HAYABUSA Orbit Determination under Low Thrust - Part II

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Abstract: Hayabusa is a spacecraft to explore the asteroid (25143) Itokawa, and it is going to get an asteroid's fragments for the first time in the world. Hayabusa carries an Ion Engines System (IES) as main propulsion in cruising. From the viewpoint of orbit determination, an error in acceleration modeling of low thrust has a great influence both on orbit determination and prediction accuracy. This paper describes an evaluation for orbit propagation under low thrust operation, as well as a method which is adopted in the routine navigation for Hayabusa.

1. Introduction

HAYABUSA was launched on 9th May, 2003, and the spacecraft goes around the sun nearby the earth orbit for a year in order to get acceleration by its ion engine. The spacecraft performed an earth swingby in May, 2004 which leads the spacecraft into trans-asteroid trajectory. The spacecraft arrives at the target asteroid (25143)Itokawa in 2005, and it stays around the asteroid for about three months, and carries out observations and touches down on the target to get fragments of the asteroid. It returns to the earth in June, 2007. Fig.1 shows the trajectory of HAYABUSA.

Fig.1 Hayabusa Trajectory in Sun-Earth Fixed Coordinate
2. Ion Engines Operation

Fig.2-1 shows accumulated delta-V achievement by the ion engines from the launch. After vacuum exposure for several weeks, the first plasma was ignited on May 26, 2003, and the first engine started its thrusting by applying a high DC voltage on the next day. At the beginning, the engines are operated only during the operation hours, that is, only in view periods from the Usuda station, and the engines are devoted to various kind of tests such as performance evaluation, autonomous control, cooperative function with other sub systems, stand-alone firing, and so on. In July all the three ion engines started continuous operation to meet with the delta-V plan, which accelerated Hayabusa at a rate of several m/s per day.

Fig.2-2 is a plot of IES propulsion history, which shows the number of active thrusters for each period. An Enlarged plot of typical IES propulsion history (Fig.2-3) shows that IES turns on and off one of the three thrusters periodically. This fluctuation is caused by the automatic power supply control aboard, since one of the DC power supplying units requires being off in a certain period in order to prevent some oscillation phenomenon in the ion engine. This operation results in degrading the drive efficiency a little, down to 2.7 with respect to the full operation case of 3.0, so that we call this operation mode as “2.7 thrusters’ operation”.

![Accumulated Delta-V by IES](image1)

![IES Propulsion History](image2)

![Example of Typical IES Propulsion History (Enlarged)](image3)
3. Interfaces with Navigators

An operation history of IES is retrieved from telemetry data. There are two types of history for IES: a raw history and an average history. The raw history contains a time series of instantaneous propulsion at every certain interval, which is every one second at highest density. This type of data can describe a detailed propulsion variation when we can communicate with the spacecraft in a high bit rate, but it loses the most of propulsion variation information under a low bit rate communication instead. As the bit rate of communication for Hayabusa is basically rather low unless the spacecraft is near around the Earth, the data of raw history are usually retrieved at the lowest rate, which is every 1024 seconds. The ion engine’s propulsion has a characteristic of periodical changes, which have amplitude of 0.5mN, and a certain period, which is from several minutes to an hour. Therefore, the usual raw history by 1024 seconds of rate is insufficient for modeling IES acceleration for orbit determination and/or precise propagation. On the other hand, the average history is a time series of average propulsion which is calculated onboard by accumulating the instantaneous propulsion at every 1024 seconds. This type of data enables us to get a more precise average acceleration history in a low bit rate communication. Fig.3 shows an example of operation results for IES raw and average history.

4. Routine Navigation under Low Thrust Operation

Performing an orbit determination under IES propulsion in routine navigation involves a certain risk because an acceleration modeling error has a significant influence on the solution. Therefore, we adopted a following procedure, so called “three pass coasting operation”, in the routine navigation for Hayabusa. The operation for sending commands is basically performed at the beginning of every week. First week operation:

1-1) turns off IES intentionally for about two days, and collect Doppler and range data for three pass,
1-2) solves the state vector in a ballistic flight using the tracking data above, and update the orbit plan.

From second week, every week operation:
2-1) uploads IES operation plan for this week to the spacecraft according to the updated orbit plan,
2-2) downloads IES operation history for the last week,
2-3) propagates the last week state vector to this week using IES operation history, and update the orbit plan according to the propagated state vector.

The period of the “three pass coasting operation” is usually every three weeks though it depends on IES operation status. IES operation history may have an error because of an unknown variation of propulsion coefficient. The amount of modeling error is expected up to a few percent according to the system design. Therefore, the propagated state vector involves errors of both ballistic solution and propagation owing to IES acceleration modeling error.

We evaluated connectivity between successive two solutions of “three pass coasting operation”. The connectivity is difference in position and velocity between a propagated state vector of a certain ballistic solution using IES history and the next ballistic solution. As IES propulsion history may involve a few percent errors in the propulsion coefficient, we can expect an improvement of the connectivity when we estimate the propulsion coefficient. Here we assume that the ballistic solution and propulsion variation are precise enough, and then we use these parameters as they are. So we estimate only the propulsion coefficient using Doppler data. Since the coefficient may change under some circumstances, we estimate the coefficients for each day. Fig.4 shows the connectivity for each case. It indicates that the trajectory propagation error decreases when we estimate the propulsion coefficients. The estimated coefficients are 90–92% while the nominal value is 92%, and this result meets well with the system design estimation.

![Fig.4 Connectivity between Two Successive Ballistic Solutions](image)

"no est" is result without an estimation of propulsion coefficient of IES, and “est” is result with an estimation of the coefficient.
5. Summary

The routine navigation procedure for Hayabusa under low thrust is presented in this paper. A method is proposed that uses a solution from short ballistic data arc, which is typically for a few days, and a propagation with IES propulsion history. This method is useful to ensure the routine navigation for a spacecraft with ion engines in deep space. The ion engine acceleration inevitably involves modeling error in propulsion coefficients. When the coefficients are estimated, the consistencies of the successive solutions are improved.

References