Trajectory Estimation of the "Hayabusa" Spacecraft around Itokawa
Using Gaskell Shape Model

Miura Akira*, Yamamoto Yuki*, Yoshikawa Makoto*
* Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency

Abstract

In this paper, we present a method to estimate the trajectory of the asteroid probe “Hayabusa” during descents and touchdowns on the asteroid Itokawa. We introduce Gaskell Itokawa Shape Models to the estimation. Gaskell Itokawa Shape Models are supposed to be the best models to represent the shape of Itokawa. Thus, in this study, we compare the shape of finest Gaskell model with telemetry data of “Hayabusa”, such as LRF ranging data and ONC-W data, to estimate the trajectory of “Hayabusa” relative to Itokawa.

Gaskell 形状モデルによる
探査機「はやぶさ」のイトカワ近辺の軌道推定

三浦昭*、山本幸生*、吉川真*
*宇宙航空研究開発機構 宇宙科学研究所

摘要

本稿では、小惑星探査機「はやぶさ」が小惑星イトカワに降下・タッチダウンした際の軌道を推定する手法について述べる。本手法においては、推定に Gaskell のイトカワ形状モデルを採用した。Gaskell のイトカワ形状モデルは、モデルの中でも最もイトカワを忠実に再現していると考えられる。よって本研究では、LRF データや ONC-W データ等の「はやぶさ」から得られたテレメトリデータを Gaskell の最高精細の形状モデルと照合することにより、「はやぶさ」のイトカワに対する位置を推定する。

1. Introduction

We have been working on methods to visualize the trajectory of Hayabusa. To visualize Hayabusa’s first trial of the touchdown on Itokawa in November 2005, it is required to estimate the point of Hayabusa in three-dimensional space at each timestamp. To visualize an appropriate trajectory, the points should be connected smoothly each other.

Kawaguchi et al.(1) estimated the positions of Hayabusa during the touchdown. They plotted many candidate points, though it is not easy to determine the most suitable point among the candidates for the visualization.

In this paper, we estimate the trajectory of Hayabusa suitable for visualization during the first trial of touchdown on November 19, 2005.

2. Estimation

We use the finest Gaskell Itokawa Shape Model(2) for the estimation described below. The model consists of 3,145,728 polygons and is assumed to be the most precise model to represent Itokawa.

The estimation consists of several parts:
- Until 20:33 Nov. 19,2005 [UTC],
- 20:34 - 20:43 Nov. 19, 2005 [UTC],
We discuss methods of estimation in each period and present the results of estimation.

2.1. Estimation until 20:33

2.1.1. ONC-W1 images

ONC-W1 is one of navigation cameras on board Hayabusa(3). FOV of ONC-W1 is aligned to -Z axis of Hayabusa. ONC-W1 was used to take images of Itokawa during the period. ONC-W1 images contain distortion caused by the lens optical system. In this paper, we estimate the distortion of ONC-W1 images by comparing the real ONC-W1 image and a CG image with supposed distortion and supposed viewpoint.

![Images](image1)

Fig. 1 ONC-W1: Estimation of Distortion

Fig. 1 shows sample images of the estimation. Fig. 1(a) shows a CG image without distortion, where Gaskell Itokawa Shape Model is rendered with a supposed viewpoint and appropriate camera rotations. Parameters of camera rotations correspond to the attitude of Hayabusa. Fig. 1(b) shows the corresponding image with supposed distortion. Fig. 1(c) shows the real ONC-W1 image. Fig. 1(d) shows the composite image of (b) and (c), where the magenta layer represents the CG image and the green layer represents the ONC-W1 image.

If both image (b) and image (c) match, we estimate that the distortion parameters are appropriate and the coordinates of the viewpoint represent the position of Hayabusa.

2.1.2. Estimation of the trajectory

As a result of the estimation in 2.1.1, for each ONC-W1 images, the position of Hayabusa can be calculated. Thus we can get the trajectory of Hayabusa as far as ONC-W1 images are available.

2.1.3. Position of the target marker

Now that optical distortion of ONC-W1 has been estimated, the position of the target marker can be estimated. Fig. 2 shows the result of estimation.

![Images](image2)

Fig. 2 Position of the Target Marker

Fig. 2(a) shows one of the last ONC-W1 image taken during the trial of the touchdown. Fig. 2 (b) shows the same image as Fig. 2(a) with enhancement, where features of Itokawa are vivid and the position of the target marker is plotted as a red circle. Fig. 2(c) shows the CG image rendered with appropriate distortion and appropriate viewpoint in order to match Fig. 2(b), where the cross point of the axes represents the estimated position of the target marker. Fig. 2(d) shows the
composite image of (b) and (c), where the magenta layer represents the CG image and the green layer represents the ONC-W1 image.

Fig. 3 shows the estimated position of the target marker. A Red sphere beside the shadow of Hayabusa represents the position of the target marker. Four spheres around the target marker represent presumed positions of the surface of Itokawa sensed by the Laser Range Finder (LRF-S1) on board Hayabusa(3). LRF-S1 has four beams of range sensors. Four lines between the spheres and Hayabusa in Fig. 3 represent the directions of the beams.

Fig. 3 Estimated Position of the Target Marker

2.2. Estimation: 20:34 – 20:43

Once the position of the target marker is estimated, the positions of Hayabusa can be estimated using the position of the target marker, LRF-S1 data and the direction of the target marker from the viewpoint of Hayabusa. Fig. 4 shows the direction of the target marker provided by the ONC-W1.

Fig. 4 Direction of the target marker from the viewpoint of ONC-W1

Fig. 5 shows the data of LRF-S1 during the trial of the touchdown. In conjunction with the direction data in Fig. 4 and attitude data of Hayabusa, we can estimate Hayabusa’s direction relative to the target marker. LRF-S1 data in Fig. 5 are used to estimate the distance between Hayabusa and the surface of Itokawa.

Fig. 5 LRF-S1 data: overview

In order to render the trajectory of Hayabusa smoothly, we use linear interpolation to calculate the direction in case the corresponding data are not available.

2.3. Estimation: 20:43 – 21:09

2.3.1. Matching LRF-S1 data and Gaskell model

With LRF-S1 data in Fig. 5 and Gaskell Itokawa Shape Model, we estimate LRF-S1 ranging errors all over Itokawa on the assumption that Hayabusa is located with minimum ranging error right over each point examined.

Fig. 6 shows the positions of Hayabusa with ranging errors on some sample frames. Blue areas represent less errors (almost 0 [m]), that is, Hayabusa is supposed to be located in the area with high probability. Green, red, and white areas represent errors around 1[m], 2[m] and 3[m] respectively. Areas with errors more than 3[m] are not shown. Fig. 6(a) corresponds to the beginning of the LRF-S1 data. Fig. 6(e) corresponds to the first touchdown at this trial. In these figures, the transparent green plane represents the plane equidistant from the Earth. The distance of each plane is calculated as an integration of range-rate in Fig. 7. White arrows point probable areas where Hayabusa is located at the time. The blue arrow in Fig. 6(e) traces supposed positions that Hayabusa may have flown.

The images in Fig. 6(f), (g), (h) and (i) corresponds to the period after the first touchdown. As far as we
examine the results of the LRF-S1 errors, it is not clear where Hayabusa flew after the first touchdown.

2.3.2. Estimation of trajectory

Fig. 8 and Fig. 9 shows firing time of the Reaction Control System (RCS) per unit time. The unit time of Fig. 8 is 128[s] and that of Fig. 9 is 16[s]. After the firing around 21:41, there are no major firing until 20:09, as suggests that Hayabusa is almost in a state of free fall during the period.

We estimate the trajectory of Hayabusa as follows.

(1) The initial position of Hayabusa at 20:43 is given by the method in 2.2.

(2) The reference velocity of Hayabusa at 20:43 is given by the estimated positions in 2.2.

(3) The gravity of Itokawa is estimated on the assumption that Itokawa consists of mass points arranged as simple cubic lattice with intervals of 5[m]. The reference mass of each mass points is 237,500[kg], that is, 1.9[\text{g}/\text{cm}^3] \cdot (500[\text{cm}])^3.
(4) The estimation consists of sub-estimations with a variety set of different initial velocity and mass of the mass points.

(5) The initial velocity and the mass of the mass points used for each sub-estimation are selected around the reference velocity and the reference mass respectively.

(6) Ranging errors of LRF-S1 data are calculated in each sub-estimation on the assumption that Hayabusa traces the trajectory calculated with the initial position, initial velocity, and the gravity of Itokawa.

(7) Among the results of the sub-estimations, the trajectory with the least ranging error of LRF-S1 is selected as the estimated trajectory.

2.4. Estimation: 21:09 – 21:12

Fig. 10 shows LRF-S1 data around the first touchdown. Obvious ranging errors are eliminated from the figure. According to Fig. 10, it seems that the touchdown consists of two bounces, but the detail seems to be hard to estimate. In this short period, we suppose that Hayabusa flew toward almost the same direction as the end of the previous period and the distance between Hayabusa and Itokawa at each frame obeys the corresponding LRF-S1 data.

2.5. Estimation: 21:12 -21:30

In this period, we use the same method described in 2.3.2 to estimate the trajectory of Hayabusa.

3. Results

Fig. 11 shows the trajectory of Hayabusa until 20:33 estimated in 2.1. The polygons represent the attitude of Itokawa as of 20:33. The magenta line represents the trajectory data taken from the public SPICE kernels at NAIF web site(5). The cyan line represents the estimated trajectory.
Fig. 12 shows the trajectory of Hayabusa after 20:34 estimated in 2.2 through 2.5.

The estimated trajectory from 20:34 to 21:09 seems to be consistent with Fig. 6. On the other hand, the consistency of the trajectory after 21:09 is hard to validate with the data used in this paper.

Fig. 13 shows an example of inconsistency seen in the estimation after 21:12. Itokawa itself obstructs the beam to one of the presumed positions of the surface, presented as a purple line in the figure.

Fig. 14 shows features corresponding to the inconsistency. Fig. 14(a) shows ONC-W1 image at the location. Fig. 14(b) shows CG image based on the Gaskell model used in the estimation. In Fig. 14(b), there seems to be a hill around the location. On the other hand, there seems to be a cluster of rocks in Fig. 14(a), as implies that the beam may not be obstructed in this case.

4. Conclusion

In this paper, we introduce a set of methods to estimate the trajectory of Hayabusa suitable for visualization of the trajectory.

Further considerations are required to estimate the trajectory more precisely. Also required are appropriate methods to evaluate the errors of the calculated trajectory.

References


