Attitude Control Flight Experience:
Coping with Solar Radiation and Ion Engines Leak Thrust in Hayabusa (MUSES-C)

Jun'ichiro Kawaguchi*, Takashi Kominato# and Ken'ichi Shirakawa#

The paper presents the attitude reorientation taking the advantage of solar radiation pressure without use of any fuel aboard. The strategy had been adopted to make Hayabusa spacecraft keep pointed toward the Sun for several months, while spinning. The paper adds the above mentioned results reported in Sedona this February showing another challenge of combining ion engines propulsion tactically balanced with the solar radiation torque with no spin motion. The operation has been performed since this March for a half year successfully. The flight results are presented with the estimated solar array panel diffusion coefficient and the ion engine's swirl torque.

1. INTRODUCTION

The Hayabusa (MUSES-C) spacecraft suffered from the fuel leak problem and lost most of chemical fuel at the end of November in 2005, and it has been in spin-stabilized state taking the advantage of Xe gas for ion engines as the cold-gas thrusters, since its restoration in January of 2006. The flight period left until the return to the Earth in 2010 requests the spacecraft spin axis to be pointed to and track the sun direction for one complete rotation. The solar radiation torque that may apply was estimated to well exceed the Xe gas amount left, if a conventional attitude control scheme is adopted. Even the diffusion component of the radiation pressure on the solar array panel is hardly known, and must be compensated with a certain manner without use of extra Xe gas aboard. This is what the troubled Hayabusa spacecraft cannot cope with easily.

The Hayabusa project team intentionally adopted the method of making the spinning spacecraft attitude drifted by the solar radiation pressure, so that the orientation can track the sun direction without use of any fuel. The typical spin direction behavior actually experienced is shown in the figures below.

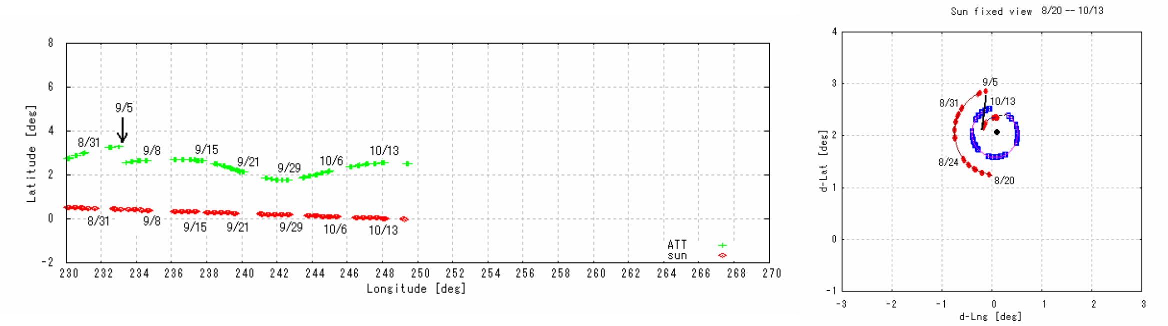

Fig. 1a Typical Spin Attitude Maneuver History using Solar Radiation Pressure (by Feb., 2007)

Left figure shows the sun angle along with time, while right figure shows the spin axis direction history with respect to the sun. The results simply show that the attitude has not been frozen in inertial frame, but had moved to track the sun direction all the time. Note no fuel was consumed for the period, once the attitude control was performed to place the spin direction into the intended direction.

The flight results above also show the diffusion coefficients of the solar array panel through its coning motion. The property is what is hardly known, however, is estimated now by introducing an ultra slow spin rate taken for Hayabusa. Hayabusa drastically lost its propulsion capability and it had to rely on this strategy to save Xenon gas aboard. The results are satisfactory and the spacecraft is sure to return to the Earth in 2010.

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* Institute of Space and Astronautical Science (ISAS), Japan Aerospace Agency,
3-1-1 Yoshinodai, Sagamihara 229-8510, Japan, E-mail: kawaguchi.junichiro@jaxa.jp
NEC Aerspace Inc.

Before March of 2007, the spacecraft was in spinning motion with the above mentioned drift maneuver tracking the Sun direction. Hayabusa restarted its ion engines operation from this March. And the spin motion stopped and the three axis stabilization started taking the advantage of a single z-axis wheel. Now the Hayabusa made another challenge to track the Sun direction through subtle balancing of solar radiation torque with the ion engine's swirl leak torque, with both its reaction wheel turned on and the ion engines gimbaled table utilized. Since the ion engine's thrust direction is specified from the trajectory point of view and the swirl torque amount is not controllable, tracking the Sun direction taking the advantage of the solar radiation torque is not precisely compatible. However, the spacecraft operation team so far successfully has operated this challenge. The figure below shows the how we have struggled to cope with the attitude and orbital maneuvers for Hayabusa.

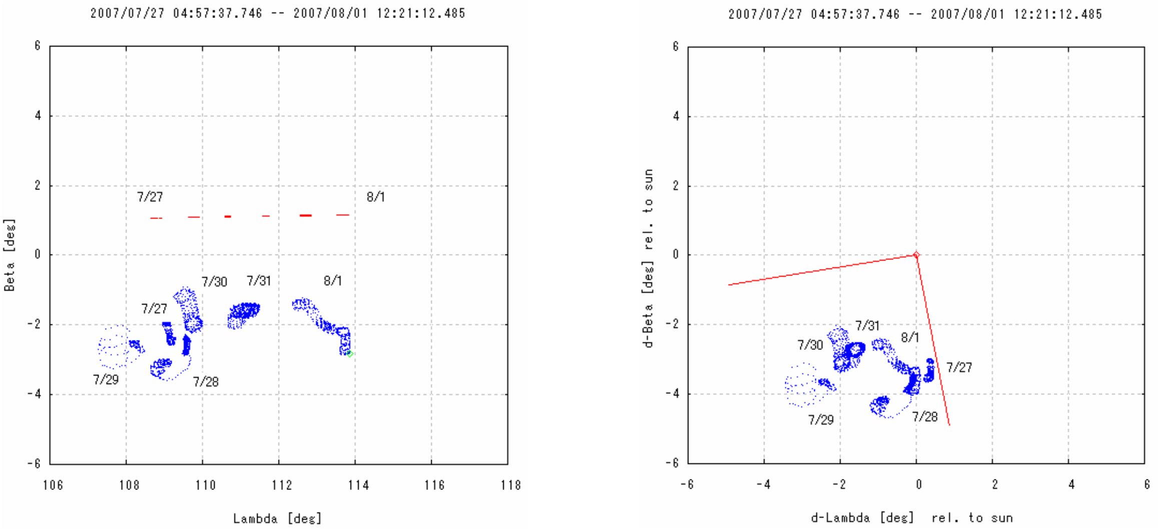


Fig. 1b Another Attitude and Orbital Maneuver with Ion Engines on. (end of July, '07)

2. CONTEXT AND THE PURPOSE OF THE MANEUVER

Hayabusa spacecraft (MUSES-C) lost its chemical fuel aboard and is operable relying only on the Xenon cold gas thrust of the ion engines aboard. The flight time left is almost three years and a half and during the period until the return back to the Earth, the spacecraft needs to expose its solar array panel to the sun to use the electric power not only for the ion engines propulsion but for the bus housekeeping activities. Even compensating solar radiation pressure making the solar array panel direction to the Sun costs a lot of Xenon gas amount and is hardly acceptable.

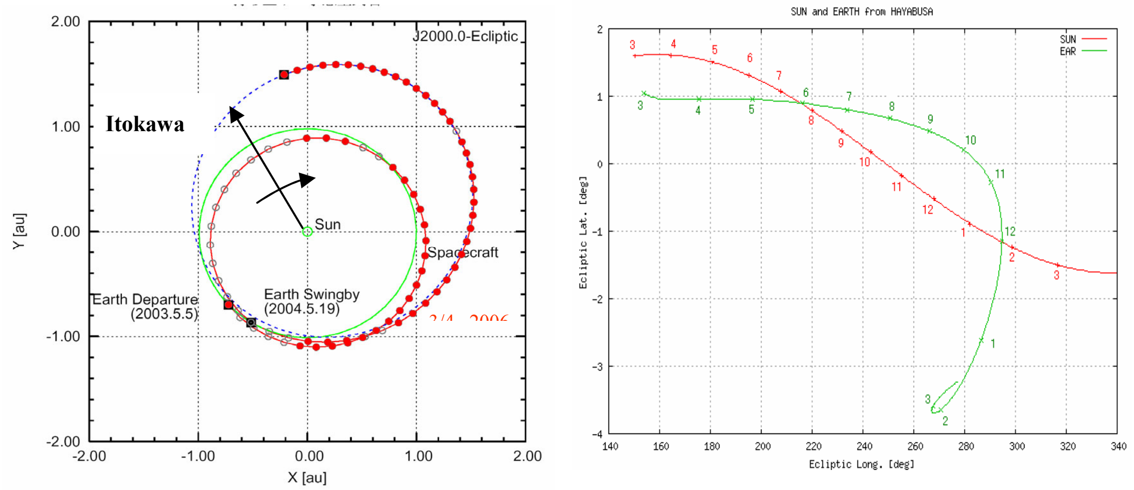


Fig. 2 The Orbit and Sun Direction History along the Hayabusa Orbit

The spacecraft must rotate its attitude two complete revolutions (i.e. 720 degrees) during the flight left against any disturbing torque applied. In order that the spacecraft extracts the solar power, the Sun angle between the normal direction of the solar array panel and the Sun direction shall be quite small. Fig. 2 below shows what the Hayabusa orbit is and how the Sun direction moves along the orbit. The problem solved here is how the spacecraft solar array direction is oriented continuously without use of any fuel aboard making use of the solar radiation pressure torque.

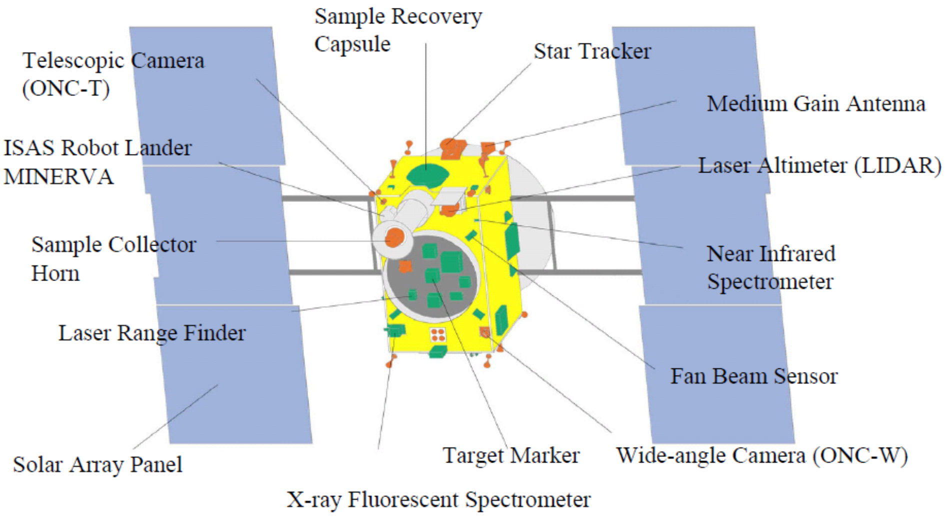


Fig. 3 The Hayabusa Spacecraft Configuration

The Hayabusa spacecraft has relatively large solar array for this class spacecraft. The Hayabusa project team decided to take the method of first of all the spin stabilization during while the spacecraft is coasting without propulsion, and the method is at the same time what utilizes the solar radiation pressure to making the attitude drift to trace the Sun direction by applying the solar radiation torque.

Historically speaking, Mariner-4 and Mariner-10 were equipped with the solar sail vane at the end of the solar array to reorient the attitude by taking the advantage of the radiation pressure. But those were three-axis stabilized spacecraft and the angular momentum to be drifted was small. And the Institute of Space and Astronautical Science (ISAS) in 1985 also applied the solar radiation torque effect to maintain the spin-stabilized interplanetary probe, Sakigake, in which the spin direction was maintained normal to the ecliptic plane taking and using the radiation torque. What was demonstrated and used for the Hayabusa is different from them in terms of the following points:

1. It is the method of actively rotating the angular momentum rather than maintenance.
2. It uses the diffusing effect of the radiation pressure associated with the solar array panel, instead of the specular reflection effect.
3. The spin direction of the Hayabusa is almost in the ecliptic plane and the attitude control was performed to trace the Sun direction.

As described above, while in spin motion, the Hayabusa spacecraft had been well controlled using the solar radiation torque. In order that the spacecraft returns home, the spacecraft should have started its ion engines cruise with no attitude control fuel aboard. It is another new challenge of very sophisticated and difficult mixture of two kinds of disturbing torque that derive from both solar radiation and ion engine's swirl leak torque. Note the spacecraft had lost two reaction wheels aboard and this attitude and orbital maneuver need to be performed only with a sing wheel with no chemical fuel. While the swirl torque magnitude is not controllable and the ion engines aperture direction must be rigorously pointed to the planned direction, there is incompatibility in what attitude the spacecraft be controlled. This difficulty is circumvented by slight shift of the equilibrium point apart beneath the Sun direction. The details are shown later in the paper.

3. DRIFT MANEUVER STRATEGY USING SOLAR RADIATION PRESSURE EFFECT

The following drawing presents the fundamental scheme taken actually by the Hayabusa flight. Note the longitude and latitude are seen from the Sun toward the spacecraft. And while the +Z axis of the spacecraft (normal direction of the solar array panels) is pointed closely to the Sun since the spin direction is reverse, the angular momentum direction is outward with respect to the celestial sphere. Fig. 4 below describes the details of the geometry. Note the coordinate system coincides with the inertial frame.

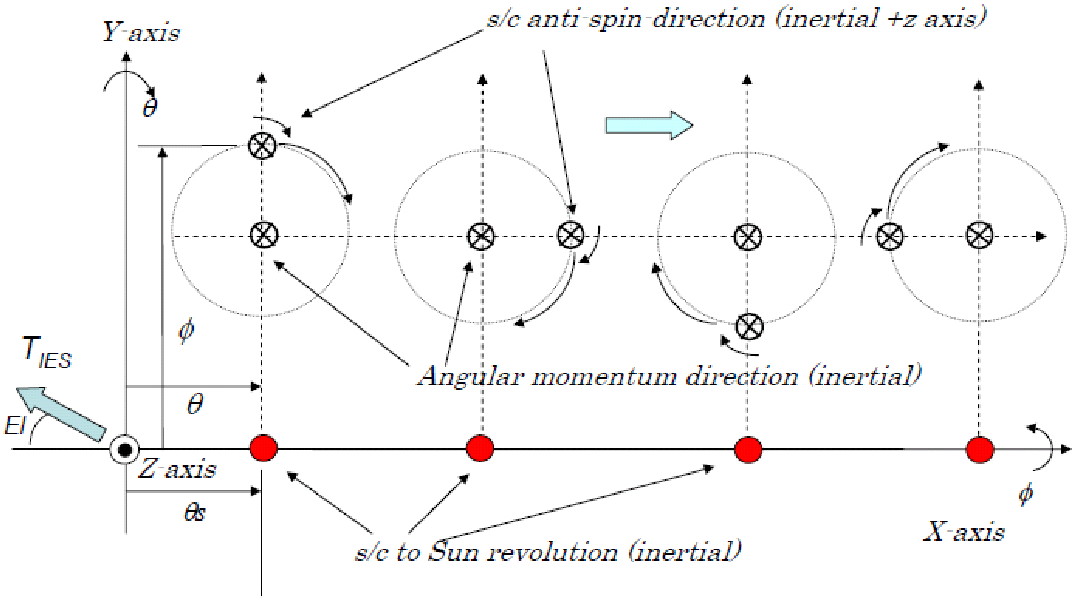


Fig. 4 Attitude Drift Strategy Using Solar Radiation Pressure

The Sun to spacecraft direction moves to the right in Fig. 4, as also the Fig.2 shows. When the spin direction is inclined upward (This implies the solar array panel is declined lower to the Sun.), the solar radiation torque increases the angular momentum $\Delta \boldsymbol{H}$ toward the +X axis direction in Fig.4 so that the drift speed can be synchronized with the Sun motion. If perfectly left to the exact direction, there will not be any long-term nutation (coning) motion around the total angular momentum direction. However, a certain initial pointing error remains and results in the very long periodic coning motion. How the solar radiation torque is generated is recognized in Fig. 5, where the radiation torques are generated around two axes. Note if no diffusion radiation force acts on the spacecraft, the solar radiation force acts always perpendicular to the solar array panels and there may not be any disturbing torque. As for the Hayabusa spacecraft, in addition to the solar array panels, the high gain antenna (parabola) antenna receives also the radiation pressure and it does apply a large contribution of drift torque to the spacecraft.

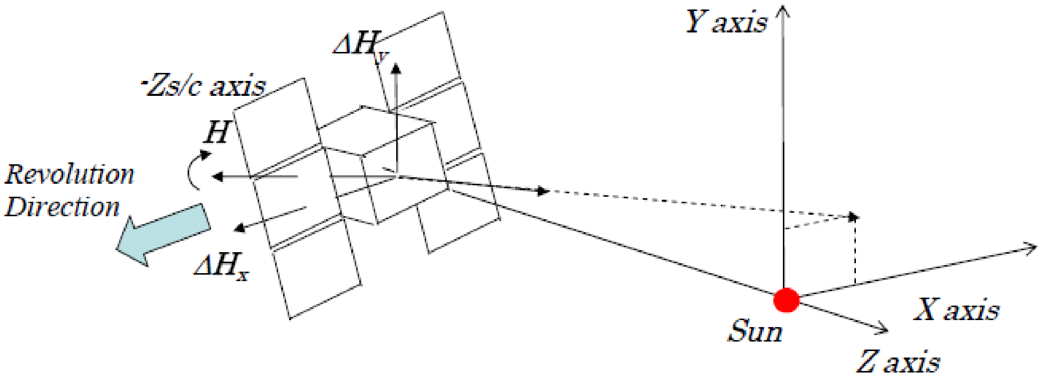


Fig. 5 Angular Momentum Fluctuation due to the Solar Radiation

4. MATHMATICAL DISCUSSION AND DRIFT PROPERTIES

Using the coordinate system in Fig. 4 and 5, using the relation of

$$\omega_x \cong -\dot{\phi}, \quad \omega_y \cong \dot{\theta}\cos\phi, \qquad (1)$$

the attitude dynamics of the spacecraft is written via the following way. Here the Spin-Free coordinate is introduced, in which the coordinate rotates with respect to the inertial space by

$$\omega_{SF} = \begin{pmatrix} \omega_x & \omega_y & 0 \end{pmatrix}^T. \qquad (2)$$

Note this coordinate is true for symmetric spacecraft but the discussion still holds approximately for the Hayabusa spacecraft. The angular momentum vector is expressed as

$$H_{s/c} = \begin{pmatrix} I\omega_x & I\omega_y & -H_0 \end{pmatrix}^T. \qquad (3)$$

Here, I denotes the moment of inertia around the axes perpendicular to the spin axis. H_0 is the total angular momentum that the Hayabusa possesses. The attitude motion is simply written as

$$\dot{H}_{s/c} + \omega_{SF} \times H_{s/c} = T_{SRP}. \quad (4)$$

Here the torque appears right is the disturbing radiation torque that derives from the following. The radiation torque direction is expressed as

$$T_{SRP} \cong \begin{pmatrix} -\phi\cos(\theta_S - \theta) \\ -\sin(\theta_S - \theta) \\ 0 \end{pmatrix} \qquad (5)$$

Here is introduced the radiation torque parameter $k = \frac{\kappa f s L}{c}$. *f, s, L* and *c* are solar flux, cross area of the spacecraft, torque arm length and the speed of light. κ here represents a certain scaling factor which corresponds to the diffusion or parabola antenna effect contribution. The equations of motion are now

$$\begin{cases} I\dot{\omega}_x - H_0\omega_y = -k\cos(\theta_S - \theta)\phi \\ I\dot{\omega}_y + H_0\omega_x = -k\sin(\theta_S - \theta) \end{cases}. \qquad (6)$$

And they are reduced to

$$\begin{cases} \ddot{\phi} + \Omega\dot{\theta} = p\phi \\ \ddot{\theta} - \Omega\dot{\phi} = -p(\theta_S - \theta) \end{cases}. \qquad (7)$$

Here, $\Omega = H_0 / I$ and $p = \frac{1}{I}\frac{\kappa f s L}{c}$. Note p has the unit of the angular acceleration. The manipulation concludes the reduced equations of motion as follows.

$$\theta^{(4)} + (\Omega^2 - 2p)\theta^{(2)} + p^2\theta = p^2\theta_S \quad (8)$$

The characteristic angular frequencies are found as

$$\omega^* \cong \begin{cases} \Omega \\ \frac{p}{\Omega} \end{cases}. \qquad (9)$$

The first type of frequency is for conventional nutation angular frequency. The second frequency is important here. It represents an extra-long period oscillation or coning effect. It is not affected by the amplitude. Note the equation (8) has a trivial solution of

$$\bar{\theta} = \theta_S. \quad (10)$$

What this means is that the spacecraft solar array direction does trace the Sun direction automatically. It behaves like an arrow in the wind. As for the f motion, a similar equation of motion appears as

$$\phi^{(4)} + (\Omega^2 - 2p)\phi^{(2)} + p^2\phi = \Omega\dot{\theta}_S p. \qquad (11)$$

The steady state solution is also found and it is

$$\bar{\phi} = \frac{\Omega}{p}\dot{\theta}_S = \frac{\dot{\theta}_S}{\omega^*}. \quad (12)$$

This characteristics also function like an arrow in the wind, and the attitude drifts automatically offset to the Sun direction. And the flight results will identify how high p parameter is.

5. FLIGHT RESULTS AND REMARKS #1

Fig. 6 presents how the first attitude auto-drift motion is accomplished.

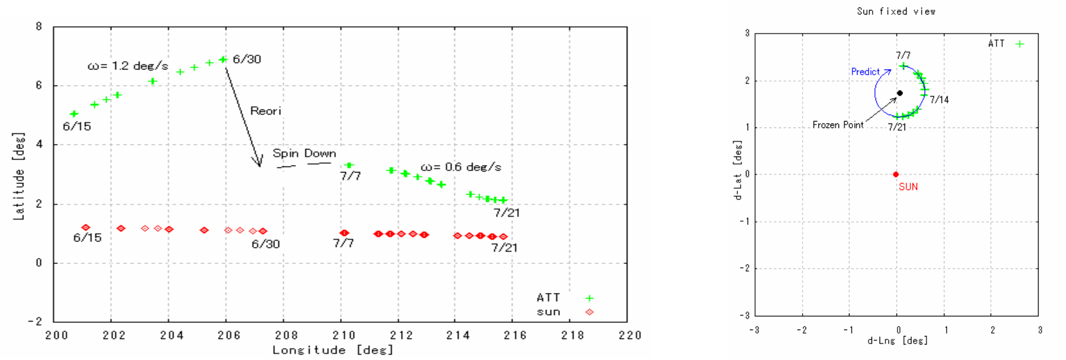


Fig. 6 Flight Results for Cycle-#1

The flight data above is for the period of the first half in July. As predicted, the attitude did revolves around a certain angular momentum direction. Note the averaged and central position is automatically determined and the attitude just circles around it.

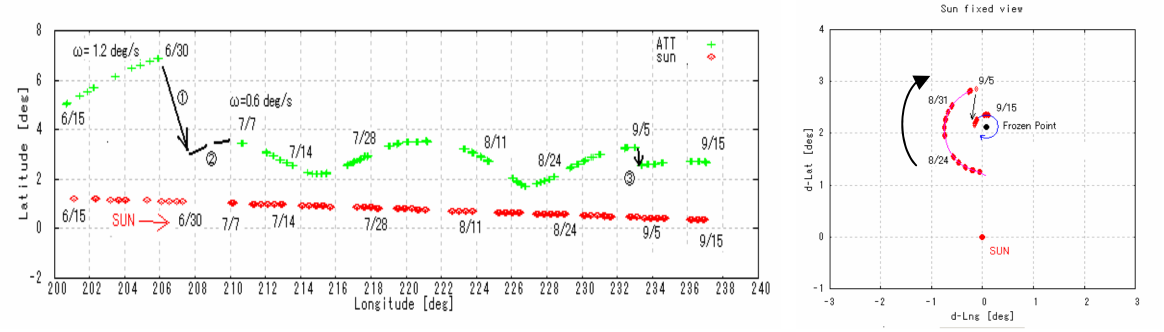


Fig. 7 Flight Results for Cycle-#2

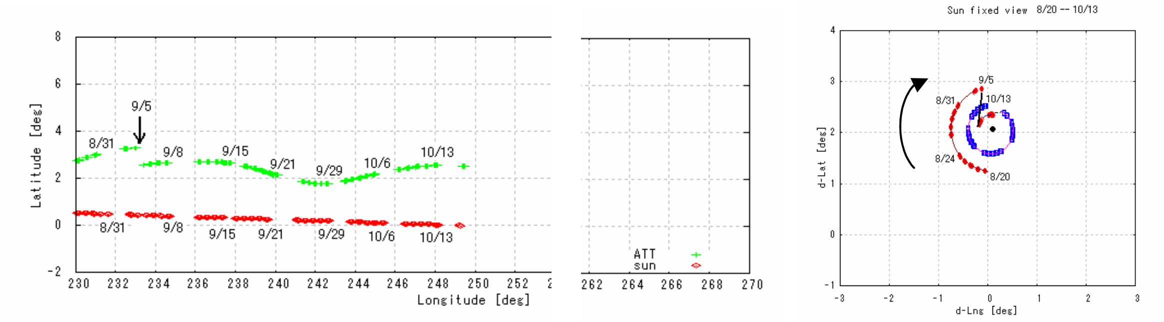


Fig. 8 Flight Results for Cycle-#3

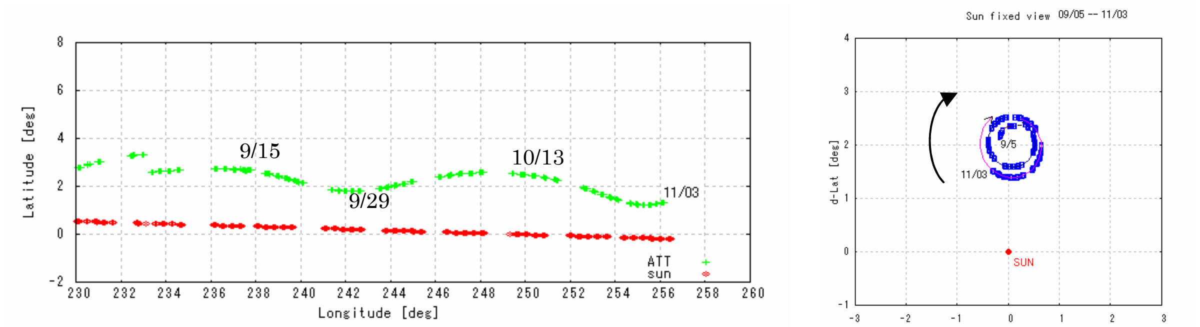


Fig. 9 Flight Results for Cycle-#4

Figures 7 to 9 present the attitude drift maneuvers flight results by the beginning of November in 2006. Regardless of the initial attitude direction, the averaged and central angular momentum direction In the Table-1, here are summarized the flight characteristics for the Cycles #1 to #4.

Table-1 Solar Radiation Pressure Attitude Control History

1. Cycle #1 (Half)	7/7-7/31, 2006		
Radius: 0.7 deg,	Period: 14 days (for half rev.),	Spin: 0.6 deg/sec,	ΔLong.= 5 deg
2. Cycle #2 (2-rev.)	7/7-9/5, 2006		
Radius: 0.7-0.8 deg,	Period: 60 days (for 2 rev.),	Spin: 0.6 deg/sec,	ΔLong.= 23 deg
3. Cycle #3 (1-rev.)	9/15-10/13, 2006		
Radius: 0.4-0.5 deg,	Period: 28 days (for 1-rev.),	Spin: 0.6 deg/sec,	ΔLong.= 11 deg
4. Cycle #4 (1.5 rev.)	7/7-7/31, 2006		
Radius: 0.4-0.5 deg,	Period: 43 days (for 1.5 rev.),	Spin: 0.6 deg/sec,	ΔLong.= 17 deg

Using the relation of $\omega^* = \dfrac{p}{\Omega}$ with the following parameters,

$$\Omega \cong 10^{-2} rad/\sec, \quad p \cong \kappa \times 3 \times 10^{-7} rad/\sec^2,$$

since $\omega^* \cong 2.5 \times 10^{-6} rad/\sec$ is what was actually observed through the flight. Here is concluded estimated

$$\kappa \cong 0.1. \qquad (13)$$

This may not be true as a diffusion reflection coefficient. However, in view of a large high gain antenna aboard, this figure might be interpreted as a typical and appropriate parameter.

Since the Sun drifts approximately

$$\dot{\theta}_S \cong 0.4 deg/day, \qquad (14)$$

during the period, the central offset angle above the ecliptic plane is automatically determined as the discussion above shows. The predicted angle for this is calculated as

$$\bar{\phi} \cong 1.9 deg. \qquad (15)$$

As the flight results indicate in the above figures, this property is actually verified satisfactorily. Thus, the analytical discussion holds for the flight results.

6. FLIGHT RESULTS AND REMARKS #2

Hayabusa started its ion engines this March toward the Earth in 2010. The difficulty is in lacking any chemical fuel aboard but ion engines plus a single reaction wheel. It was revealed that the swirl ion engines torque applies to the spacecraft and must be poised compensated by the solar radiation torque.

What the project team adopted as a strategy is:
(1) +z-axis wheel is used to maintain ion engines elevation angle.
(2) Two gimbals on the ion engines table desaturate the z-axis wheel, and also shifts z-axis north-to-south direction, so that the solar radiation torque can be balanced with the swirl torque.

When ion engines are driven, a swirl torque applies around x-axis (thrust axis), to which the solar radiation torque shall be balanced so that the spacecraft z-axis can track the Sun direction. The drift motion behaves as

$$\begin{cases} I\dot{\omega}_x - H_0\omega_y = -k\cos(\theta_S-\theta)\phi - T_{IES}\cos E_L \\ I\dot{\omega}_y + H_0\omega_x = -k\sin(\theta_S-\theta) + T_{IES}\sin E_L \end{cases} \tag{16}$$
$$\omega_x = -\dot{\phi}, \qquad \omega_y = \dot{\theta}$$

And using angular displacement, they are reduced to

.

$$\theta^{(4)} + \left(\Omega^2 - 2p\right)\theta^{(2)} + p^2\theta = p^2\theta_S - p\sin E_L \frac{T_{IES}}{I} \tag{17}$$

and

$$\phi^{(4)} + \left(\Omega^2 - 2p\right)\phi^{(2)} + p^2\phi = \Omega\dot{\theta}_S p - p\cos E_L \frac{T_{IES}}{I} \tag{18}$$

Respectively. Rigorous equilibrium conditions to track the Sun's longitude are found :

$$\bar{\phi} = \frac{1}{p^2}\left\{\Omega\dot{\theta}_S p - p\cos E_L \frac{T_{IES}}{I}\right\}, \qquad E_L = 0 \tag{19}$$

Note the latter condition is not handled, while the former condition is controlled to a certain elevation angle of the ion engine's thrust. As eq. (17) indicates, for a given, elevation angle, it should be interpreted that the ecliptic longitude θ is offset to the exact Sun direction θ_s.

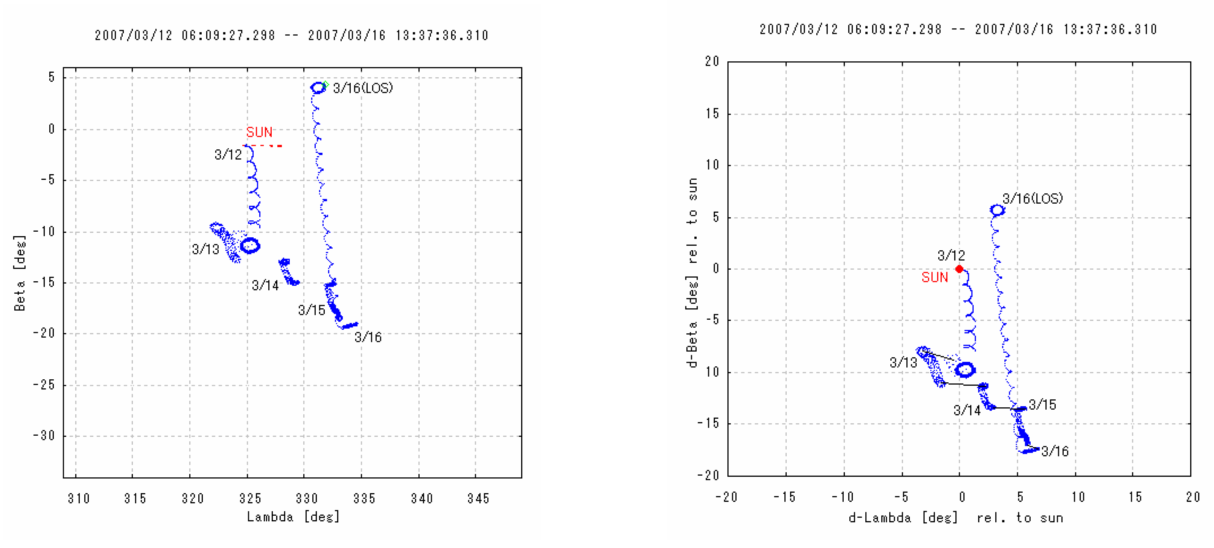


Fig. 10 Initiation of Ion Engines Operation Searching Equilibrium Points

Fig. 10 shows the first attempt to poise the solar radiation torque with the ion engines swirl torque, searching equilibrium point that tracks the Sun direction. Two ion engines were driven at the same time.

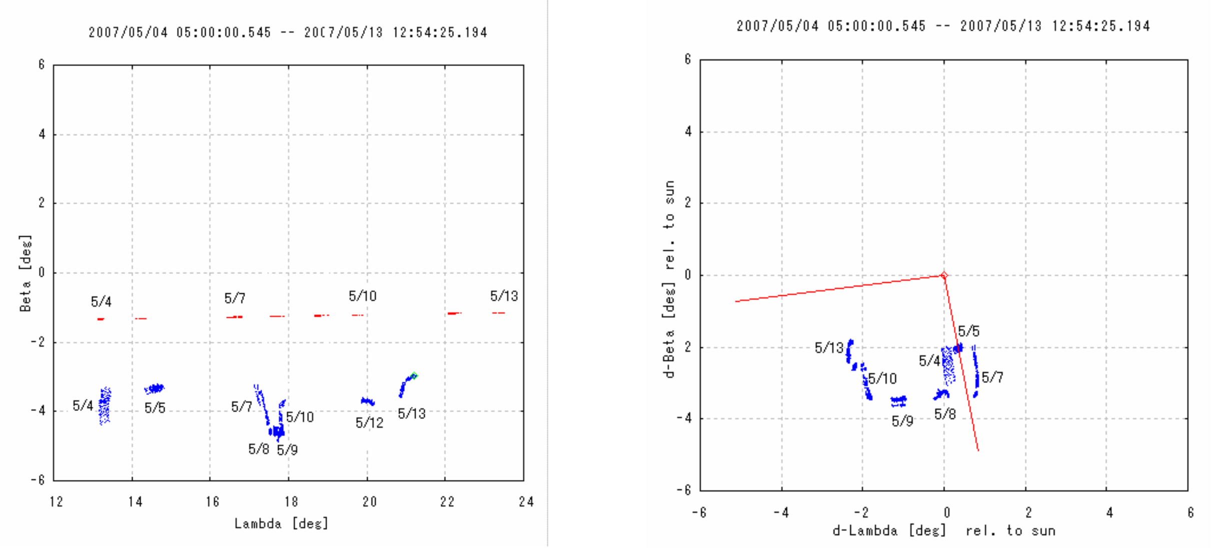


Fig. 11 5/4 to 5/13 in 2007 Engine: ITR-D

Fig. 11 shows the attitude history from 5/4 to 5/13 of 2007, when one ion engine (ITR-D) was ON. Intentionally, the z-axis is controlled to trail the Sun, so that the ion engine table can avoid the Sun light. Trailing the Sun was successful.

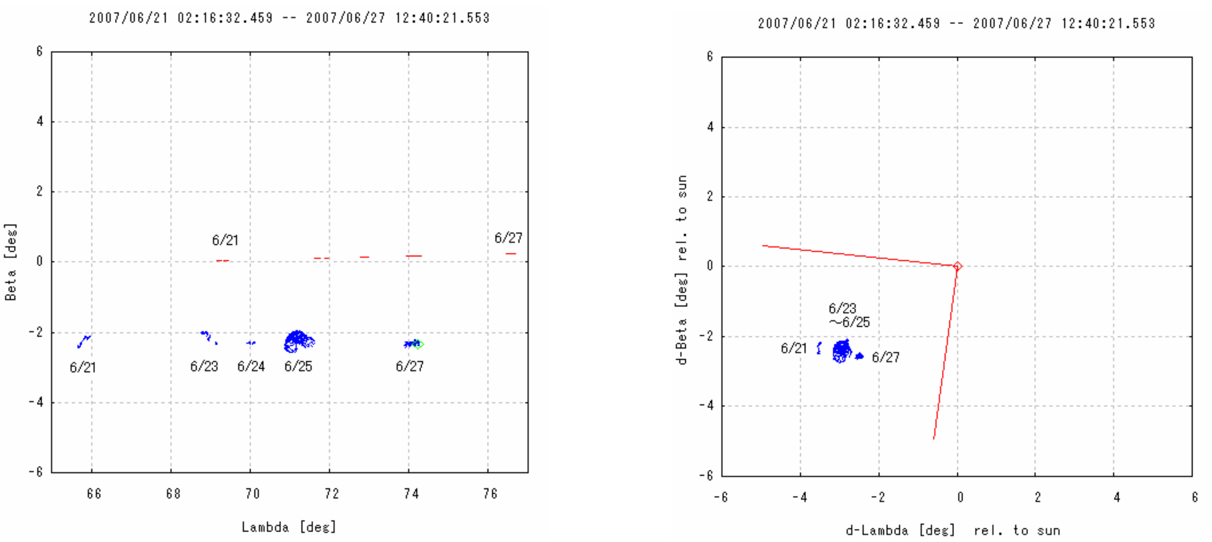


Fig. 12 6/21 to 6/27 in 2007 Engine: ITR-D

Fig. 12 shows the equilibrium point found during around the perihelion point. +Z-axis was well controlled to trail the Sun intentionally. The trail control was successful.

Fig. 13 shows the attitude history during while the ion engine head was changed from ITR-D to ITR-C. Trial-and-error maneuver was challenged. The z-axis was still well controlled within the specified region avoiding the Sun light.

Obtained flight data infers the ion engine's swirl torque will be in the order of $T_{IES} \simeq 1\ mN \cdot mm$.

However, the ion engine thrust elevation angle swiftly changes along with the attitude drift motion, and the accurate estimation of it is hardly known. Fig. 14 presents how the attitude maneuver has been taken from March to August this year. It reveals the spacecraft attitude is well controlled to track the Sun direction as planned.

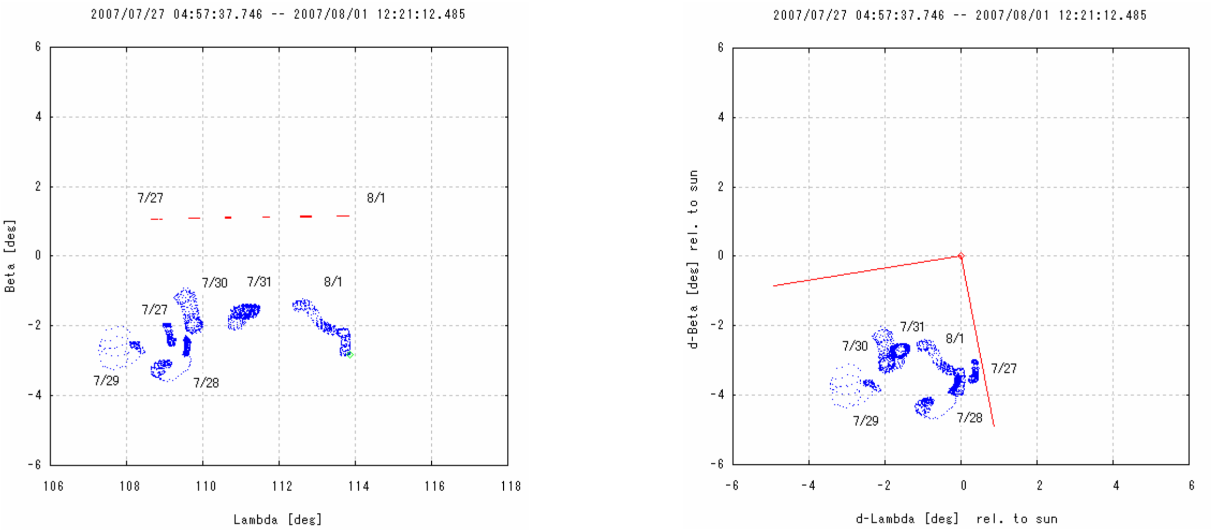
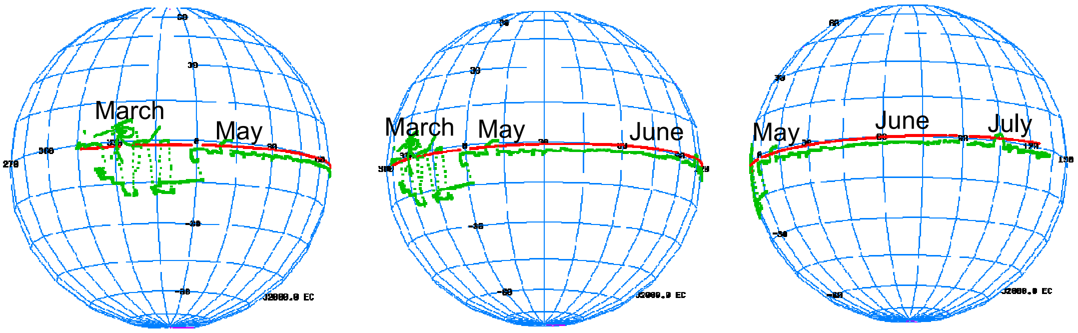


Fig. 13 7/27 to 8/1 in 2007 Engine: ITR-D switched to ITR-C

Table-2 Solar Radiation plus Ion Engines Attitude Control History

1. 3/12-3/26:
   Ω=0.0070 rad/s (3500rpm), N/A (predicted as 17.0 days)
2. 5/4-5/13:
   Ω=0.0071 rad/s (3600rpm), 18 days (predicted as 17.1 days), ϕ=-2deg
3. 6/21-6/27:
   Ω=0.0045 rad/s (2300rpm), N/A (predicted as 10.9 days), ϕ =-2deg
4. 7/27-8/1:
   Ω=0.0043 rad/s (2200rpm), N/A (predicted as 10.4 days), ϕ =-3deg



Red: Sun Direction seen from the spacecraft.
Green: Spacecraft +Z axis direction

Fig. 14 Attitude at a glance from March to August.

7. ATTITUDE TARGET FOR DRIVING ION ENGINES

Based on the above formulation, the equilibrium attitude is found as

$$\theta = \theta_s - \frac{1}{p}\sin E_L\left(\frac{T_{IES}}{I}\right), \quad \phi = \frac{\Omega\dot{\theta}_s}{p} - \frac{1}{p}\cos E_L\left(\frac{T_{IES}}{I}\right) \tag{20}$$

This is a locus on which the attitude shall lie to allow the ion engines propulsion. The locus is expressed as

$$\left(\theta - \theta_s\right)^2 + \left(\phi - \frac{\Omega\dot{\theta}_s}{p}\right)^2 = \frac{1}{p^2}\left(\frac{T_{IES}}{I}\right)^2 \tag{21}$$

Since the along the cruise trajectory,

$$\dot{\theta}_s \simeq \frac{(Angular\ Momentum)}{{R_{SUN}}^2} \qquad (22)$$

holds, and in view of the quick look at the flight data, the attitude target shall be

$$\frac{\Omega\dot{\theta}_s}{p} \propto 0.6[\mathrm{deg}] \qquad \frac{1}{p}\left(\frac{T_{IES}}{I}\right) \propto R_{SUN}[AU]^2 \cdot 4.8[\mathrm{deg}] \qquad (23)$$

This is one of the primary results we obtained for planning the subsequent cruise. Fig. 15 left shows where the target attitude shall be. In figures 11 to 13, since the ion engines propulsion specifies the thrust inclined to the ecliptic plane, the attitude targeted is not just beneath the Sun as Fig. 15 indicates.

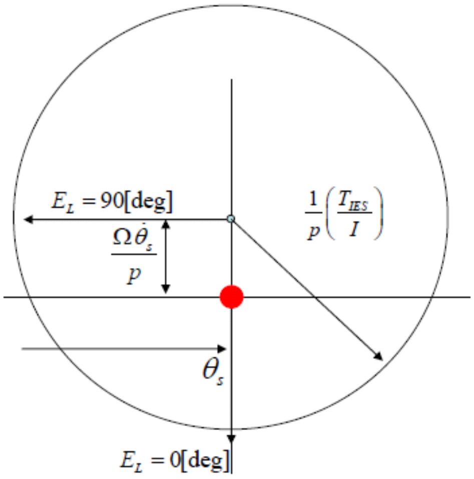


Fig. 15 Attitude Target aimed

8. REMARKS

The paper so far quickly presented how this sophisticated attitude control has been performed, from during while the spacecraft is in a spin motion to the period in which the ion engine is driven with no spin motion.

- Solar Radiation Torque passive stabilization was demonstrated for Hayabusa spacecraft, whose solar array panels and parabola antenna are atop.
- The stability is obtained toward the Sun with a certain offset angle passively determined.
- Flight results well agreed with the analysis and scaling coefficient estimated is compatible with the physical interpretation.
- Hayabusa started a new operation driving its ion engines this March toward the return to the Earth in 2010.
- Another attitude control strategy was developed and has been used to control the spacecraft to be propelled as planned.
- The spacecraft has been operated under this attitude control strategy well.

The flight period left is still three years and the spacecraft condition is hardly healthy. However, the spacecraft operation team fortunately could cope with this difficulty and succeeded in making the operation done as intended.

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