HAYABUSA Orbit Determination after the Departure from Itokawa

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Abstract: Hayabusa lost its all chemical fuels, and two of three momentum wheels do not work anymore. Under this severe condition, Hayabusa is cruising using its ion engine to get back to the earth in June, 2010. In order to control spacecraft's attitude under only one momentum wheel, Hayabusa has to operate ion engine controlling thrust directions with gimbals continuously, or keep low spin safe-hold. Therefore, it became difficult to make a short ballistic flight for orbit determination among ion engine operations. On the other hand, continuous stable ion engine operation causes less modeling error on ion engine acceleration. In this report, orbit determination after the departure from the target asteroid is described focusing on two point of view; orbit prediction under long term ion engine operation, and orbit determination under low spin safe hold mode.

「はやぶさ」地球帰還フェーズの軌道決定

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摘要：「はやぶさ」は、2005年12月に小惑星を離脱した直後に発生した燃料流出のトラブルにより、地球帰還の予定を2010年6月に変更して航行中である。使用可能なホイールは既に1台のみとなっているため、「はやぶさ」は姿勢制御のために、IESを連続運転して姿勢制御をするか、セーフホールドを維持することが必要である。したがって往路で行ったような軌道決定のために電気推進を一時停止する「3パスコースティング」の手法は姿勢喪失の危険を伴うことになる。本報告では、地球帰還フェーズにおける「はやぶさ」の軌道決定について、小惑星離脱から2007年のIES運用終了までの結果について述べる。

1.　Introduction

Hayabusa suddenly lost its attitude control at the departure from the target asteroid (25143)Itokawa in December, 2005. After Hayabusa team's continuous effort and patient operations to find the spacecraft's signal, they finally retrieved the spacecraft's communication links from ground stations in February, 2006. Telemetry from Hayabusa revealed that the spacecraft leaked its chemical fuel because of damage at the touch down, and it lost all its chemical fuels. Furthermore, two of three momentum wheels were already broken. Under this severe situation, Hayabusa is cruising using its ion engine to get back to the earth in June, 2010.

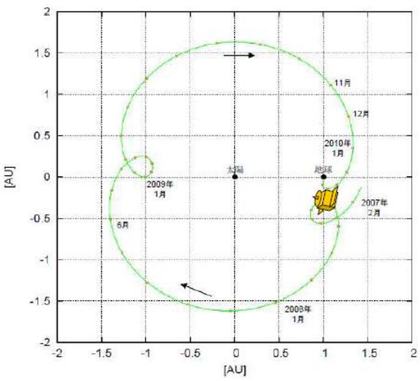

Figure 1-1 Hayabusa Trajectory in Sun-Earth Fixed Coordinate

2. Orbit Determination under Low Spin Safe-hold Mode

Hayabusa was spinning when Usuda station succeeded to acquire its beacon signal on 23 January, 2006. Spacecraft's spin rate was estimated from spin modulation on Doppler data, and the modulation is removed by data processing on orbit determination. Preliminary orbit determination was achieved using two weeks Doppler data after the beacon acquisition, and the solution told that Hayabusa was at about 10,000 km and 3 m/sec with respect to Itokawa, and estimation error was supposed to be about 1000 km and 1 m/sec. After that, Hayabusa performed attitude change by Xe gas jet for about one month. Then 2 way ranges in addition to Doppler were collected for a week, and orbit determination by both range and Doppler results in about 13,000 km and 3 m/sec with respect to Itokawa. The accuracy was expected about 900 km and 70 cm/sec. Table 2-1 is a summary of events from the viewpoint of orbit determination just after the recovery from the fuel leak.

Hayabusa changed its attitude to near the sun, and performed spin down in early July 2006. It enables Hayabusa to be sun-oriented automatically by solar pressure torque. This operation mode gives good condition for orbit determination because it causes no acceleration perturbation of thrusting to keep the spacecraft to be sun-oriented. Since then, successive range and Doppler data were collected until ion engine operation started in February 2007. Table 2-2 shows results of orbit determination from July to December 2007. Each solution is derived from 2 way range and Doppler data for one month. Connectivity of each solution is up to 500 km and 40 cm/sec, those represent accuracy of solutions.

Table 2-1 Events just after the Recovery from the Fuel Leak

Date	Events
2005-12-08	Fuel leaks. Attitude and communication was lost.
2006-01-23	Beacon acquisition
2006-01-26 ~ 2006-02-08	2way Doppler was collected. Preliminary orbit determination was performed
2006-02-09 ~ 2006-03-01	Attitude change by Xe gas jet. Telemetry retrieved on 25 Feb.
2006-03-01 ~ 2006-03-07	2way Range and Doppler were collected. Orbit determination was performed.

Table 2-2 Connectivity of Solutions during Low Spin Safe-hold in 2006

		Connectivity	
Data Arc	Epoch	in Position	in Velocity
7/7 0:00 – 8/4 0:00			
	8/5 0:00	150 km	9 cm/sec
8/7 0:00 – 9/4 17:30			
	9/5 0:00	500 km	42 cm/sec
9/5 0:00 – 10/1 0:00			
	10/1 0:00	240 km	31 cm/sec
10/2 0:00 – 10/31 0:00			
	11/1 0:00	340 km	7 cm/sec
11/7 0:00 – 12/1 0:00			

3. Orbit Prediction under Long Term Ion Engine Operation

IES operation started in February 2007. Figure 3-1 and Table 3-1 show the IES operation history. Since high rate IES operation, which is almost 100%, was required from the both viewpoint of delta-V plan and attitude control, ballistic flight time for orbit determination should be as short as possible. Continuous IES operation for a long term causes larger error in propagation because of error accumulation in IES acceleration model. It affects not only for following IES delta-V plan but also antenna pointing prediction from Usuda station which degrades signal level from the spacecraft. Therefore, orbit determination under IES operation became necessary in July 2007, when IES continued to operate for two and a half month.

Orbit determination under IES operation was performed using range and Doppler for 2 passes, in order to avoid fatal degradation of orbit determination accuracy because of large uncertainty in IES acceleration model. These solutions may have rather large error in velocity up to several m/sec, but accuracy in position up to 1000 km at the tracking data point is sufficient for antenna pointing. The solutions had to be updated every week because its large velocity error causes large prediction error in position by propagation. Figure 3-2 shows the updates of antenna pointing direction by solution under IES operation with respect to a prediction by IES acceleration model and the last ballistic orbit determination two month ago. The difference is larger than the Usuda X-band beam width which is 0.015 degrees, and the updated antenna prediction improved signal level from the spacecraft by 4 dB actually.

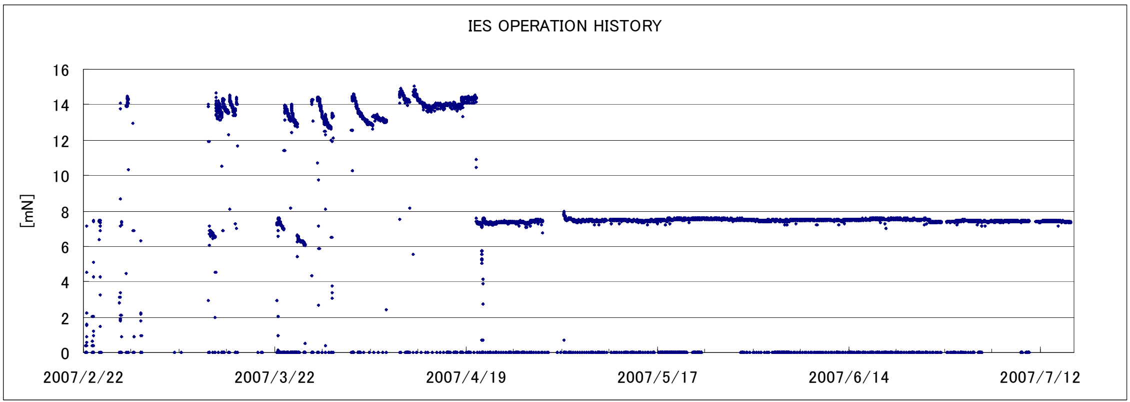

Figure 3-1 Ion Engine Operation History

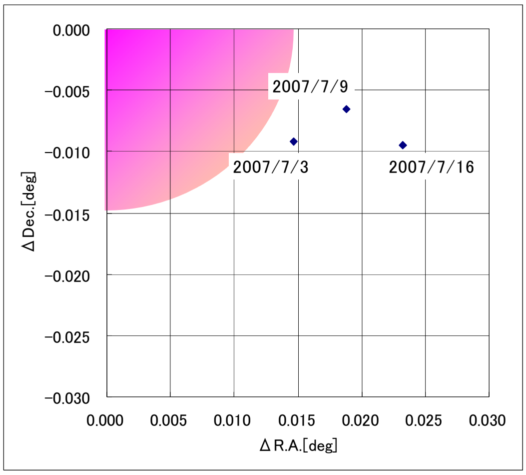

Figure 3-2 Antenna Prediction Updates by Orbit Determination under IES Operation

Table 3-1 IES Operation Status

Date	Operation
2007-02-22	Experimental IES operation started. Spacecraft was spinning yet.
2007-03-02 ~2007-03-12	Ballistic flight for orbit determination.
2007-03-13~	ΔV by IES operation
2007-03-16 ~2007-03-22	IES Stop (Safe-hold and recovery)
2007-03-23 ~2007-03-27	Spin up/down by IES
2007-03-28~	ΔV by continuous IES operation using two IES components.
2007-04-21	IES operation mode changes to use only one component.
2007-04-30 ~2007-05-02	Short ballistic flight for orbit determination

4. Future Works

Hayabusa performs delta-V until October 2007, and then it changes operation mode to low spin safe-hold till October 2008. Figure 4-1 show a result of analysis for 3 passes ballistic orbit determination accuracy. This is a covariance analysis considering only for solar pressure force error. As for orbit determination under IES, acceleration model error has to be counted in addition to it. According to this result, orbit determination under IES is possible until October 2007 because the spacecraft is so near from the earth that the accuracy of short data arc solution is enough for antenna pointing prediction. From October 2007 to November 2008, IES is stopped and orbit determination is necessary with such long data arc as 1 month because short arc ballistic solution accuracy degrades far from the earth. The distance between the spacecraft and the earth is shown in Figure 4-2. When IES starts delta-V in November 2008, it is effective until January 2009 to predict trajectory with IES acceleration model and last ballistic solution using 1 month tracking data. However, another strategy for navigation under IES is necessary after January 2009. It is a future work to establish a routine operation process that enables to make a certain precise solution for delta-V planning and antenna pointing prediction under continuous IES operation far from the earth.

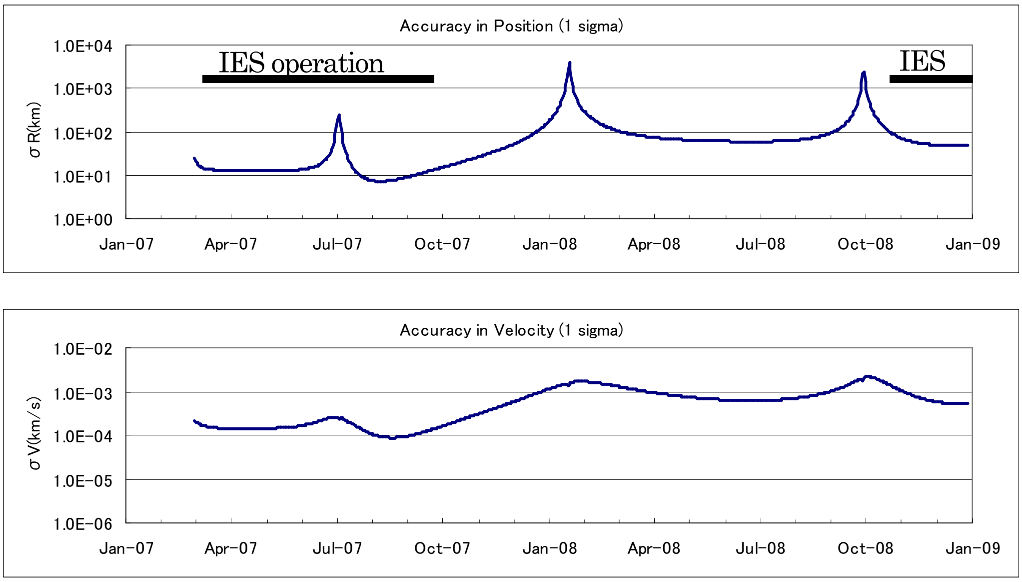

Figure 4-1 Covariance Analysis for 3 Passes Ballistic Solution

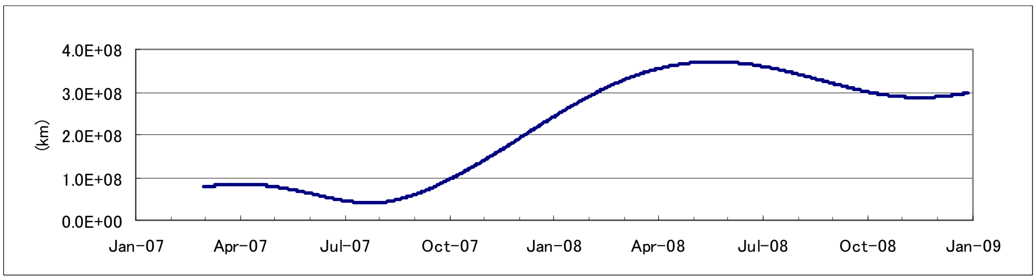

Figure 4-2 Distance between Spacecraft and the Earth

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