Entry Dispersion Analysis for the HAYABUSA Spacecraft using Ground-Based Optical Observation*

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Abstract

The HAYABUSA asteroid explorer successfully released its sample capsule to Australia on 2010 June 13. Since the Earth reentry phase of sample return was critical, many backup plans for predicting the landing location were prepared. This paper considers the reentry dispersion using ground-based optical observation as a backup observation for radiometric observation. Several scenarios were calculated and compared for the reentry phase of HAYABUSA to evaluate the navigation accuracy of the ground-based observation. The optical observation doesn’t require any active reaction from a spacecraft, and thus these results show that optical observations could be a steady backup strategy even if a spacecraft had some trouble. We also evaluated the landing dispersion of HAYABUSA only with optical observation.

Key words: astrometry — celestial mechanics — HAYABUSA — orbit determination — space vehicles

1. Introduction

Recently, many scientists have planned sample return missions to achieve further understandings of planets and small bodies. The Discovery-class mission Stardust of the National Aeronautics and Space Administration (NASA) was launched in 1999 to collect dust from comet Wild-2 (Desai et al. 2008). After a seven-year journey, Stardust finally released its capsule with cometary and interstellar dust particles into the Utah Test and Training Range.

Japanese Space Exploration Agency (JAXA) launched the HAYABUSA spacecraft in 2003 to accomplish a sample return from the near-Earth asteroid (25143) Itokawa. HAYABUSA arrived at the target asteroid in 2005 with its ion thrusters and Earth gravity assist. HAYABUSA was originally scheduled to return to Earth in 2007; however, the actual Earth entry was carried out in 2010 due to unexpected trouble at the sampling phase in 2005. Finally, the HAYABUSA capsule successfully landed in the Woomera Prohibited Area (WPA) on 2010 June 13. Since, the Earth entry phase of the HAYABUSA spacecraft was a critical event, several backup observations were prepared.

The HAYABUSA spacecraft was mainly navigated using radiometric observations. Range, Doppler and Delta Differenced One-way Range (DDOR) observables were provided by communication between the spacecraft and ground stations. However, these radiometric observations always require active reactions from a spacecraft. If a spacecraft would have some trouble with its communication module, these precise measurements would no longer be available. On the other hand, ground-based optical observations are completely passive, and don’t require any active reaction from a spacecraft. Therefore, optical observation is a steady backup strategy for any spacecraft trouble.

In this paper, we evaluate the orbit determination of the HAYABUSA reentry phase using ground-based observations as a backup strategy of the nominal radiometric observation. Several scenarios were calculated and compared for the reentry phase of HAYABUSA to evaluate the navigation accuracy of the ground-based observations. The real radiometric...
tracking data and optical observation data were evaluated. This evaluation could be a good index for future reentry missions. A comparison of these results reveals the importance of ground-based observations as a backup strategy for Earth entry events.

In section 2, we briefly describe the HAYABUSA observation, both optical and radiometric measurements. The details of observatories and their conditions are presented. The analysis method and conditions for the entry dispersion analysis are described in section 3. Several cases are discussed in order to compare the dispersion ellipses with and without optical observations. Next, the results and comparison of the analysis are described using the radiometric and optical observations in section 4. Finally, we summarize our conclusion in section 5.

2. Observation

After five series of trajectory correction maneuvers, the HAYABUSA spacecraft was guided into WPA of Australia (Kawaguchi et al. 2010). The Earth approaching trajectory is described in figure 1 on a rotating frame. The Sun is always located in the \(-X\) direction in this figure, and the HAYABUSA spacecraft approached the Earth from dayside.

2.1. Ground Based Optical Observation

HAYABUSA was observed by four ground-based optical observatories located in Arizona and Hawaii (figure 2). Table 1 shows the complete data of the HAYABUSA optical observations used in this study. Many observatories in Japan also tried to observe HAYABUSA from June 11 to 13, though none of them succeeded due to poor weather conditions.

2.1.1. Subaru observation

The HAYABUSA spacecraft was observed with Suprime-Cam (Miyazaki et al. 2002) mounted on the Subaru Telescope on the evening of June 11–13 (UT). Since the HAYABUSA spacecraft approached Earth from the dayside, the window for an optical observation was small. HAYABUSA was detected only in June 13 data (figure 3). The successful observation by the Subaru Telescope is summarized in table 2. The pointing was set so that the trajectory would be in a single

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**Fig. 1.** HAYABUSA Earth reentry trajectory with Earth center. Sun-Earth fixed rotating frame. HAYABUSA position at the radiometric and optical observations are also described. Descriptions of the limited and full radiometric data are given in section 3.

**Fig. 2.** Locations of the observatories for HAYABUSA observations.

**Table 1.** HAYABUSA optical observations.*

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<td>CFH</td>
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</table>

*The time is expressed as hours from 2010 June 13.0. The site code 926, G96, SBR, CFH correspond to Tenagra II observatory (110° 879 W, 31° 462 N, 1309 m), Mt. Lemmon Survey (110° 789 W, 32° 443 N, 2789 m), Subaru Telescope (155° 4761 W, 19° 8255 N, 4162 m), and Canada-France-Hawaii Telescope (155° 4688 W, 19° 8252 N, 4204 m), respectively.
readout channel of a chip (chip 5) of Suprime-Cam for an easy quicklook. The seeing size was 0″6–0″7. The brightness of HAYABUSA was estimated to be $V = 19.8$ mag in AB magnitude. Photometric calibrations were performed using SDSS DR7 (Abazajian 2009) stars in the observed field with a conversion of the SDSS magnitude to Suprime-Cam SDSS DR7 (Abazajian 2009) stars in the observed field with a conversion of the SDSS magnitude to Suprime-Cam $V$-band magnitude.

The time system of Suprime-Cam was synchronized to UTC using a network time protocol (NTP). The typical shift of the Suprime-Cam time from UTC was less than 2 $\mu$s. However, the Suprime-Cam FITS header of the end of the exposure (UT-END keyword) had an uncertainty of $\pm 1$ to 0 seconds because of a communication delay from the camera to the control computer. The time of start of the exposure (UT-STR) was more accurate as the start command sent from the control computer to the camera. The mean time of the observation was therefore calculated from UT-STR and half of the exposure time (EXPTIME). We then added 0.6 seconds to correct for the effect of shutter movement, since the shutter moves within 1.2 seconds and chip 5 is near the center. Because the Suprime-Cam had not implemented information about the shutter movement, either the shutter curtain moved from left to right, or from right to left in the field, and the shutter movement would cause a time uncertainty of about 0.1 second in our observations. Three data were removed because a large delay between the computer and the camera communication due to some trouble was recorded.

The data were reduced in a standard manner using nekosoft (Yagi et al. 2002): bias subtraction, flat fielding, distortion correction and sky subtraction. We did not apply any PSF equalization process among the exposures. The centroid of HAYABUSA was also measured with the software. WCS was calibrated in each exposure using WCS tools (Mink 2002) and the USNO-B1.0 catalog (Monet et al. 2003). Nine or ten stars were used in each exposure and the RMS residual was $0^\prime 07 \pm 0^\prime 02$ in the best-fit solutions.

### 2.1.2. CFHT observation

Observations of HAYABUSA were attempted on both June 12 and 13 with the 3.6-m Canada-France-Hawaii Telescope (CFHT) on Mauna Kea (table 3). The instrument Megaprime was utilized along with an r filter. The camera consisted of 36 Marconi/EEV 2048 × 4612 pixels CCDs covering a $1^\circ \times 1^\circ$ field of view; a single CCD covered a $6^\prime 4 \times 14^\prime 4$ field. The ephemeris of HAYABUSA was known good enough to place the target near the center of chip 22 of the camera, which was located immediately south of the optical axis. The exposure times were 40 s in all cases, and non-sidereal tracking at the expected rates of motion for the spacecraft were used on both nights.

Three exposures were taken on June 13, and the spacecraft was easily detected with a signal-to-noise ratio in excess of 70. The measured brightness of the spacecraft was $R = 19.0$, using nearby astrometric reference stars from the USNO-B1.0 catalog to determine the photometric zero point.

The astrometric solutions utilized a quadratic field distortion model and a minimum of 62 reference stars from the USNO-B1.0 catalog. The three independent solutions for the three exposures showed RMS residuals of $0^\prime 15$ to $0^\prime 17$ for the reference sources; thus, the contribution from the astrometric solution to the overall positional uncertainty was only about $0^\prime 02$. The centroiding error on the spacecraft contributed another $0^\prime 01$. A $+5.0$ s correction to the exposure start times in the FITS headers was applied to compensate for the known delay between when the clock was read and when the camera shutter actually opened. The 0.3 s jitter in this delay contributed about $0^\prime 12$ of the astrometric uncertainty in declination and about $0^\prime 02$ in right ascension. Because the reference stars were all trailed by 49 (binned) pixels due to the non-sidereal tracking mode used for the exposures, a model consisting of a trapezoid in the trailed direction and a Gaussian in the orthogonal direction was used to find the centroid of each reference star’s image. A Gaussian model was used for the image of HAYABUSA, itself, which was not trailed (see figure 4).

### Table 2. HAYABUSA observation by the Subaru Telescope.

<table>
<thead>
<tr>
<th>Camera</th>
<th>Suprime-Cam</th>
</tr>
</thead>
<tbody>
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<td>Pixel size</td>
<td>0″202</td>
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<tr>
<td>Seeing</td>
<td>0″6–0″7</td>
</tr>
<tr>
<td>Exposure time</td>
<td>5.0 s × 11 shots</td>
</tr>
<tr>
<td>Filter</td>
<td>V-band (W-J-V; 5500 Å)</td>
</tr>
<tr>
<td>Tracking mode</td>
<td>Sidereal tracking</td>
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<tr>
<td>RA, Dec</td>
<td>08:56:34, +27:57:33</td>
</tr>
<tr>
<td>Time</td>
<td>Twilight time on 2010 June 13</td>
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### Table 3. HAYABUSA observation by the CFHT.

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<tr>
<th>Camera</th>
<th>Megacam</th>
</tr>
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<tbody>
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<td>Pixel size</td>
<td>0″187, binned 2 × 2 to 0.374</td>
</tr>
<tr>
<td>Seeing</td>
<td>0″7</td>
</tr>
<tr>
<td>Exposure time</td>
<td>40.1 s × 3 shots</td>
</tr>
<tr>
<td>Filter</td>
<td>R-band (r.MP9601)</td>
</tr>
<tr>
<td>Tracking mode</td>
<td>non-sidereal at expected spacecraft rates</td>
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<tr>
<td>Queue observer</td>
<td>A. Draginda</td>
</tr>
<tr>
<td>Queue coord.</td>
<td>G. Morrison</td>
</tr>
</tbody>
</table>

![Three HAYABUSA images taken with the Subaru Telescope. North is up and east is left. Since they were observed in the sidereal tracking mode, the HAYABUSA image (indicated with a circle) elongates in the direction of the movement.](Image)
2.2. Radiometric Observable

Continuous radiometric tracking data were provided by the JAXA Usuda deep-space center and the NASA deep-space network. We could receive radiometric data observable for 24 hours using these networks. Actual reentry was navigated by radiometric data. These measurements provided 2-way Doppler and range observable data. These observables were sensitive with respect to the line-of-sight direction, but not the tangential direction. Also, these observables required the reaction of a spacecraft. A spacecraft needs to receive radio signals from ground and to transmit them back to a ground station. Therefore, these observables are only available if the spacecraft’s communications system is in a healthy condition.

3. Analysis and Its Conditions

In this section, we compare the dispersion ellipse with and without the optical observations in order to evaluate the impact of optical observations. The orbit determination and entry dispersion analysis were investigated to evaluate the impact of the ground-based observations of HAYABUSA. The trajectory of HAYABUSA were estimated using several data sets, and evaluated with a dispersion ellipse on the B-plane (Portock 2000) and Earth’s surface. The estimation method is a conventional weighted least-squares fit. We adopted the weights of the 2-way Doppler and range observation as 0.5 mm s⁻¹, 10 m, respectively. The weights of the optical observation varied with the observatories. The observations of Tenagra observatory, Mt. Lemmon survey, Subaru Telescope and CFHT were weighted as 0.6, 1.0, 0.3, and 0.3, respectively. These values were validated using the residuals of the orbit determination process. A planetary perturbation using the Jet Propulsion Laboratory ephemeris DE423² was considered for trajectory propagation. The solar-radiation pressure was considered using the cannonball model (Montenbruck & Gill 2000). The Earth orientation model for terrestrial to celestial coordinate transformation was compliant with the IAU 2000A CIO based system.³

The B-plane is a useful plane to design the targeting condition of entry and flyby. The plane is normal to the incoming hyperbolic velocity (figure 5). The origin of the B-plane coordinate system is the Earth center; the horizontal axis (B.T) is parallel to the equator plane of Earth. The dispersion ellipse on the ground was calculated without considering the atmospheric effect, because the purpose of this study was to compare the dispersion ellipse with and without optical observations, and to describe the impact of ground-based observations.

Three data sets were prepared for the observations, and are summarized in table 4. Data set A includes the all optical observation data taken by four observatories. Data set B is a limited version of the radiometric data, which assumes that the HAYABUSA spacecraft had an unexpected issue on June 10. Data set C is the nominal case of the radiometric data, which includes all of the radiometric data up to June 13. Four cases were analyzed using a combination of the data sets, and are summarized in table 5. Case 1 investigated the dispersion

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Fig. 4. R-band images of HAYABUSA taken with the Canada-France-Hawaii Telescope on 2010 June 13 at (left to right) 6:10:00, 6:11:28, and 6:12:57 UT. North is up and east is left. The stars were trailed by 18″ during 40 s exposures tracked at the spacecraft’s rates of motion. The measured magnitude of HAYABUSA was about R = 19.0 with SNR in excess of 70.

2.1.3. Other observations

HAYABUSA was also observed from two sites in Arizona. One site is Mt. Lemmon Survey operated by A. Gibbs. No filters were used and the UCAC2 (Zacharias et al. 2004) star catalog was used as a reference with sidereal tracking. The exposure time was 30 seconds.

Another site is Tenagra II observatory. P. Holvorcem observed HAYABUSA with the Apogee AP8 camera (back-illuminated STiE chip, 1 K × 1 K). The reference catalog was USNO A2.0¹ and the tracking mode was non-sidereal. Unfortunately, detailed information is not available because the original data were lost.

2.1.4. Brightness of HAYABUSA

The Subaru data taken on June 12 were 1-minute exposures and 2 shots of 2-minute exposures in the V-band. The estimated detection limit in each exposure was about 22.3 mag. Since the tracking mode of Subaru observations was sidereal, the limiting magnitude was shallower than that of the CFHT observation.

Two exposures were taken on June 12 with CFHT, but the target was not detected in either of them, or in a stacked version of both exposures, which has an effective exposure time of 80 s. Using the inverse-square law, the topocentric distance on June 12 suggests a brightness of V = 22.7, which should have been detectable. The difference in the phase angle between the two nights (133°7 on June 12, 132°4 on June 13) shouldn’t have been enough to cause an appreciable brightness difference (an asteroidal phase function would predict a 0.14 mag brightening between the two nights). We therefore attribute the nondetection on June 12 to the spacecraft’s orientation with respect to the observer. An object with large, flat surfaces and specular reflection could easily have a large variation of brightness.

We also stacked both CFHT 40-second exposures and the three Subaru 60/120/120-second exposures to detect the position of HAYABUSA on June 12. However, we could not detect the signal, and it seems that HAYABUSA was fainter than expected based on the June 13 data corrected for distance.

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for the limited case and compared it with case 2 to understand the effect of the optical observations. The difference of cases 1 and 2 is the availability of the optical observations; therefore, the difference of the dispersion ellipse describes the impact of the optical observations for reentry object navigation. Case 3 describes the nominal dispersion of the HAYABUSA mission. The effect of the tracking arc for radiometric measurement is presented for comparing cases 1 and 3. Case 4 shows the dispersion only with the optical observations; this case corresponds to the test case for the Earth impact prediction of near-Earth objects.

**Table 4.** Observation data.

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<tr>
<td>B Limited radiometric data</td>
<td>6/9 11:00 – 6/10 6:30</td>
</tr>
<tr>
<td>C Full radiometric data</td>
<td>6/9 11:00 – 6/13 0:00</td>
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</table>

**Table 5.** Analysis cases.

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<th>Case</th>
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<td>B</td>
<td>Some issue happen in the spacecraft</td>
</tr>
<tr>
<td>2</td>
<td>A, B</td>
<td>Follow up observation by ground-based telescope</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>Nominal case (No trouble in the spacecraft)</td>
</tr>
<tr>
<td>4</td>
<td>A</td>
<td>Optical observation only</td>
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4. Results and Discussion

The results of the orbit determination (OD) and the dispersion ellipses are discussed in this section. The post-fit residuals of case 4 are described in figure 6. Five observations of the Mt. Lemmon Survey were rejected due to their large residuals. The observations of Subaru Telescope and Canada France Hawaii Telescope (CFHT) are quite stable, and all observations fit within 0.5'. The rms of 2-way Doppler and range data are 0.064 mm s^{-1} and 0.30 m, respectively. The standard deviations of the position and velocity vectors at the OD epoch are summarized in table 6. The impact of the optical observations is found in the difference between cases 1 and 2. Especially, the uncertainties for the velocity dramatically decrease. This would be due to extension of the tracking arc duration by the optical observation. However, the OD solution using the full radiometric observation (case 3) is much better than the hybrid case (case 2). Since case 4 has only 2.5 hours of optical observation, the solution has large uncertainties along both the position and velocity vectors. The main uncertainty is along the velocity direction, because optical imaging provides no information along the line-of-sight direction.

The 3σ dispersion ellipse on the B-plane is described in figures 7 and 8. The major axis of case 4 is 291 km, and it looks small compared with the uncertainty of the OD epoch, because the B-plane is orthogonal to the hyperbolic infinite velocity and the main uncertainty is along the velocity direction. Dramatic
improvements on the uncertainties by the optical observations were found by comparing the ellipse of cases 1 and 2. The size of the ellipse becomes about 1/600 of the original ellipse, and the mean value becomes much closer to the value of case 3. It is natural that the ellipse of case 3 is the smallest in these cases, just because this case used the better quality and longer duration of observation data.

Figure 9 depicts the landing dispersion ellipse for cases 1, 2, and 3 with the actual landing site of the HAYABUSA capsule. Since we haven’t considered the atmospheric effect, there is a difference in the landing ellipse and the capsule landing site. Comparing cases 1 and 2, it is found that the major axis is reduced by more than one order due to the followup optical observation. The ground-based optical observations significantly improved the entry dispersion ellipse. This is because the observations were just before the entry, and the sensitivity of the optical observation to the trajectory was perpendicular to that of the radiometric observable. The position dispersion history for cases 1, 2, and 4 are shown in figure 10 along with the observation time. The figure shows the relationship between the uncertainty and the observation. These results show that the optical observation becomes a strong backup strategy for sample return missions.

The linear covariance method can break down if the position uncertainty grows too large. A linear assumption becomes less adaptive if the uncertainties increase. In this study, the uncertainties of case 4 are too large to analyze the landing dispersion with the linear covariance method. The landing dispersion ellipse of case 4 is described in figure 11 along with the final landing location of the HAYABUSA sample capsule. This dispersion ellipse is the result of a Monte-Carlo simulation with 1000 particles. The terminate condition of the analysis was 0 km altitude for the WGS-84 ellipsoid model. The consequence of a large uncertainty along the velocity direction is that the landing time uncertainty becomes 87.4 s (1σ). The landing site prediction had about a 500 km accuracy, despite the fact that we only had optical observations. The main difference between the actual capsule landing site and the predicted site was due to the atmospheric effect; however, systematic biases on the star catalogs could affect the prediction.
Entry Dispersion Analysis for HAYABUSA

5. Conclusion

This paper investigated the entry dispersion analysis for the HAYABUSA spacecraft using ground-based optical observations. The dispersion ellipse with and without optical observations showed a significant impact of the ground-based observations to the landing footprint. This results validated the idea that optical observations allow a strong backup strategy for Earth reentry missions.

The landing error ellipse are depicted while considering the $^\circ\!^\prime\!^\prime\!^\prime$ declination biases on the Subaru and CFHT observation in figure 12. It is found that the star-catalog biases are negligible in this situation. This is because HAYABUSA was close to the observatories during the operation, and the impact of the errors in astrometric angular observations were limited.

USNO A2.0 and USNO B1.0 are known to have bias to the 2MASS catalog, particularly in declination, and a bias as large as a half arcsecond is quite possible (Chesley et al. 2010). The landing error ellipse are depicted while considering the $\pm 0^\circ 5$ declination biases on the Subaru and CFHT observation in figure 12. It is found that the star-catalog biases are negligible in this situation. This is because HAYABUSA was close to the observatories during the operation, and the impact of the errors in astrometric angular observations were limited.

The authors would like to acknowledge Dr. T. Ohnishi of Fujitsu Ltd. for providing radiometric tracking data of HAYABUSA. We also thank to the staff of Subaru Telescope and CFHT for supporting the observations of HAYABUSA. We are grateful to A. Gibbs of Mt. Lemmon Survey and P. Holvorcem of Tenagra II observatory, who provided HAYABUSA observations. Parts of the data analysis were carried out in the common-use data-analysis computer system at the Astronomy Data Center (ADC) of the National Astronomical Observatory of Japan. We would like to acknowledge an anonymous reviewer to clarify some points in this paper. Finally, we are sincerely grateful to all of the observers who tried to observe the HAYABUSA reentry. This work was supported by a Grant-in-Aid for Japan Society for the Promotion of Science (JSPS) Fellows.

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