Optical Tracking and Spectroscopic Measurement of Hayabusa Capsule Reentry Fireball

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The asteroid explorer HAYABUSA finally returned to the earth on June 13rd 2010 and the sample return capsule experienced a super-orbital atmospheric reentry. To recover the sample return capsule and to conduct optical measurements, the Japan Aerospace Exploration Agency organized a ground observation team and conducted optical tracking of the sample return capsule, spectroscopy of the fireball as well as the fireball trail, and measurement of infrasounds and shock waves generated by the fireball. In this article, an overview of the ground observation is presented, and the preliminary results derived from observations are reported.

I. Introduction

MUSES-C (Mu Space Engineering Satellite C)[1] was launched as the world's first asteroid explorer from Uchinoura Space Center (USC) on May 9th 2003, after which the explorer was named as *HAYABUSA*. HAYABUSA arrived the asteroid *ITOKAWA*, touched down on it to collect samples in November 2005. Getting around a lot of difficulties, HAYABUSA finally returned to the earth on June 13rd 2010, and the sample return capsule (SRC) and its mother ship made a final flight across the sky, changing into arrows of light. To meet this historical event, and to reliably recover the SRC, Japan Aerospace Exploration Agency (JAXA) organized a ground observation team consisting of 15 staffs, as a part of the SRC recovery team dispatched to the South Australia, and conducted optical as well as acoustical measurements. In this article, an overview of the ground observation activities is described, and the preliminary results derived from the measurement are presented.

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II. Scope of Ground Observation

In the nominal scenario of the HAYABUSA SRC recovery, a beacon signal transmitted from the SRC after parachute deployment is detected by multiple ground sites prepared for radiolocation, and the touchdown point of the SRC is deduced as a crossing point of lines of beacon reception measured at the individual ground site.[1] However, such a radiolocation scheme may fail when the SRC goes into hard touchdown without separation of the thermal protection system (TPS) or without parachute deployment, and when the beacon is not transmitted after parachute deployment. When the SRC recovery team was organized, such malfunctions of the SRC were considered to occur with a considerable probability, because HAYABUSA had been operated for an excessively longer period than originally designed. On the other hand, it was obviously expected that the SRC makes a hypersonic flight accompanied by intense luminescence due to aerodynamic heating, like a fireball.[2] For these reasons, the primary purpose of the ground observation is to enhance redundancy of the SRC touchdown point prediction by conducting the optical tracking of the SRC fireball, reconstructing the reentry trajectory at high altitudes, and estimating the descent trajectory at low altitudes after extinction to predict the touchdown point.

The second purpose of the ground observation is to obtain trajectory-based information on temperature of the SRC TPS by conducting spectroscopy of blackbody radiation emanated from the TPS surface, on thermochemical behavior of the TPS by conducting spectroscopy of gas radiation in the trail of the SRC fireball, and on erosive destruction of the mother ship by conducting spectroscopy of luminescence emitted from components of the mother ship. Such information is useful for reconstruction of the flight environments during the atmospheric reentry, assessment of the TPS performance in flight, and validation of computational fluid dynamic (CFD) codes as well as super charring materials ablation (SCMA) codes in post-flight analyses.[3]

The third purpose of the ground observation is to acquire scientific data valuable for the meteor researches, such as the reference data to estimate the physical and chemical properties of a meteor as well as its entry velocity, and the unique data of luminescent processes and interactions between meteors and the atmosphere. In the meteor researches, the physical properties and the thermochemical processes of meteors are in general estimated from the measured quantities such as the luminous intensity, the spectra, and the acoustic waves generated by meteors. However, since it is hard to succeed in comprehensive measurements of a meteor due to unexpected apparition, and since most meteors are burnt out before a touchdown, it is difficult to validate the measurement-based estimations. Reentry of the HAYABUSA SRC is an unparalleled chance to examine a correlation between the measured quantities and the physical and chemical properties, the entry velocity, and the trajectory of a meteor, all of which are exactly known since the SRC is an artificial meteor.

The fourth scope of the ground observation is to record the historical event, the HAYABUSA atmospheric reentry. As described later, the SRC recovery operation was carried out in the Woomera Prohibited Area (WPA) where unauthorized people have no admittance, and the SRC reentry trajectory was set in the ski over the WPA as well. Photographing and filming from outside of the WPA may have limitations since such areas are located far from the SRC reentry trajectory. For this reason, photographing and filming experts were invited to take part in the ground observation team.

III. Deployment of Observation Sites

The ground observation team consists of 15 members, 5 staffs from JAXA and the others from universities and research institutes over Japan, including amateur astronomer, as shown in Table 1. The JAXA staffs were mainly engaged in optical tracking of the SRC using a specialized optical tracking system described below. Asst. Prof. Masa-yuki Yamamoto from Kochi University of Technology (KUT), Dr. Yoshiaki Ishihara from National Astronomical Observatory of Japan (NAOJ), Asst. Prof. Yoshihiro Hiramatsu from Kanazawa University (KU), and Prof. Muneyoshi Furumoto from Nagoya University (NU) made an attempt to measure audible sound and infrasound generated by the SRC and the mother ship, and seismic wave induced by the shock produced by the SRC. Asst. Prof. Shinsuke Abe from National Central University of Taiwan (NCU), who had also joined in the airborne observation campaign of the STARDUST sample return capsule[4] with Asst. Prof. Masa-yuki Yamamoto, Dr. Ohmi Iiyama Iiyama from Osaka science museum (OSM), and Dr. Yoshihiro Kakinami from National Cheng Kung University of Taiwan (NCKU), conducted spectroscopy of the HAYABUSA fireball and its train from a UV to NIR wavelength range, as well as photographing and filming of the HAYABUSA reentry and recovery event.

In addition to above members, to construct a redundant system for touchdown point prediction by the

Table 1. **Constitution of ground observation team.**

Site Name	Location	Functions	Members
GOS1	Mt. Vivian	• Optical tracking of SRC fireball • Trajectory determination • Touchdown point prediction • Hub station between GOS and RCC • High-resolution spectroscopy	K. Fujita (JAXA) H. Takayanagi (JAXA)
GOS2	Ingomar Homestead	• Optical tracking of SRC fireball • Measurement of audible sound, seismic wave, and infrasound • Spectroscopy of fireball and train • Video recording and photographing • Detection of FM radio wave scattering	T. Yanagisawa (JAXA) M. Yamamoto (KUT) Y. Ishihara (NAOJ) Y. Hiramatsu (KU) M. Furumoto (NU)
GOS2A	McDouall Peak Homestead	• Measurement of infrasound and seismic wave using data loggers	
GOS2B	Bulgunnia Homestead	• Measurement of infrasound and seismic wave using data loggers	
GOS3	Tarcoola	• Optical tracking of SRC fireball • Trajectory determination (backup) • Spectroscopy of fireball and train • Video recording and photographing	Y. Kurosaki (JAXA) S. Abe (NCU) O. Iiyama (OSM) M. Shoemaker (KU) M. Ueda (NMS)
GOS4	Coober Pedy	• Optical tracking of SRC fireball • Spectroscopy of fireball and train	T. Suzuki (JAXA) Y. Shiba (NMS) Y. Kakinami (NCKU)

optical tracking, Mr. Masayoshi Ueda and Mr. Yasuo Shiba from the Nippon Meteor Society (NMS), and Mr. M. Shoemaker from Kyushu University were invited to collaborate with the JAXA team. The NMS is well experienced in optical tracking of meteors, having constructed a meteor observation network over Japan using the automated meteor capture system to determine the trajectory and the velocity of meteors.[5] On the other hand, Mr. M. Shoemaker adopted a trajectory determination scheme using dynamic analysis of the SRC coupled with video image processing,[6] which is essentially different from that of JAXA and NMS. In addition to the above fundamental roles in the ground observation, the members brought additional observation instruments of their own interests, so that a variety of observations were made possible among the ground observation team.

The ground observation was performed at 4 ground observation sites (GOS) distributed around the SRC reentry trajectory, as illustrated in Table 1 and Fig. 1. The SRC recovery operation was conducted in the Woomera Prohibited Area (WPA), where unauthorized people have no admittance. The most part of the WPA is desert area so that the location of the GOS was chosen from viewpoints of safety and accessibility as well as observability of the SRC trajectory. Finally, the GOS1 and the GOS2 were placed in the desert area within the WPA, while the GOS3 and the GOS4 were located at peopled towns, Tarcoola and Coober Pedy, respectively, which are on the outside edge of the WPA.

The GOS1 located at Mt.Vivian (30.579641 deg. S., 135.721291 deg. E.) is the hub station of the ground observation at which all the observational data are collected, analyzed, and transmitted to the SRC recovery headquarters located at the Range Control Center (RCC) of the WPA. Taking advantage of the geometric attribute that the GOS1 is located straight ahead of the SRC trajectory, telescopic video recording of the SRC and high-resolution spectroscopy of blackbody radiation from the SRC TPS, separately from the mother ship, was attempted using a 1500-mm telescope equipped with an automatic follow-up system. The observational equipment layout at GOS1 is shown in Fig. 2.

The GOS2 located at Ingomar Homestead (29.658600 deg. S., 134.822910 deg. E.) is approximately at a 30-km distance in the west from the Stuart Highway running north-south across the WPA. In addition

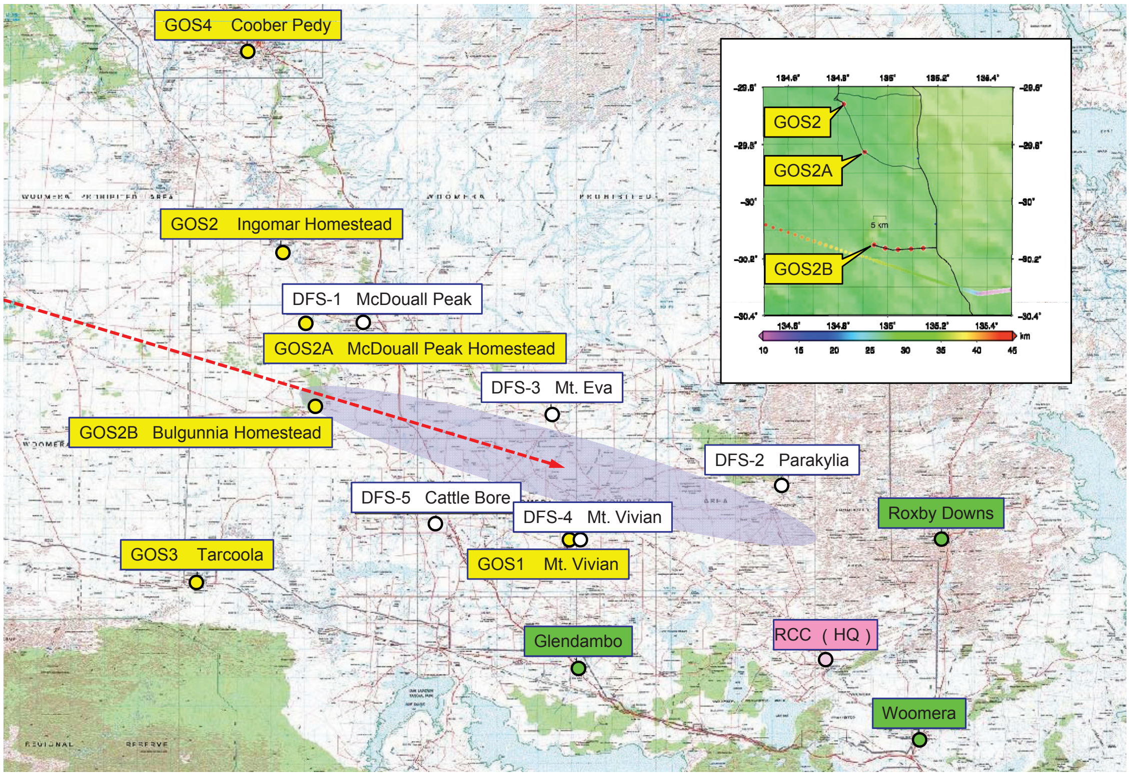


Figure 1. Deployment of ground observation sites (GOS, denoted by yellow symbols). Observation sites for radiowave direction finding system (DFS) and principal towns are also shown by white and green symbols, respectively. RCC is the range control center where the HAYABUSA recovery headquarters are located.

Figure 2. Observation equipment layout at GOS1.

to optical tracking of the SRC, measurements of the seismic wave and the infrasound were attempted at this site.[7] The GOS2 had two satellite sites, GOS2A and GOS2B. They are unattended sites at which the seismic wave and the infrasound were continuously recorded in data loggers. The layout of the infrasound sensor and the seismograph at the GOS2 is shown in Figs. 3a and 3b, respectively. The infrasound sensor and the seismograph were all installed at the GOS2, the GOS2A, and the GOS2B. At the GOS2B, in order to clarify propagation of the seismic wave along with the fireball motion, five seismographs were aligned in the east-west direction with a 5-km interval, as shown in Fig. 1.

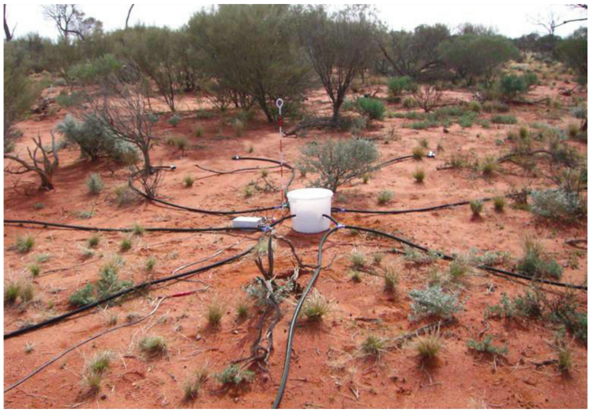
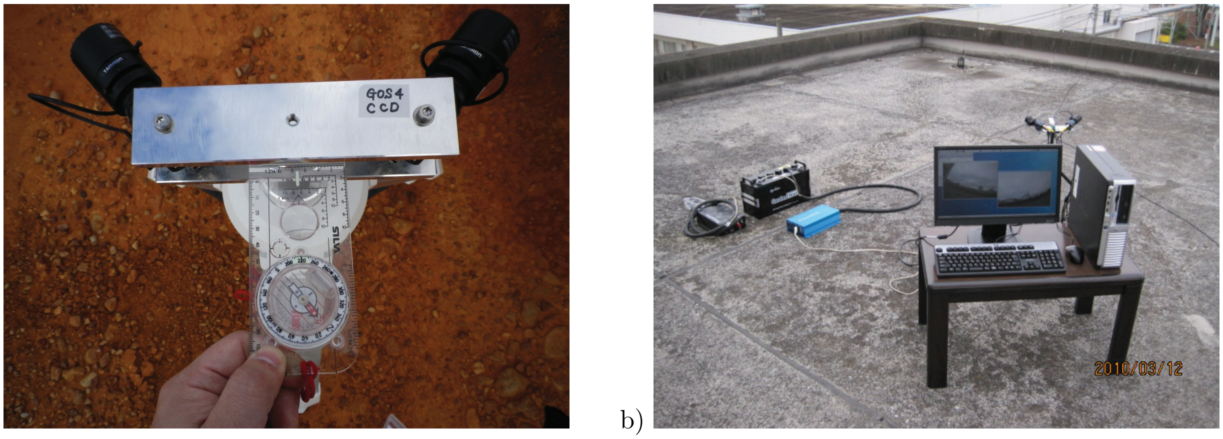
a)  b) 

Figure 3. Instrument layout of a) infrasound sensor and b) seismograph used at GOS2.

Figure 4. Observation equipments used at GOS3.

The GOS3 located at Tarcoola (30.699114 deg. S., 134.558580 deg. E.) is the southernmost site of the ground observation. This observation site was closely coupled with the northern site, GOS4, located at Coober Pedy (29.033954 deg. S., 134.718348 deg. E.), taking advantage of the broadband wireless Internet service (NextG) available in both towns. While the JAXA's optical tracking system was installed at every GOS with the GOS3 as the hub station, the NMS has its own optical tracking systems placed at the GOS2, the GOS3, and the GOS4 with the GOS3 as the hub station, for a redundant trajectory determination procedure. Mr. M. Shoemaker was engaged in the SRC trajectory determination at the GOS3 as well, using dynamic analysis of the SRC coupled with image processing of the video recorded at the GOS3 and that transmitted from the GOS4 via the broadband Internet connection. All the SRC trajectories estimated at the GOS3 were transmitted to the GOS1 where the SRC touchdown point was predicted from the estimated trajectories, and was reported to the headquarters. In addition to the multiple redundant trajectory determination systems described above, a lot of video and still cameras, such as an all-sky camera, a fish-eye camera, a high-sensitive high-power zoom video camera, and a hi-vision video camera, were applied for video recording, photographing, and spectroscopy at the GOS3 and the GOS4, as shown in Fig.4. Low-resolution spectroscopy was conducted as well at these sites, using both the video and the still cameras equipped with a transmissive grating.

Voice communication and data transfer between the GOS and between the GOS1 and the RCC were



a) b)

Figure 5. Instrument layout of a) a fireball recording camera (in Woomera, Australia) and b) an optical tracking system (demonstrated at Aerospace Research Center, JAXA).

made by using satellite phones and satellite modems (Iridium and Inmarsat BGAN). At the GOS3 and the GOS4 which are close to peopled areas, mobile phones and broadband Internet connections enabled by the Next G mobile network of Telstra Inc. were used in addition.

IV. Optical Trajectory Determination Method

The HAYABUSA fireball was recorded for optical tracking by a specialized camera system shown in Fig. 5a. The fireball recording camera is composed of two high-sensitive monochrome charge-coupled device (CCD) cameras, WATEC WAT-902H ULTIMATE, equipped with a wide-angle lens, FUJINON YV2.7X2.9LR4D-SA2. The two CCD cameras are set up at an angle of 100 degrees so that a 170 degrees horizontal × 60 degrees vertical field of view can be continuously obtained at a time. Comatic aberration of the optical system was precisely calibrated as a whole prior to the SRC recovery operation in Australia, in a way that each CCD pixel is mapped by a pair of an azimuthal (AZ) and an elevational (EL) angle in relation to the major axes of the camera system. At each GOS, the major axes of the camera system was roughly set up by a compass according to the predicted trajectory, then the Eulerian angles of the CCD major axes were accurately determined in relation to the World Geodetic System 84 (WGS84) by stellar observation. In this way, all the CCD pixels are mapped to the local azimuthal and elevational angles within errors of ±0.2 degrees.

The fireball images were captured by a video capture system installed in a personal computer (PC) at 30 frames per second, and processed every one second to obtain azimuthal and elevational angles of the SRC fireball. In order to synchronize the observed data at every GOS, a Global Positioning System (GPS) sensor, GARMIN GPS16$^{\text{TM}}$, was connected through a serial interface to the PC to accurately set the PC clock at the universal time coordinated (UTC). By using a pulse per second (PPS) signal of the GPS, the PC clock was adjusted every 20 seconds to realize accuracy of time within ±1 millisecond. Electric power was supplied to the optical tracking system as well as other observation instruments from a battery having a 130 Ah capacity through an electric inverter having a 600W capacity. The entire view of the optical tracking system is shown in Fig. 5b.

The time-series data of the azimuthal and elevational angles of the SRC fireball measured at each GOS were transmitted to the GOS1 where the SRC fireball trajectory was determined. At the GOS1, the SRC position at each UTC was determined as an intersection point of lines of sight from the GOS. As easily expected, lines of sight do not exactly intersect at a point due to measurement errors. In order to cope with this problem, the intersection point was determined so that a sum of the distance between the target point and the line of site divided by the possible maximum deviation at the fireball position due to measurement errors can be minimized. In this way, the time-series point data of the SRC fireball position can be obtained as *the primary trajectory*.

However, since the primary trajectory so determined is a series of points scattered around the true trajectory with a certain amount of dispersion, it is not convenient to directly use the primary trajectory

Table 2. Timeline of trajectory data report from GOS1 to headquarters.

#	Reported time	Source data	Accuracy	Remarks
1	R+00:30	AZ/EL data at every 10 seconds	Low	Quick report.
2	R+01:00	AZ/EL data at every 5 seconds	Moderate	Video and photos of fireball are transmitted at the same time.
3	R+02:00	AZ/EL data at every 1 second	High	Accurate report.

for touchdown point prediction. For this reason, *the most probable trajectory* is determined through Monte-Carlo trajectory calculations in the following way. 10^5 trial calculations of the SRC atmospheric reentry are performed based on the physical properties of the SRC, the aerodynamic characteristics, and the atmospheric entry conditions with uncertainties involved in each parameter, which are deduced from the interplanetary orbit of HAYABUSA determined in collaboration with NASA JPL using the Δ Differential Oneway Range (DDOR). Among the trial results, the trajectory whose deviation from the primary trajectory is the least was chosen as the most probable trajectory. The advantage of the above procedure is that continuous trajectory data, including the touchdown point, and possible dispersions in each parameter can be obtained at the same time.

The most probable trajectory data were reported to the headquarters by three times, increasing accuracy in calculation, as summarized in Table 2. The first trajectory data, which were calculated using the azimuthal and elevational data at every 10 seconds, was reported to meet the request for the trajectory determination within half an hour from the HAYABUSA reentry. The second data, transmitted to the headquarters one hour after the HAYABUSA reentry with videos and photos of the HAYABUSA fireball for press releases, was calculated from the azimuthal and elevational data at every 5 seconds to improve accuracy. The final trajectory data was calculated using the observation data at every second, and reported to the headquarter 2 hours after the reentry.

V. Results Overview

The ground observation team members got to Woomera on June 2nd, joined in the plenary meeting of the HAYABUSA recovery operation on June 4th, and deployed to their corresponding observation sites. After several daytime and nighttime rehearsals, the GOS members waited for the HAYABUSA reentry on June 13rd. It had been cloudy with occasional showers of rain for days until the night of June 12nd. However, thanks God, all of the GOS could have clear skies on June 13rd, which allowed the members to observe the HAYABUSA fireball from beginning to end. The HAYABUSA SRC reentered the atmosphere together with its mother ship, emanating a brilliant luminescence, as shown in Fig. 6.

Typical examples of the HAYABUSA fireball images taken by the optical tracking system are shown in Fig. 7. During the SRC reentry, the optical tracking system worked well at every GOS, and the SRC trajectory was determined successfully and reported to the headquarters as scheduled in Table 2. In Figs. 8a and 8b, the azimuthal and the elevational angles of the SRC measured at the GOS1 and the GOS2, respectively, are plotted and compared with the ones predicted prior to the HAYABUSA reentry based on the reentry conditions determined by the DDOR. Good agreement between the measured and the predicted angles is seen, suggesting accuracy in the trajectory prediction using the reentry conditions determined by the DDOR. Since the SRC could not be clearly distinguished from the HAYABUSA components until luminescence of the HAYABUSA components reduced (see Fig. 7), the accurate trajectory data for the SRC were only available after 13:52:20. Finally, the primary trajectory determined from the azimuthal and the elevational angles, and the most probable trajectory deduced by the Monte-Carlo calculations using the primary trajectory, are plotted and compared with the predicted trajectory in Fig. 9. The most possible trajectory determined by optical tracking is seen to be close to the predicted trajectory. The SRC trajectories determined by the NMS members and Mr. M. Shoemaker showed good agreement with the most possible trajectory shown in Fig. 9, though the results are not shown here.

In spite of the successful trajectory determination by optical tracking, the measured trajectory data was not used for the touchdown point prediction, since the SRC perfectly functioned as planned, transmitting the beacon signal after the parachute deployment. The radiowave direction finding system quickly found out

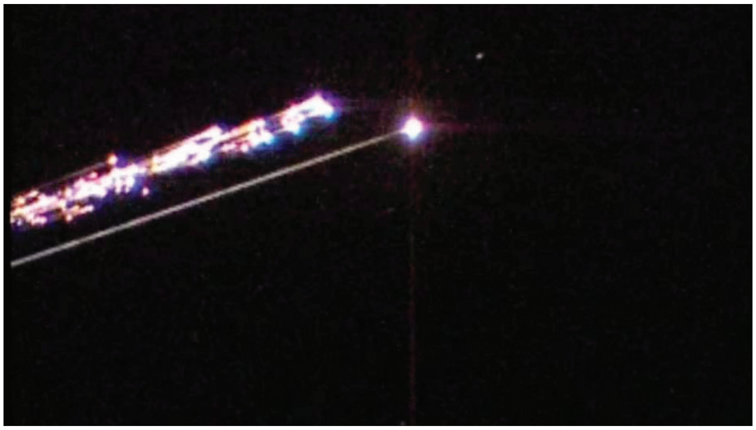


Figure 6. SRC fireball followed by HAYABUSA components (filmed by Dr. O. Iiyama at GOS3, using a high-sensitive zoom video camera NC-R550a offered by GOTO Inc.)

Figure 7. HAYABUSA fireball recorded by an optical tracking camera of GOS2 at a)13:51:57, b)13:52:11, c)13:52:13, d)13:52:20, e)13:52:23, and f)13:52:27 UTC.

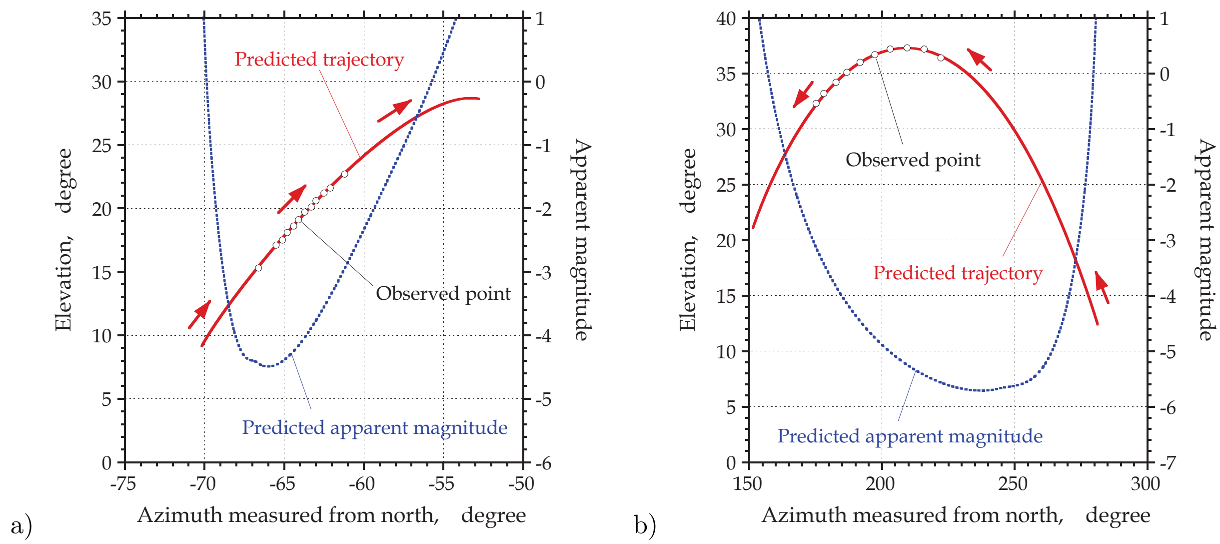


Figure 8. Comparison between measured and predicted azimuthal and elevational angles of HAYABUSA SRC at a) GOS1 and b) GOS2.

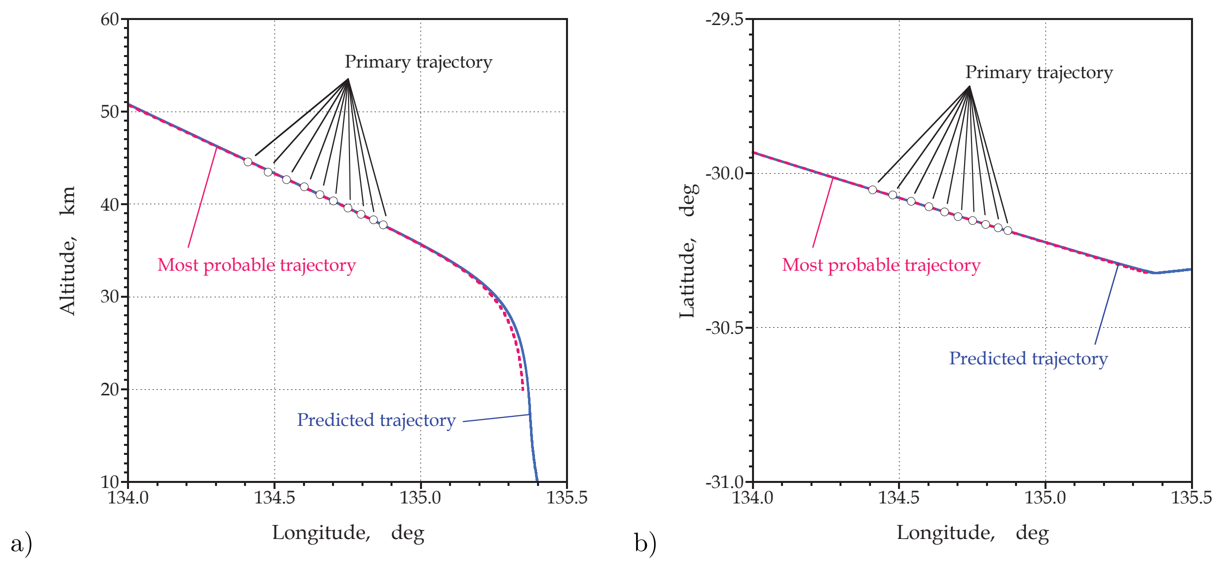


Figure 9. Comparison between measured and predicted SRC trajectory; a) altitude vs. longitude and b) latitude vs. longitude.

the SRC touchdown point with an accuracy of a few hundred meters, and the helicopter discovered the SRC instrument module soon after the touchdown.

In addition to great success in the optical trajectory determination described above, most of the scientific measurements were successfully conducted as well. To sum up, the ground observation team has achieved

1. the SRC trajectory data by the optical tracking system
2. long-exposure photographs by the all-sky camera, the fish-eye camera
3. photographs by the telephotographic camera
4. videos by the high-sensitive high-power zoom color video camera, the hi-vision color video cameras, the high-sensitive monochrome video camera, and the video camera attached with a bandpass filter for atomic oxygen lines

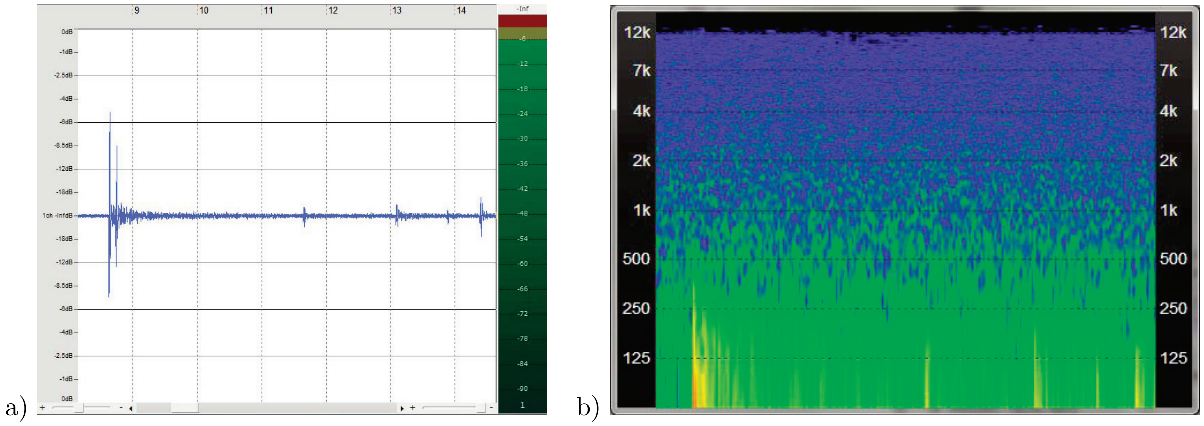


Figure 10. Shock wave arrival detected at GOS2; a) acoustic pressure and b) spectrograph.

Figure 11. A long-exposure wide-angle photograph of HAYABUSA fireball taken at GOS2 (photographed by Dr. Y. Ishihara).

5. low-resolution spectra by the video and the still cameras equipped with a transmissive grating
6. infrasound data at GOS2, GOS2A and GOS2B
7. seismic wave data at 6 sites
8. particle motion data by a triaxial seismograph
9. audible sound data (shock wave)

Unfortunately, the high-resolution spectroscopy attempted at the GOS1 failed since the radiation from the mother ship following the SRC was so intense that the tracking camera in the automatic follow-up system was saturated and could not distinguish the SRC from the mother ship. Detailed results of each measurement will be presented in the future by the corresponding authors, so that only an outline is given below.

The seismic wave and the infrasound was successfully recorded at the GOS2, the GOS2A, and the GOS2B. At the GOS2, arrival of the shock wave was recorded at 13:56:08 UTC in the audible sound data, as shown in Fig. 10. At a rough estimate, this shock wave was generated by the HAYABUSA fireball approximately at an altitude of 40 km, where the SRC is separated from the GOS2 at a 68-km distance. In addition to the acoustic measurements, optical measurements were conducted at the GOS2 as well. Figure 11 is a long-exposure wide-angle photograph taken by Dr. Y. Ishihara. A series of long-exposure photographs taken by Asst. Prof. M. Yamamoto have revealed that persistent trains were produced by the HAYABUSA fireball, as

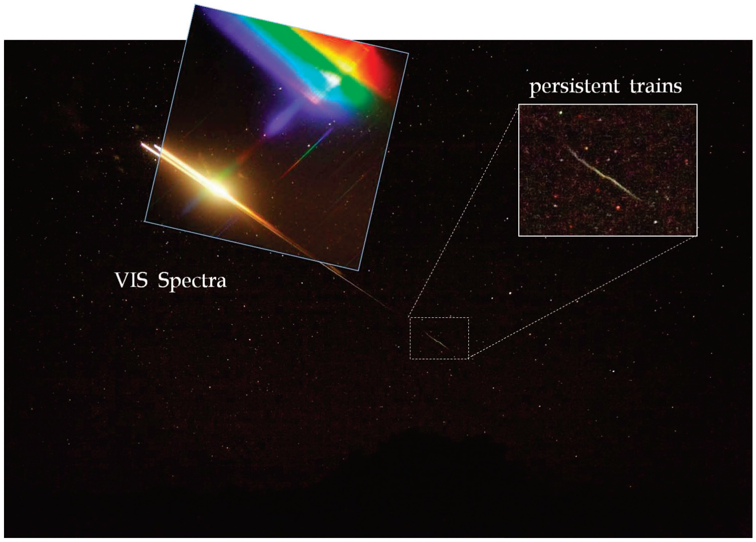


Figure 12. persistent trains produced by HAYABUSA fireball (photographed by Asst. Prof. M. Yamamoto at GOS2).

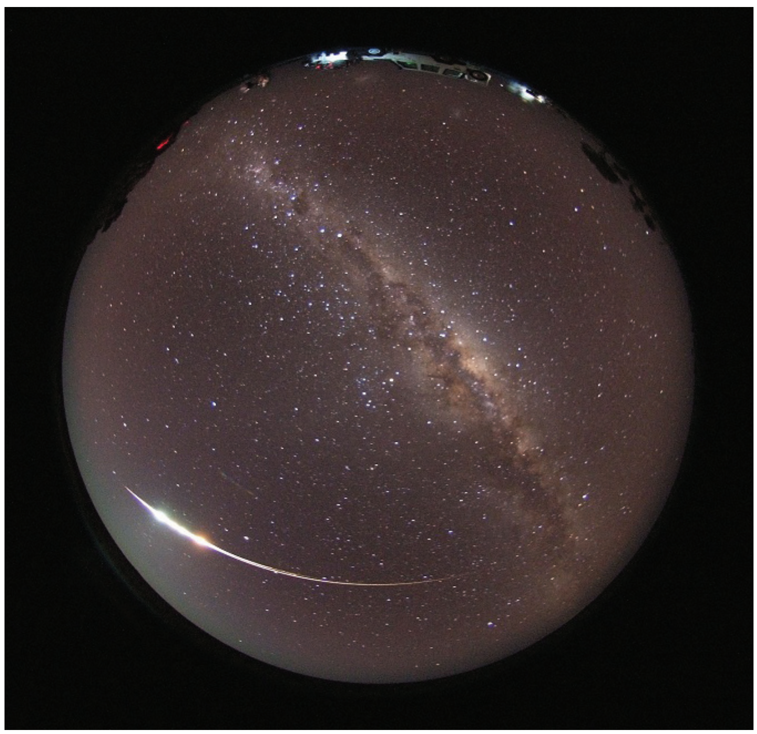


Figure 13. An all-sky photo taken at GOS3 (recorded by Dr. O. Iiyama).

shown in Fig. 12. According to the recorded data, its duration was at the order of 10 seconds. Spectroscopic measurements were also conducted in the visible wavelength range, the results of which are schematically inserted into the long-exposure photograph as seen in Fig. 12.

At the GOS3 and the GOS4, a lot of videos, photographs, and spectra of the TPS radiation as well as the gas radiation were obtained. As an example, an all-sky photograph taken by Dr. O. Iiyama at the GOS3 is presented in Fig. 13. By courtesy of Goto Kogaku Kenkyusho Inc., the SRC fireball followed by HAYABUSA components in flight were filmed using a high-sensitive zoom video camera, NC-R550a (see the snapshot given in Fig. 6). A series of spectra obtained at the GOS4 are schematically shown in Fig. 14. Unfortunately, at the time of writing this article, quantitative analyses of the spactra have not yet been

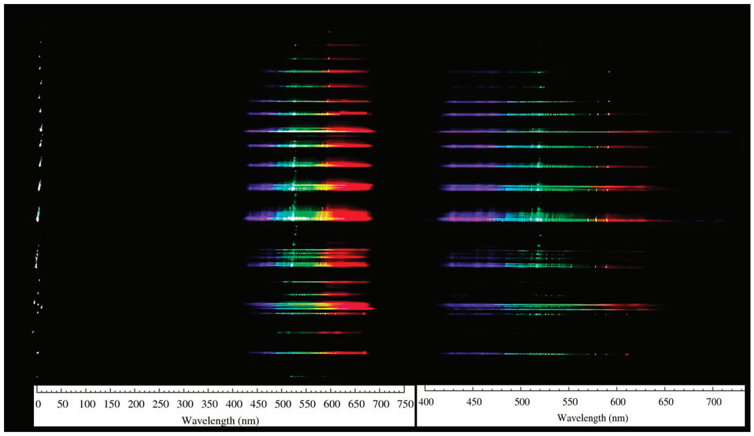


Figure 14. Spectra of HAYABUSA and SRC observed at GOS4 (recorded by Dr. Y. Kakinami at GOS4 and processed by Asst. Prof. S. Abe).

completed to make detailed discussions on the flight environments of the SRC and behaviors of the TPS, which will be presented elsewhere in the future. As a quick report, it has been found that emission from the shock layer is at the same order of the blackbody radiation from the TPS surface. Such a trend is different from the case of the STARDUST reentry, where the TPS radiation dominated in comparison to the gas radiation from the shock layer.[8] This is possibly because the HAYABUSA SRC is only a half of the STARDUST capsule in diameter, which reduced the contribution of the blackbody radiation by one fourth.

VI. Conclusion

In order to recover the HAYABUSA sample return capsule and to conduct optical measurements, the Japan Aerospace Exploration Agency organized a ground observation team consisting of 15 members, and successfully conducted optical tracking of the sample return capsule, spectroscopy of the fireball as well as the fireball trail, and measurement of infrasounds, shock waves, and audible sounds generated by the fireball. The reentry trajectory of the capsule determined by optical tracking was seen to show excellent agreement with the prediction based on the reentry conditions determined by the Δ Differential Oneway Range. Arrival of the shock wave generated by the fireball was detected. A series of long-exposure photographs have revealed that persistent trains were produced by the HAYABUSA fireball. A lot of low-resolution spectra were obtained, and expected to contribute to analyses of the flight environments and the behavior of the thermal protection system in the future.

References

[1]Working Group of Asteroid Sample Return Mission, "Program of Exploring an Asteroid (MUSES-C), The Proposal," Institute of Space and Astronautical Science, Kanagawa, Japan, March 1995.

[2]Fujita, K., Sato, S., Abe, T., and Ebinuma, Y., "Experimental Investigation of Air Radiation from Behind a Strong Shock Wave," *Journal of Thermophysics and Heat Transfer,* Vol.16, No.1, pp.77-82, 2002.

[3]Suzuki, T., Fujita, K., and Sakai, T., "Experimental Study of Graphite Ablation in Nitrogen Flow, Part II: Further Numerical Analysis," *Journal of Thermophysics and Heat Transfer,* Vol.24, No.3, pp.589-597, 2010.

[4]"Stardust Hypervelocity Entry Observing Campaign Support," NASA Engineering and Safety Center Report, RP-06-80, August 31, 2006.

[5]Fujiwara, Y., Ueda, M., Shiba, Y., Okamoto, S., Fujita, K., Kuninaka, H., and Kawaguchi, J., "Optical Trajectory Determination of Hayabusa Sample Return Capsule Using Ground-based Video Observation Systems," An International Conference on Minor Bodies in the Solar System (Meteoroids2010), Beaver Run Resort, Breckenridge, Colorado USA, May 2010.

[6]Shoemaker, M., van der Ha, J.C., and Fujita, K., "Trajectory Reconstruction of Hayabusa's Atmospheric Reentry," IAC Paper 10.C1.6.1, 61st International Astronautical Congress, Prague, Czech Republic, October 2010.

[7]Yamamoto, M., Abe, S., Ishihara, Y., Hiramatsu, Y., and Fujita, K., "Observation Plan of HAYABUSA SRC Reentry: for the Third Opportunity of Man-Made Fireball from Interplanetary Orbit," An International Conference on Minor Bodies in the Solar System (Meteoroids2010), Beaver Run Resort, Breckenridge, Colorado USA, May 2010.

[8]Trumble, K., Cozmuta, I., Sepka, S., Jenniskens, P., and Winter, M., "Postflight Aerothermal Analysis of the Stardust Sample Return Capsule," *Journal of Spacecraft and Rockets,* Vol.47, No.5, pp.765-774, 2010. 2010