mathbf{A}_1 \\ \mathbf{A}_2 \\ \mathbf{A}_3 \end{bmatrix} \begin{bmatrix} J_{11}^1 \\ J_{11}^2 \\ J_{11}^3 \end{bmatrix} + \mathbf{B}_1
\]

(20)

with the matrix \( \mathbf{A} \) and \( \mathbf{B} \) described as follow:

\[
\mathbf{A}_0(\hat{r}) = \begin{bmatrix} -\rho_c \rho_1 & \rho_1 & 0 \\ -\rho_c \rho_1 & \rho_1 & -\rho_1 \rho_2 \\ -\rho_c \rho_1 & \rho_1 & 0 \end{bmatrix}, \quad \mathbf{B}_0 = \begin{bmatrix} 0 \\ -2 \rho_2 \pi (R_s^2 - R_2^2) / A \\ 0 \end{bmatrix}
\]

(21), (22)

After some transformation from Eq. (20), we notice the form of the equation become measurement equation of the linear least-square;

\[
\mathbf{y} = \mathbf{H} \mathbf{x}
\]

(23)

where the observation vector \( \mathbf{y} \) can be expanded as Eq. (24) and
the force matrix $F$ in Eq. (24) is the actual measurement provided by the first stage OD, the measurement matrix $H$ consists of the attitude matrix, $H = [A_1, A_2, \ldots, A_J]^T$, and the state vector $x$ is composed by the $J$ coefficients $x = (J_1^T, J_2^T, \ldots, J_J^T)^T$.

$$y = \frac{F(r)}{P(r)} A$$

By using measurement equation, Eq. (23), we can implement the primitive linear least-square estimation and solution is given by the following equation:

$$x = (H^TH)^{-1}Hy$$

Therefore, we estimate the $J$ coefficients and construct the on-orbit photon acceleration model by using these $4$ estimated parameters. Although the simple least-square is implemented in this paper as a preliminary study, there are many options in terms of the estimation method and its algorithm. For instance, we consider that the non-linear case for the measurement equation in the next study. As the example of the actual estimation problem, we estimate the $J$ coefficients by using the simulation data of acceleration. The estimation conditions are described in Table 4.

### Table 4. Estimation conditions in the simulation.

<table>
<thead>
<tr>
<th>Method</th>
<th>Linear Least-Square</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>315 [kg]</td>
</tr>
<tr>
<td>Spacecraft Shape</td>
<td>Rotational (Circle)</td>
</tr>
<tr>
<td>Measurement</td>
<td>Acceleration</td>
</tr>
<tr>
<td>Number of Measurements</td>
<td>8 points</td>
</tr>
</tbody>
</table>

We assume that the $1^{st}$ stage OD is performed at $8$ points which is shown as the aqua blue line in Fig. 11, and use the accelerations at each point as the measurement for the $2^{nd}$ stage estimation. Although there are some noises caused by the several reasons should be considered, the measurements are assumed to be clean data without noises in this simulation. Fig. 11. shows the difference of accelerations between the estimates and the measurements and Table 5. is the summary of result of this estimation. Because the order of the nominal magnitude of the photon acceleration for IKAROS is supposed to be $10^{-9}$ [km/s$^2$] (which means the difference is less than hundreth of that), we can mention that the result shows this method works adequately as the first impression. The eight OD points are the realistic number of OD points in the actual operation, and the estimation result shows the adequacy of this estimation method in practice.

![Fig. 11. Difference of accelerations between measurement & estimates.](image)

### Table 5. Summary of results of estimation.

<table>
<thead>
<tr>
<th>Max difference [km/s$^2$]</th>
<th>$\Delta a_x = 0.0$</th>
<th>$\Delta a_y = 8.1e-3$</th>
<th>$\Delta a_z = 4.2e-12$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimates</td>
<td>$J_1 = 0.318$</td>
<td>$J_2 = 2.2e-3$</td>
<td>$J_3 = 0.039$</td>
</tr>
<tr>
<td></td>
<td>$J_{11} = -2.6e-3$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In Fig. 11., there is still some difference between the estimates and the simulated acceleration and that difference are synchronized with the attitude sequence. This is clearly because the intension of the input of solar power is changed with the sun angle. The main reason of this difference is from the difference of optical properties. In the simulated acceleration, the optical properties are split up to $3$ parts as mentioned in section 3.1. On the other hand, in the estimation process, the optical properties are averaged by sum of all parts of the membrane surface. This result indicates the optical properties also should be taken into account in GSM, which means the optical properties in Eq. (12) should be included in the integral.

### 6. Conclusion

In this study, we discuss about the acceleration model constructed by based on the on-ground experiment and the analysis, and also the calibration method on-orbit. This research now initialized and it needs more study. The launch of the IKAROS spacecraft is scheduled in 2010, and we must construct this acceleration model by that date under the responsibility for the mission criteria. In remaining one year, the following study should be implemented.

- Experiments to obtain the reflectivity of each component on sail membrane
- Precise thermal analysis
- Analysis for more precise membrane configuration model
- Construct the calibration method by on-orbit attitude data

It is significant to construct the acceleration model based on-ground experiments and the analysis, in terms of the design of navigation of the spacecraft. If the acceleration model can be calibrated by the actual on-orbit data, it will be large contribution to the deep space exploration as the first actual photon acceleration model of the solar sail. Also this model can be applied for the future solar sail planed to develop by JAXA.

### References