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Trajectory of HAYABUSA Reentry Determined from Multisite TV Observations

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Abstract

The asteroid explorer HAYABUSA reentered into the Earth's atmosphere on 2010 June 13. We made simultaneous TV (television) observations at seven ground sites in order to calculate the trajectories of HAYABUSA and its sample return capsule (SRC), which both reentered into the atmosphere. Our TV observations showed that, after HAYABUSA reentered the atmosphere, the beginning time of its light emission on video was 13:51:57.4 UT at a height of 101.0 ± 0.2 km. The end time was 13:52:42.0 UT at a height of 38.6 ± 0.2 km. The initial velocity at the beginning was $12.1 \pm 0.3\,\mathrm{km\,s^{-1}}$, and the entry angle was 9°. After identifying SRC as separated light emission independent of the mother spacecraft, we analyzed the trajectory of SRC from a height of 52.9 km to 35.7 km based on video images. The actual trajectory of the capsule, determined from the TV observations, was almost the same as the predicted trajectory in terms of the position, velocity, and time. We then calculated the fall spots of the SRC heat shields from the multisite TV observations.

Key words: meteors: meteoroids — space vehicles: individual (HAYABUSA) — space vehicles: trajectory

1. Introduction

The asteroid explorer HAYABUSA and its capsule reentered into the Earth's atmosphere on 2010 June 13. By conducting simultaneous multisite TV observations and trajectory analysis immediately on site, we were able to support the JAXA's capsule resumption team by providing optical tracking parameters in the forecast of a possible landing point of the capsule as well as to get one of the best opportunities for checking the accuracy of trajectory analyses by reducing multisite TV observations. The initial velocity of a meteoroid into the Earth's atmosphere widely varies from a minimum of $11.2\,\mathrm{km\,s^{-1}}$ to a maximum of $72.8\,\mathrm{km\,s^{-1}}$ (e.g., Beech 2006). Reentries of HAYABUSA and the capsule are extremely rare events of an artificial meteor directly from interplanetary space. Precise observations of the reentry by various types of methods lead to meaningful data in the context of meteor science as well as the technology of artificial reentry. Data obtained from the simultaneous TV observations include the trajectory of the light emission, the velocity deceleration, the light curve, and the length of the capsule tail. HAYABUSA was remotely controlled by a ground control center of JAXA just before reentry. The artificial meteor enables us to make a comparison between the predicted trajectory of the capsule and the actual trajectory determined from optical observations.

2. Observation

We took TV observations for the reentry of HAYABUSA at seven ground sites (table 1). The baselines between the observation sites were as follows: a 191 km baseline between No. 1, Coober Pedy (GOS4), and No. 4, Tacoola (GOS3); a 119 km baseline between No. 6, GOS2, and No. 4, Tacoola (GOS3); and a 243 km baseline between No. 3, Coober Pedy, and No. 7, Glendambo. With a wide-angle lens attached to the Watec CCD video camera used for imaging, their horizontal fields of view were found to be between 56° and 90°. We used the following softwares for confirmative image detection and the determination of precise coordinates of HAYABUSA and the capsule:

- Observation software: UFOCaptureV2 by SonotaCo,
- Position measurement: UFOAnalyzerV2 by SonotaCo,
- Measurement of luminous intensity: RBAviMeteor by T. Kumamori,
- Calculation of the trajectory: Orbit3 by M. Ueda.

These tools are frequently used for observations of meteors and their trajectory analyses (e.g., Hasegawa 1976). It has been confirmed that the error in position measurement at this time was within 0°.03 from the fixed-star measurement result.

Table 1. List of observation sites.

No.	Location	Longitude (E) (°)	Latitude (S) (°)	Sea level (m)	Observers	Equipments
1	Coober Pedy (GOS4)	134.75853	−29.00253	212	Shiba	Watec WAT-902H2 ULTIMATE, *f* 2.9–8 mm, 2 cameras
2	Coober Pedy (GOS4)	134.71819	−29.03393	200	Kakinami	Watec, *f* 6 mm, 1camera
3	Coober Pedy	134.54736	−29.04258	180	Sato et al.	WATEC Neptune100, *f* 6 mm, 3 cameras
4	Tacoola (GOS3)	134.57080	−30.70913	122	Ueda	Watec WAT-902H2 ULTIMATE, *f* 2.9–8 mm, 2 cameras
5	Tacoola (GOS3)	134.55858	−30.69911	152	Abe	Watec, *f* 6 mm, 1 camera
6	GOS2	134.82291	−29.65860	148	Yamamoto	Watec WAT-902H2 ULTIMATE, *f* 2.9–8 mm, 2 cameras
7	Glendambo	135.73808	−30.96450	190	Uehara et al.	Watec WAT-902H2 ULTIMATE, *f* 6 mm, 3 cameras

3. Results and Discussion

3.1. *Trajectory of the Capsule*

The capsule was separated from HAYABUSA before its reentry into the atmosphere. However, HAYABUSA itself also reentered because of a malfunction of its attitude control; both HAYABUSA and the capsule reentered apparently close to each other. After the predicted passing time at an altitude of 200 km, at 13:51:12.19 UT on 2010 June 13, the two objects were first observed as a point of light emission because of the great distance from the ground sites. At 13:52:21.4 UT, the capsule could be identified on video images as a point completely separated from the mother spacecraft. The height of the capsule at that time was 52.9 ± 0.2 km. It disappeared from the video at 13:52:41.5 UT, at a height of 35.7 ± 0.2 km, and was then considered to have changed from the light emission into a dark flight. The method used for meteors assumes that the meteor trajectory is a straight line. We calculated the trajectory of HAYABUSA's capsule by dividing the track so that the trajectory length would be approximately 100 km (figure 1). We considered that such a calculation would enable us to use ordinary trajectory calculation methods like those used in meteor astronomy. We used a formula of Hasegawa (1976) for calculating the in-air trajectories of simultaneously observed meteors. We calculated the capsule trajectories from two-point-observation data. Based on the results of a combination of several calculations, we plot relations between capsule height (H) and longitude ($\lambda_{\rm a}$) in figure 2, between height (H) and latitude ($\phi_{\rm a}$) in figure 3, and between height (H) and velocity ($V_{\rm a}$) in figure 4, and we derived the following equations which fit individual observed trajectories:

$$\lambda_{\rm a} \pm 0.^{\circ}007 = 137.^{\circ}38337 - 0.^{\circ}067103\,H, \qquad (1)$$

$$\phi_{\rm a} \pm 0.^{\circ}003 = -30.^{\circ}92004 + 0.^{\circ}019567\,H, \qquad (2)$$

$$V_{\rm a} \pm 0.3\,(\mathrm{km\ s^{-1}}) = 233.98901 - 23.05248\,H + 0.81660\,H^2 - 0.012297\,H^3 + 0.00006778\,H^4, \qquad (3)$$

where numbers with $\pm$ signs mean the standard error of observed values. Table 2 gives the trajectory of the capsule in the atmosphere that is derived from simultaneous multisite TV observations. It can be seen that the velocity of the capsule clearly decelerated (figure 4). Table 3 gives a comparison between the predicted reentry trajectory of the capsule and the actual trajectory calculated from our simultaneous multisite TV observations. The relations between the passing time and the corresponding heights of the capsule and HAYABUSA are shown in figure 5. From the TV observations, it was precisely derived that when the capsule passed at a height of 50.0 km it was 13:52:23.40 UT. The predicted time of 50 km passage was 13:52:23.69 UT, showing only a discrepancy of 0.29 s. It was revealed that the reentry of the capsule was just on the same predicted trajectory, suggesting that a high-precision remote control was operated.

Table 2. Actual trajectory of the capsule determined from TV observations (2010 June 13).

Height (km)	Velocity $\pm 0.3\,\mathrm{km\,s^{-1}}$	Longitude (E) $\pm 0.^{\circ}007$	Latitude (S) $\pm 0.^{\circ}003$	Passing time ± 0.1 s (UT)
52.9	10.1	133.834	−29.885	13:52:21.4
52.0	9.9	133.894	−29.903	13:52:21.9
51.0	9.6	133.961	−29.922	13:52:22.7
50.0	9.4	134.028	−29.942	13:52:23.4
49.0	9.1	134.095	−29.961	13:52:24.2
48.0	8.8	134.162	−29.981	13:52:24.9
47.0	8.4	134.230	−30.000	13:52:25.7
46.0	8.0	134.297	−30.020	13:52:26.5
45.0	7.6	134.364	−30.040	13:52:27.4
44.0	7.2	134.431	−30.059	13:52:28.4
43.0	6.7	134.498	−30.079	13:52:29.4
42.0	6.1	134.565	−30.098	13:52:30.5
41.0	5.6	134.632	−30.118	13:52:31.8
40.0	5.0	134.699	−30.137	13:52:33.2
39.0	4.4	134.766	−30.157	13:52:34.8
38.0	3.7	134.833	−30.176	13:52:36.5
37.0	3.1	134.901	−30.196	13:52:38.4
36.0	2.5	134.968	−30.216	13:52:40.5
35.7	2.4	134.988	−30.221	13:52:41.5

3.2. *Fall Spots of Heat Shields*

At a height of 10 km the capsule (mass, 16.5 kg) separated two heat shields (mass of the forebody heat shield, 7.8 kg; mass of the aftbody heat shield, 2.5 kg), and sequentially opened its parachute. At that time the two heat shields disconnected from SRC maintained free fall, so we calculated these fall

Table 3. Comparison between prediction data and observation results.

Prediction data					Observation results			
Time (UT)	Height (km)	Velocity ($km\,s^{-1}$)	Longitude (E) (°)	Latitude (S) (°)	Height ± 0.16 km	Velocity $\pm 0.29\ km\,s^{-1}$	Longitude (E) $\pm 0\overset{\circ}{.}0022$	Latitude (S) $\pm 0\overset{\circ}{.}0076$
13:52:25.19	48.0923	8.712301	134.1748	−29.98417	47.6	8.7	134.187	−29.988
13:52:30.19	42.67119	6.345783	134.5392	−30.0912	42.4	6.3	134.540	−30.091
13:52:35.19	38.87841	4.190349	134.7918	−30.16422	38.7	4.2	134.790	−30.164
13:52:40.19	36.28792	2.724789	134.9566	−30.21118	36.2	2.7	134.954	−30.211

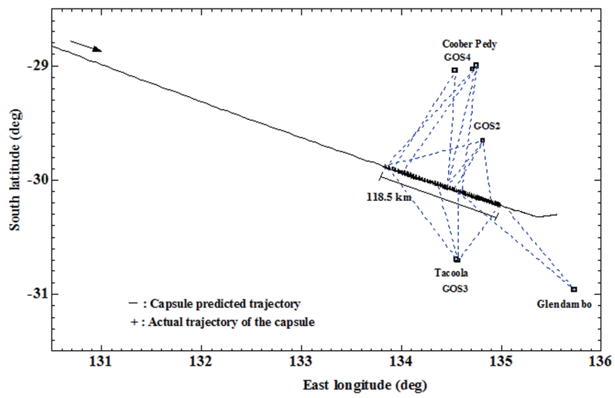

Fig. 1. Trajectory of HAYABUSA's capsule and the observation sites. The trajectory length would be approximately 100 km.

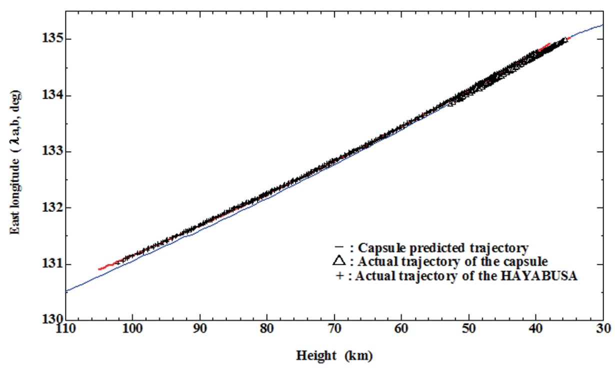

Fig. 2. Trajectory (height and longitude) of HAYABUSA and the capsule.

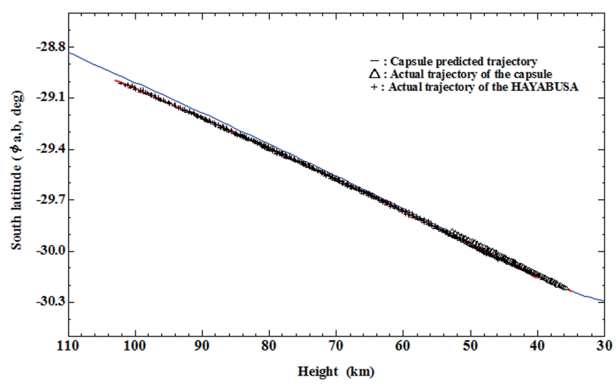

Fig. 3. Trajectory (height and latitude) of HAYABUSA and the capsule.

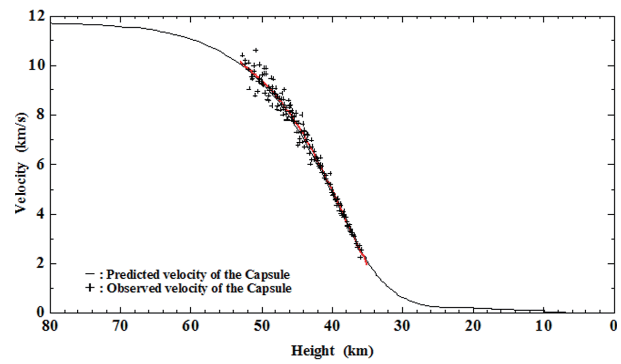

Fig. 4. Observed velocity of the capsule in the atmosphere; $V \pm 0.3\ (km\,s^{-1}) = 233.98901 - 23.05248H + 0.81660H^2 - 0.012297H^3 + 0.00006778H^4$.

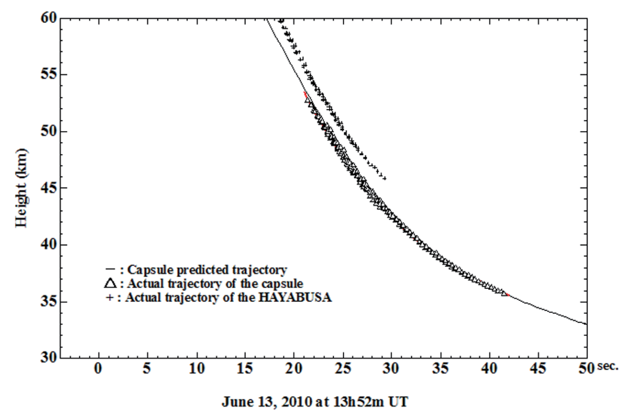

Fig. 5. Relation between the passing time and the corresponding height of the capsule, $H \pm 0.16\ (km) = 112.42994 - 4.24708T + 0.07982T^2 - 0.000531T^3$.

spots. About the calculation of the forecasted drop point of the capsule's heatshield, we used a formula of Nagasawa (1980), and for constants we used the values of ReVelle (1979). The geographical coordinates of the spots where the heat shields were actually found and those predicted from the TV observations are given in table 4. The distance between the above-mentioned a-1 and b-1 fall spots was 1.2 km, while the distance between a-2 and b-2 was 0.9 km.

3.3. *Tail of the Capsule*

The capsule reentry was observed as an object with a long illuminating tail because of its ablative characteristics. We calculated the length of the capsule tail using images obtained

Table 4. Geographical coordinates of the spots where the heat shields were actually found and of those predicted from TV observations.

	Longitude	Latitude
a Predicted fall spots derived from TV observations		
a-1 Forebody heat shield	$135\overset{\circ}{.}3863$ E	$30\overset{\circ}{.}3146$ S
a-2 Aftbody heat shield	$135\overset{\circ}{.}3911$ E	$30\overset{\circ}{.}3091$ S
b Actual fall spots		
b-1 Forebody heat shield	$135\overset{\circ}{.}38900$ E	$30\overset{\circ}{.}30367$ S
b-2 Aftbody heat shield	$135\overset{\circ}{.}38550$ E	$30\overset{\circ}{.}30317$ S

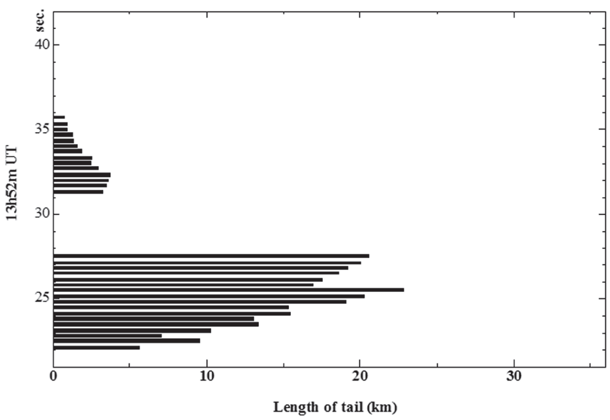

Fig. 6. Tail length of the capsule; we calcuated it from a video image which we photographed in Tacoola (GOS3). It disappeared from view of the TV camera at 13:52:27.7 UT and stepped into another camera's view at 13:52:31 UT.

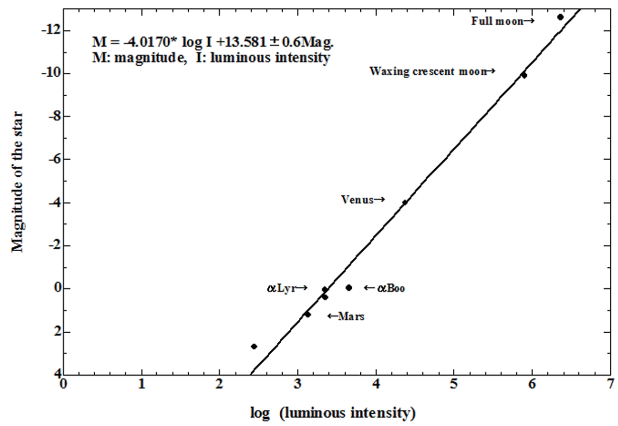

Fig. 7. Relation between the total luminous intensity and the magnitude of the star catalogue.

at Tacoola (GOS3) (figure 6). The capsule tail could be separated as a bright beam of light from SRC and HAYABUSA, starting at 13:52:22.3 UT with changing its length. At that time the capsule reached at a height of 51.5 km. The tail remained on video up to 13:52:35.7 UT, when SRC was at a height of 38.4 km. At a height of 47.0 km, the largest length of the tail, 22.9 km, appeared at 13:52:25.7 UT.

3.4. Brightness of the Capsule

The maximum magnitude of SRC occurred at 13:52:29.4 UT at a height of approximately 43 km. Its brightness reached to a magnitude of -5 ± 1 in terms of the absolute magnitude scale at a distance of 100 km. This result was slightly brighter than the value observed by Sato et al. (2011) at the same time. The determination steps of the magnitude are as follows. (1) For all stars and other luminous objects identified, we measure the relative 8-bit luminous intensities of all pixels in each area, and obtain a sum. (2) From the sum of the luminous intensity, we subtract the luminous intensity of the background. (3) We prepare an equation between each sum of the luminous intensity of each star on image and the star magnitude based on a star catalogue (THE SKY, Software Bisque Inc.).[1] (4) We measure the sum of the luminous intensity of the capsule from the image, and determine its magnitude from the equation shown in figure 7. As shown in figure 7, we fit an expression,

$$M \pm 0.6(\mathrm{Mag}) = -4.0170 \log I + 13.581, \tag{4}$$

where a number with $\pm$ signs means the standard error of observed values. Based on the relation between the comparison star's (eight heavenly bodies) total sum of the luminous intensity and the magnitude, we determined the magnitude from the total sum of the capsule's luminous intensity. Here, M is an absolute magnitude of the capsule to be found and I is the total sum of the luminous intensity. The maximum magnitude was within the same level of the prediction. The temperature of SRC found in a spectrum analysis is described by Abe et al. (2011).

3.5. Trajectory of HAYABUSA

Triangulation was carried out to calculate the trajectory of HAYABUSA from TV observations obtained at seven sites (table 5, figure 8). Using the same method as for calculating the trajectory of HAYABUSA's capsule, we calculated the trajectory of HAYABUSA by dividing the track so that the trajectory length would be approximately 100 km. We give a plot of the calculation results for the trajectory of HAYABUSA in figure 8. Then, the following relations between HAYABUSA's height (H) and longitude (λ_b) and between height (H) and latitude (ϕ_b) fit the observed trajectories (figures 2 and 3):

$$\lambda_\mathrm{b} \pm 0\overset{\circ}{.}013 = 137\overset{\circ}{.}78926 - 0\overset{\circ}{.}08125 H + 0\overset{\circ}{.}0001496 H^2, \tag{5}$$

$$\phi_\mathrm{b} \pm 0\overset{\circ}{.}006 = -30\overset{\circ}{.}99102 + 0\overset{\circ}{.}02180 H - 0\overset{\circ}{.}0000232 H^2, \tag{6}$$

1 ⟨http://www.bisque.com/⟩.

Table 5. Actual trajectory of HAYABUSA, which was determined from TV observations (2010 June 13).

Height (km)	Velocity $\pm 0.3\,\mathrm{km\,s^{-1}}$	Longitude (E) $\pm 0.^{\circ}006$	Latitude (S) $\pm 0.^{\circ}013$	Passing time $\pm 0.2\,\mathrm{s}$ (UT)	
101.0	12.1	131.109	−29.026	13:51:57.4	
100.0	12.1	131.160	−29.043	13:51:57.8	
95.0	12.1	131.421	−29.129	13:52:00.0	
90.0	12.0	131.689	−29.217	13:52:02.4	
85.0	12.0	131.964	−29.306	13:52:04.9	
80.0	11.9	132.247	−29.396	13:52:07.4	
75.0	11.9	132.537	−29.487	13:52:10.0	
70.0	11.8	132.835	−29.579	13:52:12.6	
68.2	11.7	132.944	−29.612	13:52:13.6	Large explosion (1st), −13.0 Mag*
65.0	11.6	133.140	−29.672	13:52:15.3	
63.6	11.5	133.227	−29.698	13:52:16.1	Large explosion (2nd), −11.8 Mag*
61.6	11.3	133.352	−29.736	13:52:17.2	Large explosion (3rd), −11.8 Mag*
60.0	11.2	133.453	−29.767	13:52:18.2	
57.3	10.8	133.625	−29.818	13:52:19.9	Large explosion (4th), −13.0 Mag*
55.0	10.5	133.773	−29.862	13:52:21.4	
50.0	8.8	134.101	−29.959	13:52:25.0	
48.6	7.0	134.194	−29.986	13:52:26.2	
41.5	4.7	134.655	−30.123	13:52:37.3	Fragment
40.0	4.0	134.438	−30.148	13:52:39.4	Fragment
38.6	2.7	134.826	−30.171	13:52:42.0	Fragment

* Mag: absolute magnitude.

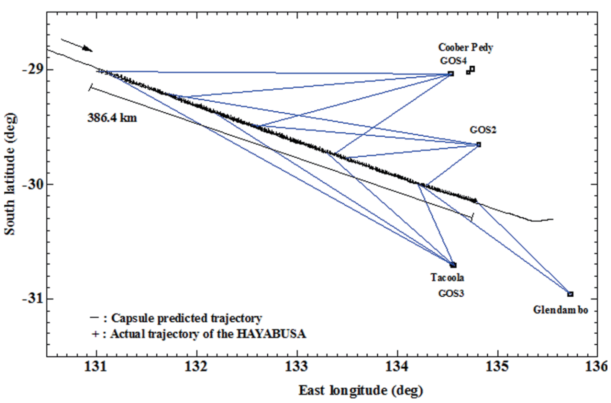

Fig. 8. Trajectory of HAYABUSA and the observation sites. The trajectory length would be 386.4 km.

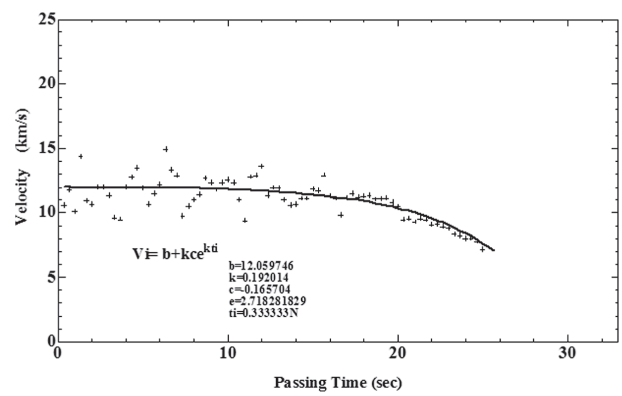

Fig. 9. HAYABUSA velocity from the observation dates of GOS2 and GOS3.

where numbers with $\pm$ signs mean the standard error of observed values. About the initial velocity, we used equation (48) of Whipple and Jacchia (1957) on the relation between the time elapsed (t_{i}) and the velocity (V_{i}) (figure 9):

$$V_{\mathrm{i}} = b + kce^{kt_{\mathrm{i}}}, \tag{7}$$

$b = 12.059746$, $k = 0.192014$, $c = -0.165704$, and $t_{\mathrm{i}} = 0.333333\,N$, where N is the number of frames from the first HAYABUSA's image. The time when HAYABUSA initially appeared on video was at 13:51:57.4 UT on 2010 June 13, and the height was 101.0 km, with an initial velocity of $12.1 \pm 0.3\,\mathrm{km\,s^{-1}}$. Position measurements for HAYABUSA were possible up to 13:52:26.2 UT at a height of 48.6 km, being followed by vehement fragmentation, which made it difficult to identify the same object on the image for trajectory calculations. The last remaining fragment of HAYABUSA identified on video under simultaneous observation conditions was tracked from 13:52:37.3 UT to 13:52:42.0 UT (table 5). The video containing the image of HAYABUSA was of 44.6 s duration; the trajectory length, 386.4 km, the incoming angle, 9°; the apparent radiant, RA $170.^{\circ}4$, Dec $+12.^{\circ}2$; and the corrected radiant, RA $135.^{\circ}2$, Dec $+28.^{\circ}7$ (J2000.0).

3.6. *Brightness of HAYABUSA*

Figure 10 shows a result of the luminous intensity of HAYABUSA obtained by video observations at three sites (GOS2, GOS3, and GOS4). As can be seen in figure 10, explosive brightenings took place 4 times. In table 5, spots of the explosive brightenings are shown in detail. The absolute magnitude of HAYABUSA was determined in the same way as that of the capsule. The fragmentation process of HAYABUSA found in a close-up video image analysis is described by Watanabe et al. (2011) and Yamamoto et al. (2011).

3.7. Distance between HAYABUSA and the Capsule

The capsule, which had already been released from HAYABUSA, reentered into the atmosphere ahead of HAYABUSA (figure 11). The distance between HAYABUSA and the capsule was 2.2 ± 0.3 km when the height of the capsule was 52.0 km. Due to different deceleration parameters for two objects, it was confirmed that the distance increased up to 3.4 ± 0.3 km when the capsule height was at 46.0 km (table 6).

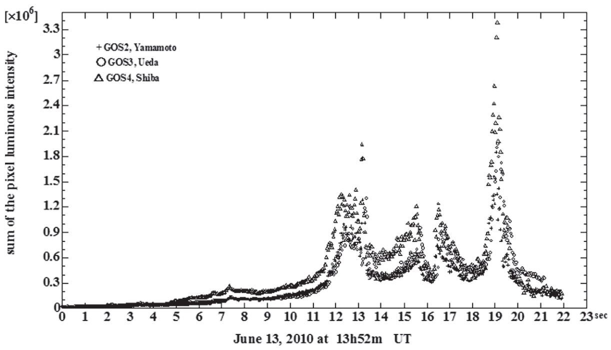

Fig. 10. Light curve of HAYABUSA at GOS2, GOS3, and GOS4.

4. Conclusion

In the case of HAYABUSA reentry, the two objects, the capsule and HAYABUSA, whose masses and sizes were precisely known, reentered into the atmosphere. Throughout our simultaneous multisite TV observations of those artificial-meteor events, we obtained many fruitful results, i.e., the emission by HAYABUSA and SRC reentry was first found at 101.0 km as one point light source; it then gradually increased in brightness to an absolute magnitude of -13.0, while having 4 explosive enhancements at 68.2, 63.6, 61.6, and 57.3 km, just before a predicted altitude of SRC peak heat, 57 km. After passing 53 km high point, HAYABUSA and SRC were identified separately on video images; then, the former was fragmented into many tiny parts, whereas the latter gradually

Table 6. Distance from the capsule to HAYABUSA in the atmosphere.

Height* (km)	Distance† ± 0.3 km	Elevation‡ ± 2°	Azimuth§ ± 2°
52.0	2.2	30	290
50.0	2.6	29	289
48.0	3.0	28	289
46.0	3.4	27	289

* Hight of the capsule (km).
† Distance from the capsule to HAYABUSA (km).
‡ Elevation of HAYABUSA from the capsule (°).
§ Azimuth of HAYABUSA from the capsule (°).

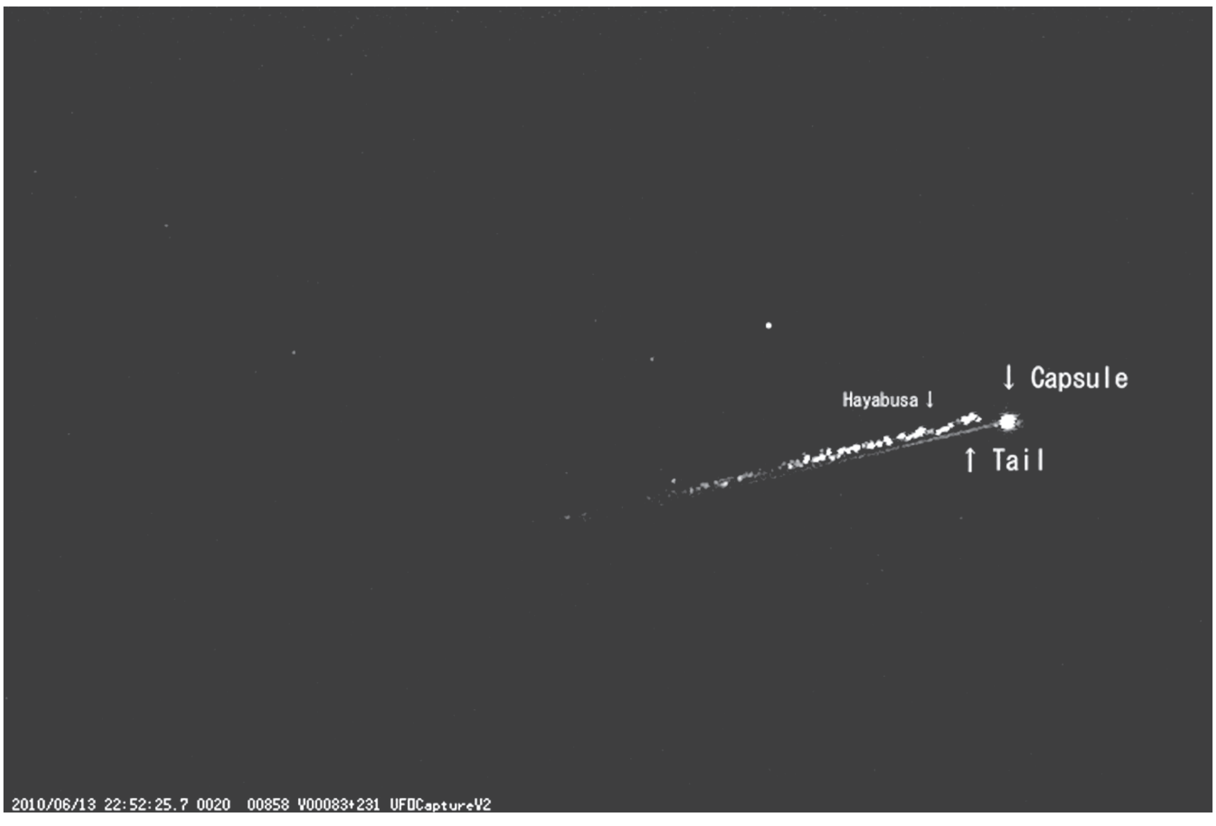

Fig. 11. Capsule, its tail, and HAYABUSA into fragments. Photography in Tacoola (GOS3).

increased its brightness to a maximum absolute magnitude of −5 at 43 km, having a long tail of its ablator materials up to a length of 22.9 km. The reentry trajectory was precisely determined from multiplesite triangulation analyses within an error range of 300 m, showing a close correspondence to the predicted nominal trajectory. Fall spots of separated heat shields were calculated as well, showing a close correspondence between observed and predicted spots within an error range of 1.2 km. These data are useful not only for clarifying meteor physics, but also for confirming precise parameters of heat-control technology in the case of a hypersonic reentry directly from interplanetary space.

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