HIGH SPEED FLIGHT DEMONSTRATION PROJECT

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Abstract

The High-Speed Flight Demonstration (HSFD) project is the latest in a series of flight experiments in a research program into reusable space transportation systems being conducted by Japan Aerospace Exploration Agency (JAXA). The project consists of two phases which use sub-scale demonstrators based on the HOPE-X (H-II Orbiting Plane, Experimental) winged re-entry vehicle configuration. Phase I uses a vehicle that operates from a conventional runway to verify an approach and landing system for the final part of the return phase of a winged reentry vehicle, while Phase II was a drop test from a stratospheric balloon to clarify the transonic aerodynamic characteristics of the HOPE-X configuration and to obtain data to validate wind tunnel tests and computational fluid dynamics (CFD) predictions. The Phase I and Phase II vehicles are built from a common set of core components to reduce costs.

The Phase I flight experiment was conducted at Christmas Island in the Republic of Kiribati from October to December 2002. During three flights, the approach and landing system was evaluated during steep gliding, a characteristic of the terminal phase of winged reentry vehicle flight, and autonomous flight technologies essential for future space transportation systems were demonstrated and validated.

The first Phase II flight was conducted at the Esrange test site in Sweden in July 2003 in collaboration with Centre National d'Etudes Spatiales of France (CNES), which developed and operated the balloon system. Although the experiment had to be discontinued after an anomaly of the recovery system resulted in damage to the vehicle, flight test data were obtained at Mach 0.8, and fully autonomous flight control technologies for the transonic speed region were demonstrated.

The data obtained from the HSFD project are expected to provide essential information for development of future reusable space transportation systems.

1 Introduction

The National Aerospace Laboratory of Japan (NAL) and the National Space Development Agency of Japan (NASDA) [1] have been conducting joint research and development on reusable space transportation systems. A series of flight experiment programs: the Orbital Re-entry Experiment (OREX) [1], the Hypersonic Flight Experiment (HYFLEX) [2], and the Automatic Landing Flight Experiment (ALFLEX) [3], has been completed to support this research, and a further flight experiment, the High Speed Flight Demonstration (HSFD), has recently been conducted.

The HSFD project consists of two phases: Phase I to verify an approach and landing system for the return flight of a winged re-entry vehicle that lands on a conventional runway [4], and Phase II to clarify the transonic aerodynamic characteristics of a winged re-entry vehicle [5]. The Phase I flight experiment was completed in November 2002, and the first flight of Phase II was performed in July 2003 in collaboration with Centre National d'Etudes Spatiales of France (CNES).

This paper overviews the HSFD project and summarizes the results of the flight experiments.

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[1] NAL and NASDA were merged to form Japan Aerospace Exploration Agency-JAXA on October 1st, 2003

2 Phase I

2.1 Outline

The Phase I experiment objective is to verify an approach and landing system for the final part of the return phase of a winged reentry vehicle that lands horizontally. The HSFD Phase I vehicle is a sub-scale demonstrator based on the HOPE-X (H-II Orbiting Plane, Experimental) configuration powered by a jet engine.

Shown in Fig. 1 is the HSFD Phase I flight experiment mission profile. Following engine start, the vehicle takes off from a runway upon receiving a command from a ground station. After receiving this command, the vehicle operates completely autonomously, being controlled by its on-board Flight Control Computer (FCC), until the end of the landing roll. The mission profile is preprogrammed as a reference trajectory or a series of waypoints in FCC. The ground station monitors the vehicle's status via telemetry, and in case of emergency can transmit "return to base" or flight termination emergency commands.

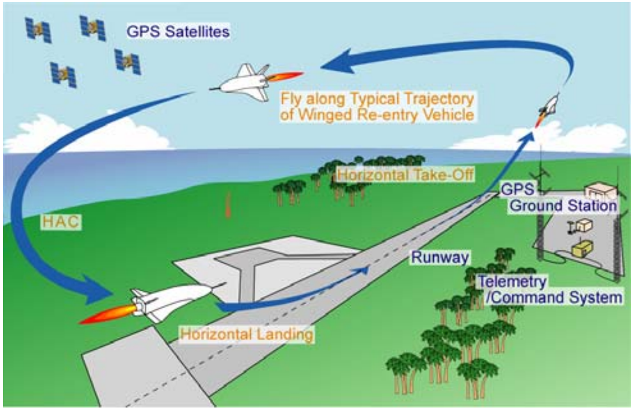


Fig. 1. Phase I Mission Profile

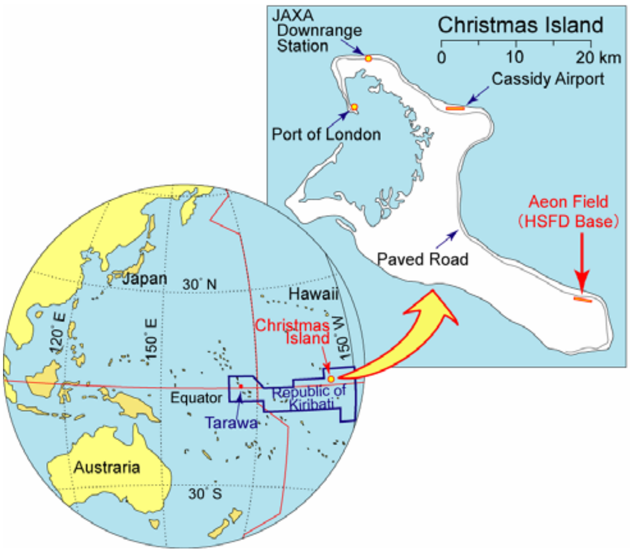


Fig. 2. Christmas Island

After reaching cruising altitude, the vehicle tracks a steep glide path simulating a typical airfield and runway approach path of a winged reentry vehicle, and the functions of the approach and landing system are evaluated on the steep glide path. The vehicle then returns and lands on the runway horizontally.

The Phase I experiment was conducted at Christmas Island's Aeon airfield in the Republic of Kiribati, located on the equator in the Pacific Ocean as shown in Fig. 2. The airfield has a 1,800m-long runway of 30m width.

Figure 3 shows a schematic diagram of the HSFD Phase I experiment system. Readily available off-the-shelf components are used throughout except for the Integrated Inertial Measurement Unit (IIMU), which is a CDGPS (Differential GPS using GPS carrier phase to enhance accuracy) / INS (Inertial Navigation System) hybrid navigation unit developed by NAL specifically to meet the required navigation performance of the Phase I experiment. The flight control system is designed to allow operation in up to 90% of the probable wind conditions at the airfield. Since it is experimental, the vehicle has no redundancy; all onboard systems are simplex except for an emergency flight termination system which will prevent the vehicle from damaging ground facilities and personnel.

A three-view diagram of the Phase I vehicle is shown in Fig. 4 and its main characteristics are given in Table 1. The vehicle's configuration is based on a 25% scaled HOPE-X, with the wing area increased over the baseline configuration to allow reduced take-off and landing speeds and relaxation of the landing gear design requirements. Besides elevons and rudders, the vehicle has speed brake surfaces on the aft fuselage for speed control while simulating steep approach flight. The landing gears are retractable. The vehicle incorporates a small jet engine for propulsion, with a ventral intake under the forward fuselage.

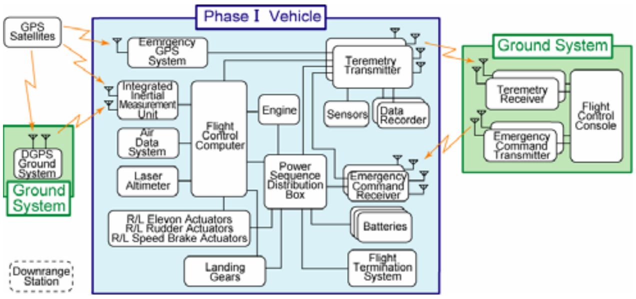


Fig. 3. Phase I Flight Experiment System

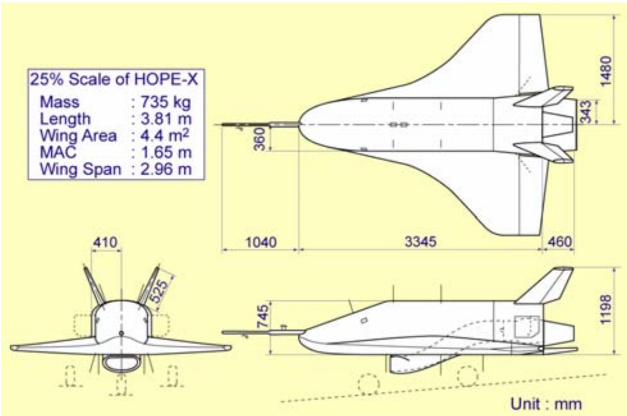


Fig. 4. Three View Diagram of Phase I Vehicle

Table 1. Phase I Vehicle's Major Characteristics

Design maximum take-off mass	735 kg
Design empty mass	631 kg
Maximum landing velocity	71 m/s
Maximum dynamic pressure	15.7 kPa
Maximum aerodynamic load	+2.5 to –1.0 G
Propulsion system	
engine type	TCMTE 382-10
maximum static thrust (nominal)	4410 N
maximum fuel	104 kg

2.2 Results of Flight Experiment

A total of three flights were performed in October and November 2002. Table 2 shows the overview of the flights.

The first flight, conducted on October 18th, 2002, was to verify the vehicle's basic autonomous flight performance and the functions of the on-board equipment. The flight pattern is shown in Fig. 5(a).

On the second flight, the flight envelope was expanded as shown in Fig. 5(b). After the take-off, the vehicle climbed to an altitude of 2,500m and then simulated a steep spiral approach trajectory around a Heading Alignment Cylinder (HAC). The flight path angle of the steep glide slope was –13 degrees, half as steep as the projected HOPE-X glide path, and a maximum speed of 95m/s EAS (Equivalent Air Speed) was achieved. Afterwards, the vehicle made a pass over the runway, then flew the same trajectory as the first flight and finally landed successfully.

The main objective of Phase I, verification of the approach and landing system on a typical re-entry vehicle airfield and runway approach trajectory, was achieved on the third flight. The flight envelope was expanded to an altitude of 5,000m and a speed of 136m/s EAS (Fig. 5(c)). After reaching 5,000m altitude, the vehicle glided along an extremely steep spiral approach trajectory around the HAC with a flight path angle of –25 degrees, and the steep glide slope tracking performance was evaluated.

Figure 6 shows photographs of the flights.

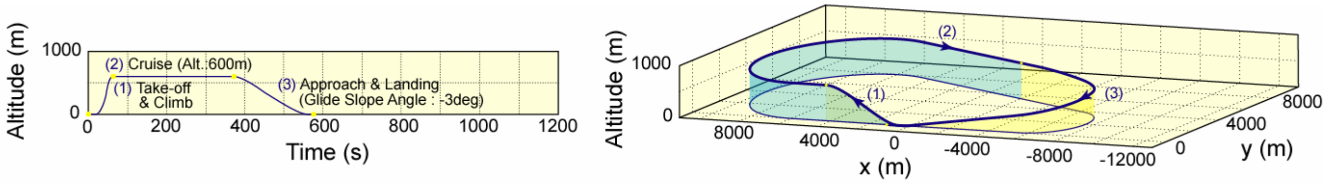
Table 3 shows the design requirements of the navigation, guidance and control system and the results of each flight corresponding to each requirement. All the requirements were satisfied for all flights. Figure 7 shows the time histories of the responses to altitude and EAS commands during steep glide slope tracking on the third flight. The vehicle closely followed the commands. The take-off and touch down performance for the three flights is shown in Fig. 8 together with the results of 1,000 Monte-Carlo pre-flight simulations. The vehicle's flight conditions coincide with the simulation results.

JAXA's Christmas Island downrange tracking station (XDRS), used for monitoring the H-IIA rocket, could potentially be used for monitoring the approach and landing phase of a reentry vehicle that lands on Christmas Island, eliminating the need for a dedicated telemetry receiver. To investigate this possibility, the telemetry signal levels at the receiver input of XDRS during the entire flight were obtained on the third flight. It was found that the received telemetry signal levels were high enough to receive data from an off-the-shelf telemetry transmitter even at altitudes as low as 100m.

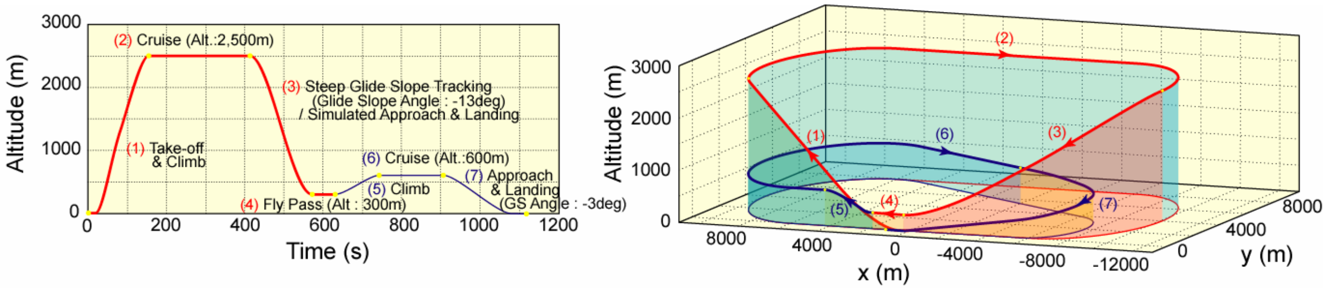
All of three flights were conducted as planned and the Phase I flight experiment was completed successfully.

Table 2. Overview of Phase I Flight Experiments

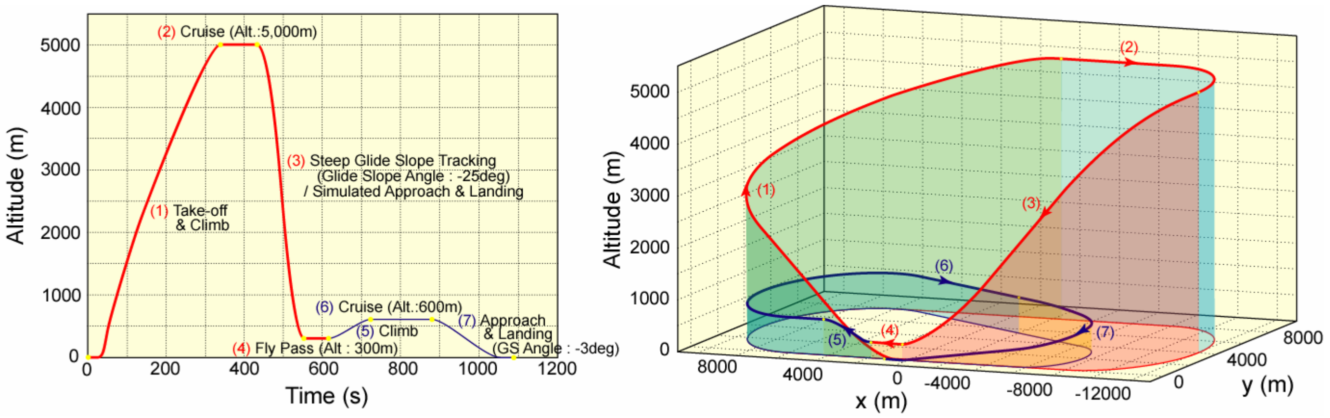
	Start Time (Local)	Evaluation Items	Max. Altitude	Max. Velocity	Glide Slope Angle	Total Flight Time (Start ~ Stop)
#1	Oct. 18, 2002 5:50 AM	Verification of Autonomous Flight Function Verification of Onboard Equipment	603 m	93 m/s (M 0.27)	—	9' 35"
#2	Nov. 5, 2002 5:22 AM	Steep Glide Path Tracking	2,503 m	95 m/s (M 0.29)	-13°	18' 36"
#3	Nov. 16, 2002 5:40 AM	Steep Glide Path Tracking Telemetry Link Check with XDRS	5,005 m	136 m/s (M 0.46)	-25°	18' 08"



(a) First Flight



(b) Second Flight



(c) Third Flight

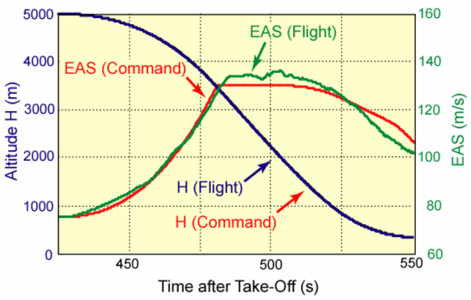
Fig. 5. Flight Profiles

(a) Final Approach (b) Ground Roll (c) Post Flight Check

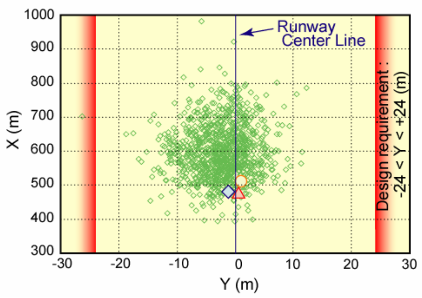
Fig. 6. Photos of Flight Experiments

Table 3. Design Requirements and Flight Results of Navigation, Guidance and Control System

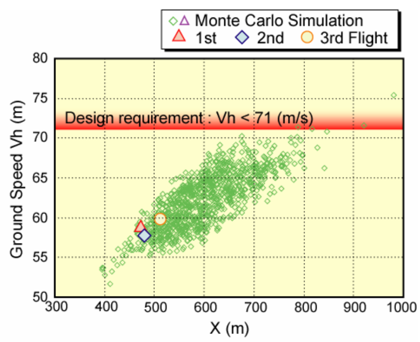
Flight Phase		Item		Requirement	Flight Result Flight #1	Flight #2	Flight #3
Take Off							
	Ground Run	Lateral Position		Runway Center Line ±24m	-0.9	-1.2	1.4
	Airborne	Velocity (GS)		less than 71 m/s	58.8	61.0	61.2
		Attitude	Pitch	less than 24 deg	15.5	15.4	15.5
			Roll	within ±10 deg	1.5	1.0	1.8
Steep Glide Slope		Velocity (EAS)		Command ±10 m/s	-	13.2	6.3
		Position	Altitude	Command ±15 m	-	-3.4	-10.2
			Horizontal	Nominal Trajectory ±50 m	-	11.3	18.2
Landing							
	Approach	Velocity (EAS)		Command ±10 m/s	3.2	-3.3	-2.8
		Position	Altitude	Command ± 4 m (Final Flare Initiation)	-0.6	-0.8	-0.6
				Command ±15 m (Others)	2.2	-1.8	-2.6
			Horizontal	Nominal Trajectory ±14 m (Final Flare Initiation)	-3.3	-0.6	0.3
				Nominal Trajectory ±50 m (Others)	12.7	7.5	10.7
	Touch Down	Lateral Position		Runway Center Line ±14 m	-4.7	-1.8	-0.7
		Velocity (GS)	Horizontal	less than 71 m/s	62.5	58.9	61.8
			Sink Rate	less than 3.0 m/s	1.8	1.4	1.4
		Attitude	Pitch	less than 17.4 deg	15.8	14.5	15.1
			Roll	within ±10 deg	0.8	0.7	0.3
			Yaw	within ± 6 deg	0.2	1.1	0.0
	Ground Roll	Lateral Position		Runway Center Line ±24 m	-4.7	-2.1	1.1
	Stop	Longitudinal Position		less than 1800 m from Runway Threshold	1224.7	1132.6	1260.3
Other Phases		Velocity (EAS)		Command ±10 m/s	-	7.9	-4.7
		Position	Altitude	Nominal Trajectory ±500 m	-	-2.4	-3.0
			Horizontal	Nominal Trajectory ±360 m	-	-13.6	11.4
Operational Limitation		Max. Velocity (EAS)		less than 160 m/s	92.5	94.9	136.3
		Load Factor		within -1 ~ +2.5	0.5 ~ 1.1	0.7 ~ 1.3	0.7 ~ 1.3



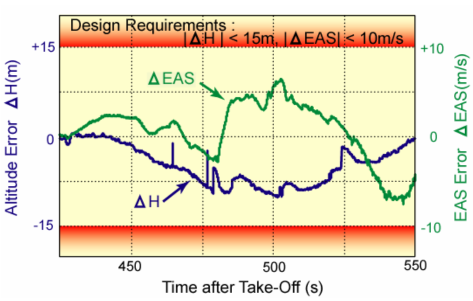
(a) Response to Command



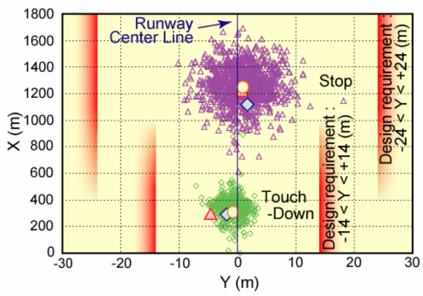
(a) Airborne Position



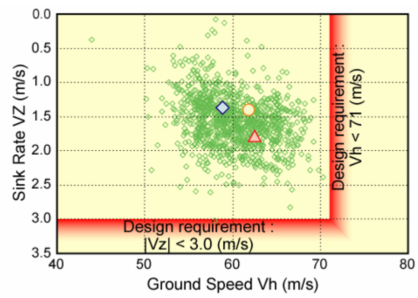
(b) Airborne Position-Velocity



(b) Tracking Error



(c) Touch-Down/Stop Position



(d) Touch-Down Velocity

Fig. 7. Altitude/EAS Response during Path Tracking

Fig. 8. Take-off & Touch Down Performance

3 Phase II

3.1 Outline

Figure 9 shows the mission profile of the HSFD Phase II. This is a drop test of an unpowered, fully autonomous vehicle. The vehicle is lifted by stratospheric balloon to an altitude of 20 to 30km, is released into free fall and accelerates to transonic speed. When the vehicle reaches a preprogrammed target Mach number (M0.8, 1.05, or 1.2), a constant Mach number flight phase is initiated during which the vehicle maintains the target Mach number with a specified tolerance of ±M0.03 while its angle of attack (AOA) is reduced quasi-statically. If the rate of change of AOA is kept small, the vehicle will maintain a trimmed flight condition while changing attitude, and trimmed flight characteristics over a wide AOA range can thus be obtained. The pressure distributions on the vehicle's surface and the hinge moments of aerodynamic control surfaces such as elevons and rudders are also measured. After the constant Mach phase, the vehicle decelerates under the maximum load factor condition.

In consideration of the variability of the point of release from the balloon, multiple landing sites are prepared in the recovery area (see Fig. 10). After decelerating, the vehicle selects a landing site within its range capability and flies towards it. When the vehicle reaches an altitude of 1,300m over the landing site, the recovery system is activated and the vehicle is recovered using parachutes and air bags.

The experiment was in collaboration with CNES, which was responsible for development of the balloon system, the launch operation and the recovery of the vehicle after touch down. It was conducted at the Esrange flight test site near Kiruna, Sweden, shown in Fig. 10, which is operated by the Swedish Space Corporation (SSC). The vehicle's flight is normally conducted within the ZONE B range, but the flight area can be extended to the east of ZONE B by permission of the Esrange safety officer. There are 14 candidate landing sites within ZONE B.

A schematic diagram of the HSFD Phase II experiment system is shown in Fig. 11. In order to reduce costs, components have maximum commonality with the Phase I vehicle; in particular the navigation system, flight control computer, control surface actuation system, telemetry/command system are common with the Phase I vehicle.

Figure 12 shows a three-view diagram of the experimental vehicle, a 25% scaled HOPE-X. Since the Phase II mission objective is to obtain reference data on transonic HOPE-X aerodynamic characteristics, the vehicle's shape is made as similar as possible to that of HOPE-X; only the nose boom for the air data system is peculiar to the experimental vehicle. Elevons and rudders are used as control surfaces. The vehicle's major characteristics are listed in Table 4.

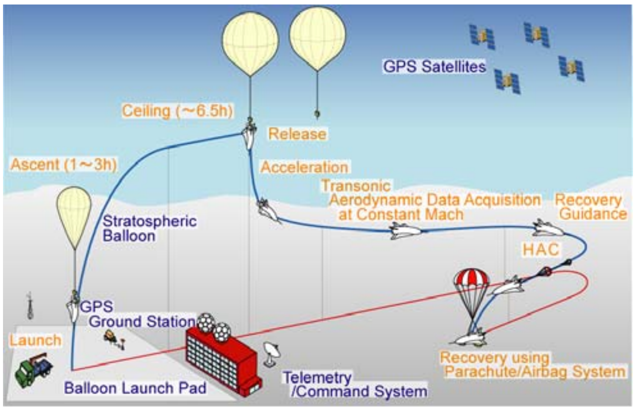


Fig. 9. Phase II Mission Profile

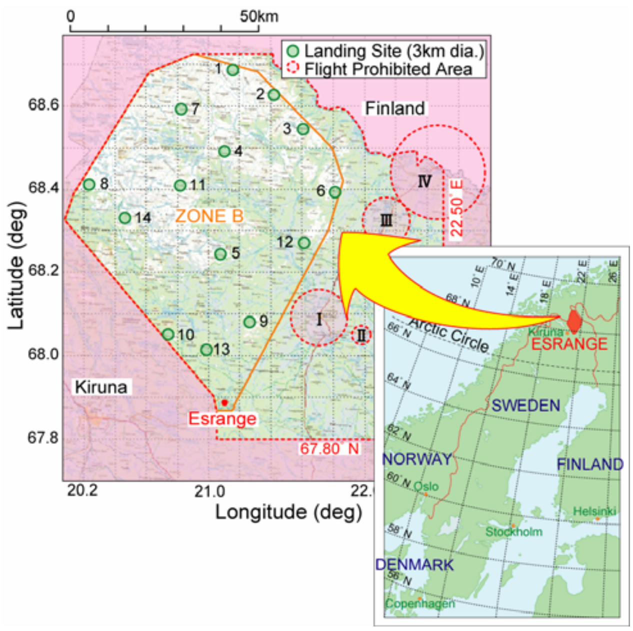


Fig. 10. Esrange Flight Test Site

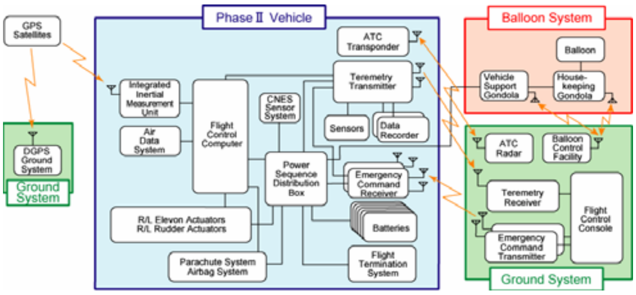


Fig. 11. Phase II Flight Experiment System

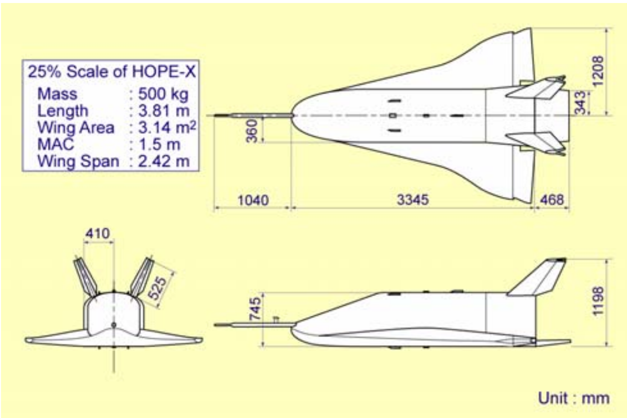


Fig. 12. Three View Diagram of Phase II Vehicle

Table 4. Phase II Vehicle's Major Characteristics

Design mass	500 kg
Maximum dynamic pressure	15.7 kPa
Maximum aerodynamic load	+3.5 –1.0 G
Maximum descent rate before landing	6.2 m/s
Maximum impact acceleration at landing	8 G

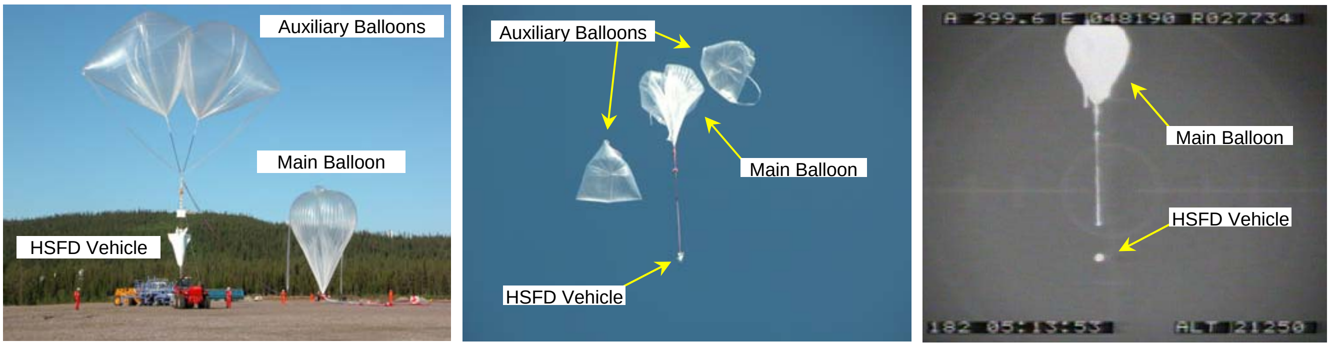
3.2 Results of Flight Experiment

The first Phase II flight was performed on July 1st, 2003. The target Mach number was 0.8. Figures 13(a) and (b) are photographs of the vehicle during the launch operation. For the crucial initial vertical ascent phase, the main balloon is assisted by auxiliary balloons which are later jettisoned to allow the main balloon to climb to the proper altitude. The experiment vehicle was launched under the balloon at 06:03 local time, and was released from the balloon around the target altitude of 21km at 07:14. Figure 13 (c) shows the vehicle just after release from the balloon.

The vehicle's flight, which consists of 6 phases, went almost as planned. The time sequence of the flight is shown in Table 5, and Figs. 14 and 15 show the time histories and the trajectory of the vehicle. Twenty-nine seconds after release, the vehicle reached the target Mach number 0.8 and constant Mach number data acquisition was initiated. After data acquisition, the vehicle decelerated to M0.75 and the return phase was started. During this phase, the vehicle selected #5 landing site shown in Fig. 10, and was guided to the selected site by the FCC by flying along the surface of the HAC. When the vehicle reached the recovery site, recovery system activation commands were transmitted from the FCC, but the recovery system did not work as expected and the vehicle was damaged on touchdown. As a result, the flight experiment campaign was interrupted.

Figure 16 shows the guidance and control system design requirements and Figs. 17 to 19 show the corresponding flight results. All the requirements were satisfied and the function of the fully autonomous flight control system was verified.

The vehicle's longitudinal aerodynamic characteristics were estimated from the data obtained during the constant Mach phase. The results are shown in Fig. 20 together with the results of wind tunnel predictions. The uncertainties of the wind tunnel predictions are also plotted. All estimates derived from the flight test data are within the wind tunnel uncertainties, but there is a bias between the predicted and estimated pitching moment characteristics. This indicates that the wind-tunnel database for pitching moment coefficient may have error due to, for example, the sting effect. Figure 21 shows the elevator angle during the constant Mach phase together with the trimmed elevator angle predicted using the wind tunnel data. It can be seen that the difference between the predicted and estimated pitching moment coefficients corresponds to an elevator angle of about 1 degree. These results will contribute to improving the accuracy of wind tunnel testing.



(a)Pre-Launch Check (b) Launch (c) Release

Fig. 13. Photos of Flight #1

Table 5. Flight #1 Time Sequence

Event	Time after Release (s)
Release (Altitude 21.3km)	0
Constant Mach Phase Start (M0.8)	29
Deceleration Phase Start	75
Return Phase Start	82
HAC Capture	127
Final Approach	148
Recovery Phase Start	256
Touch Down	318

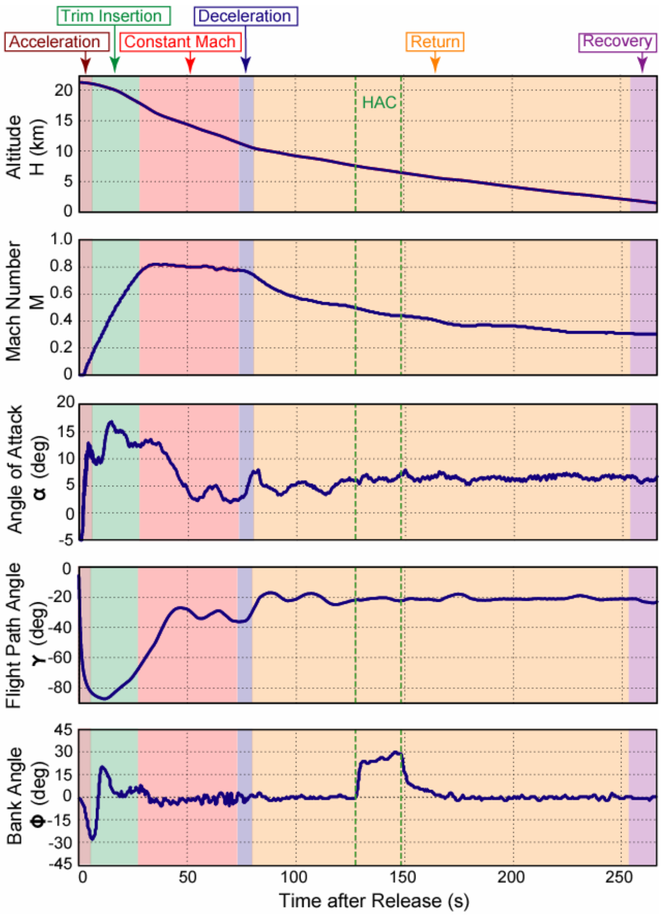
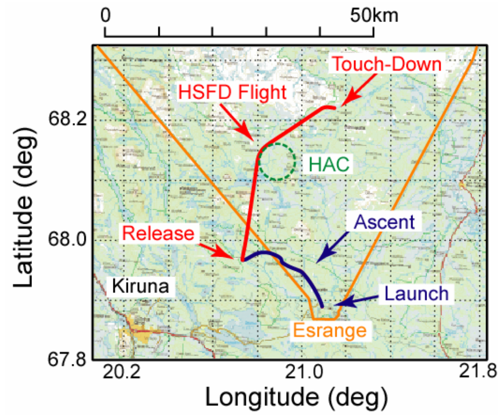
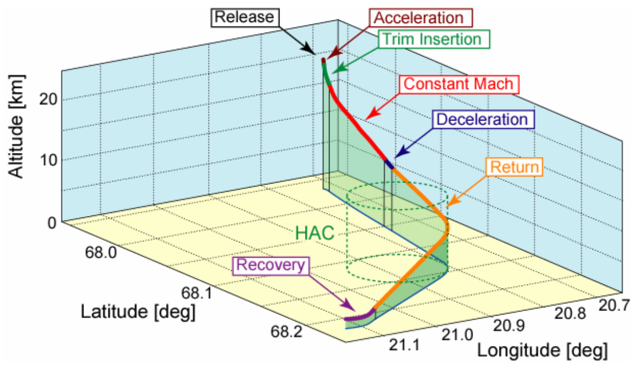


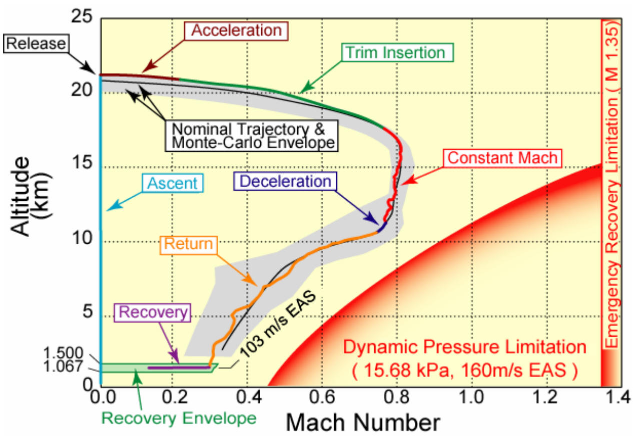
Fig. 14. Time Histories of Flight #1



(a) Launch to Touch Down (2D)



(a) Release to Touch Down (3D)



(c) Altitude vs Mach

Fig. 15. Trajectory of Flight #1

Constant Mach Phase	Mach Number	: 1.2, 1.05, or 0.8 ±0.03
	Duration	: more than10 s
	AoA Sweep Range	: wider than 10 deg ~ 2.5 deg
	AoA Sweep Rate	: -2 deg/s ~ +2 deg/s
	Altitude	: higher than 11 km
Recovery Interface	Position	: within Recovery Cone
	Equivalent Air Speed	: less than 103 m/s
Through the Flight	Dynamic Pressure	: less than 15.68 kPa (160 m/s EAS)
	Normal Load Factor	: -1.0 G ~ +3.5 G
	Prohibited Area	: no entry

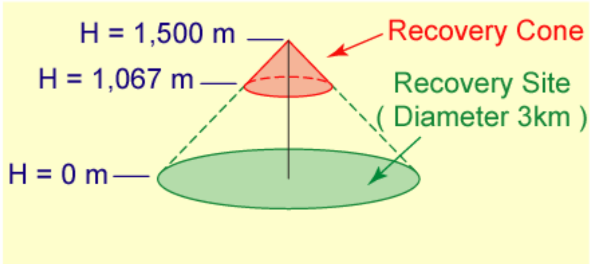


Fig. 16. Design Requirements for Navigation, Guidance and Control System

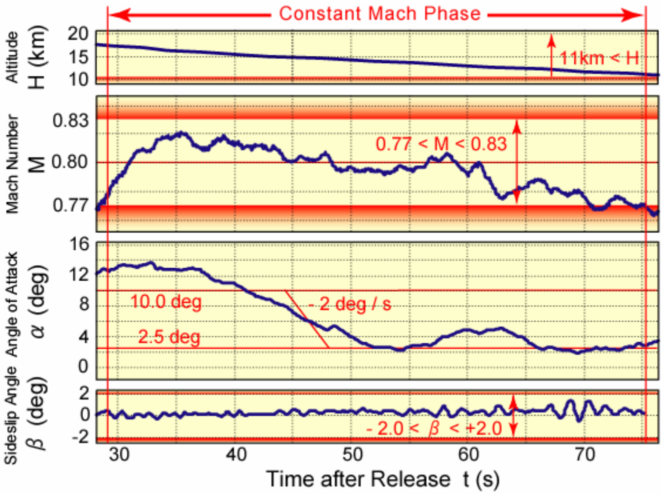


Fig. 17. Constant Mach Phase of Flight #1

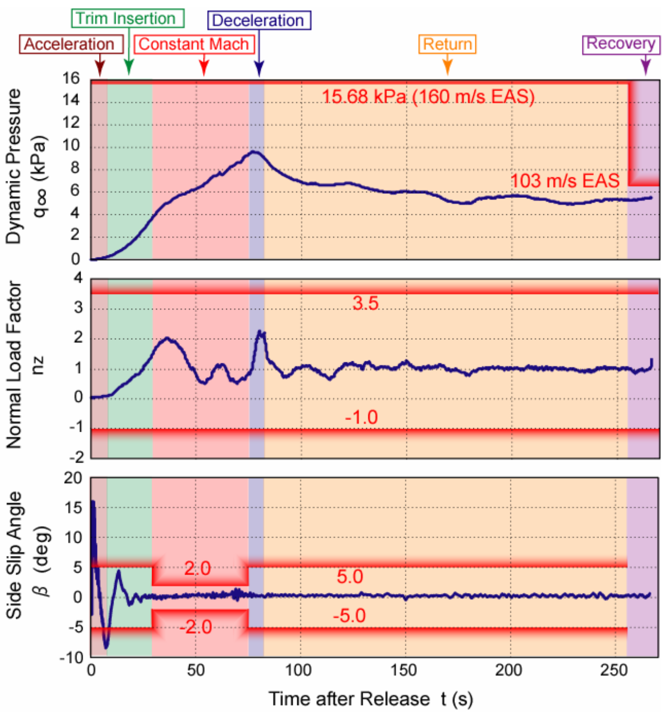


Fig. 18. Time Histories of Flight #1

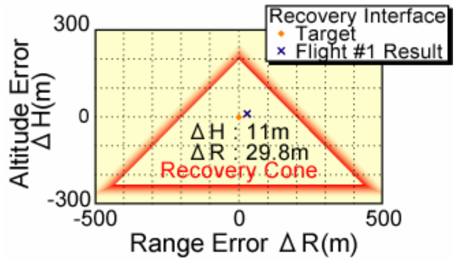


Fig. 19. Recovery Interface Point of Flight #1

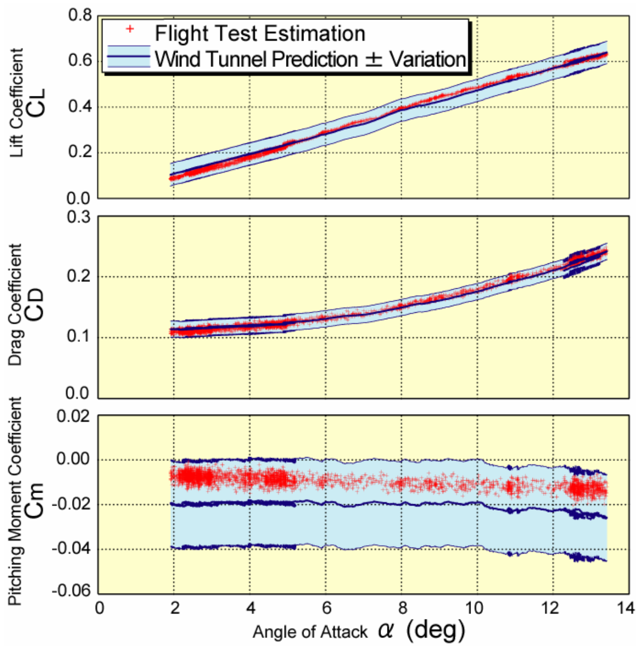


Fig. 20. Estimated Aerodynamic Characteristics

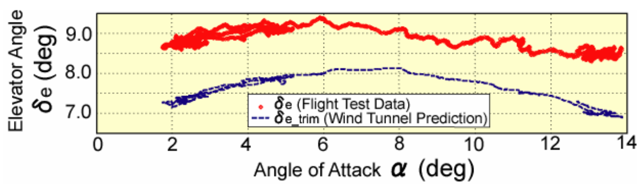


Fig. 21. Elevator Angle of Flight #1

4 Conclusion

The data obtained from the HSFD project will provide essential information for the development of future reusable space transportation systems.

Phase I

The Phase I flight experiment was successfully completed realizing the anticipated results as follows:

- Establishing fully-autonomous flight control design technology, including take-off, tracking an extremely steep flight path, and landing;
- Proving the flight capability of a newly-developed CDGPS / INS hybrid navigation system, which requires only a mobile ground station as ground support infrastructure;
- Proving the capability of the Christmas Downrange Station for the H-IIA rocket to track a reentry vehicle to low altitudes of about 100m.

Phase II

Although the Phase II flight experiment was suspended due to a recovery system anomaly, various data were obtained on the first flight:

- Transonic aerodynamic characteristics of the HOPE-X configuration were estimated from the flight data, which will be used to reduce uncertainties in wind tunnel test data and CFD calculations, which are greater for the transonic region than for other speed regions;
- Verifying guidance and control system design for the transonic speed region;
- Providing foundations of transonic flight experiment technology using a stratospheric balloon system with respect to future reentry/reusable space transportation system development.

Advances in guidance, control and navigation have increased the potential of using unmanned experimental vehicles for flight testing, and this program has realized the potential ability of automatic flight control. In fact, automatic flight control technology is now allowing the expansion of flight test possibilities in much the same way as it was explored by human test pilots in the past.

Finally, international collaboration between Japan and France in HSFD Phase II was mutually beneficial. The project was based on equal partnership and mutual confidence between NAL, NASDA and CNES, and the extensive technical experience of the parties achieved an effective and efficient flight experiment. This cooperation will be a positive step towards international collaborative activities for reusable space transportation systems.

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