CURRENT STATUS OF JAPANESE AEROSPACE PROGRAMS – FOCUSING ON THE HIGH SPEED FLIGHT DEMONSTRATION

Yoshikazu Miyazawa

The Institute of Space Technology and Aeronautics
Japan Aerospace Exploration Agency, Tokyo, Japan

Abstract: The paper presents an overview of the current status of Japanese aerospace programs, including launch vehicles, satellites, university space programs, and aeronautical research and development. Following the overview, the paper describes the High Speed Flight Demonstration program, a flight experiment program using sub-scale vehicles to investigate the re-entry terminal flight phase of re-usable space vehicles. The program was conducted in two phases: a Phase I experiment at Christmas Island in 2002, and a Phase II experiment at Esrange, Sweden in 2003. Phase II is a joint program between NAL/NASDA and CNES.

Keywords: programs, aerospace engineering, space vehicles, flight control, guidance system, navigation system, tests

ACRONYMS

ADEOS	Advanced Earth Observing Satellite
ADC	Air Data Computer
ADS	Air Data System
AGE	Aerospace Ground Equipment
ALFLEX	Automatic Landing Flight Experiment
ALOS	Advanced Land Observing Satellite
AOA	Angle of Attack
ARLISS	A Rocket Launch for International Student Satellite
ATC	Air Traffic Control
CFD	Computational Fluid Dynamics
CMD	Command
CNES	Centre National d'Études Spatiales of France
DGPS	Differential GPS
DRTS	Data Relay Test Satellite
EAS	Equivalent Air Speed
EMS	Emergency Medical Service
ESA	European Space Agency
ETS	Engineering Test Satellite
FCC	Flight Control Computer
FCP	Flight Control Program
FHI	Fuji Heavy Industries Ltd.
FTS	Flight Termination System
GPS	Global Positioning System
GNC	Guidance, Navigation and Control
HAC	Heading Alignment Cylinder
HOPE-X	H-II Orbiting Plane Experimental
HSFD	High Speed Flight Demonstration
HYFLEX	Hypersonic Flight Experiment
IGS	Information Gathering Satellite
IIMU	Integrated Inertial Measurement Unit
INS	Inertial Navigation System
ISAS	Institute of Space and Astronautical Sciences
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JDA	Japan Self Defense Agency
JFY	Japanese Fiscal Year
JEM	Japanese Experiment Module
KHI	Kawasaki Heavy Industries, Ltd.
MMO	Mercury Magnetospheric Orbiter
MPO	Mercury Planetary Orbiter
MDS	Mission Demonstration Test Satellite
MHI	Mitsubishi Heavy Industries, Ltd.
MTSAT	Multi-functional Transport Satellite
MuPAL	Multi-Purpose Aviation Laboratory
NAL	National Aerospace Laboratory of Japan
NASDA	National Space Development Agency of Japan
OREX	Orbital Re-entry Experiment
PSDB	Power Sequence Distribution Box
REM	Re-entry Module
SELENE	Selenological and Engineering Explorer
SEM	Service Module
SPF	Stratospheric Platform Airship System
SRB	Solid Rocket Booster
SSC	Swedish Space Corporation
SST	Supersonic transport
TLM	Telemetry
UAV	Unmanned (Uninhabited) Aerial Vehicle
UNISEC	University Space Engineering Consortium
USERS	Unmanned Space Experiment Recovery System
VLBI	Very Long Base Interferometry
VTOL	Vertical Take-off and Landing
XDRS	Christmas Downrange Station

1. INTRODUCTION

In October 2003, the three Japanese national aerospace research and development organisations, the National Aerospace Laboratory (NAL), the National Space Development Agency (NASDA) and ISAS (Institute of Space and Astronautical Sciences), merged to form the Japan Aerospace eXploration Agency (JAXA) in order to streamline Japanese aerospace exploration efforts. Just after this organizational change, JAXA faced three consecutive failures in major space programs; the first stage solid rocket booster (SRB) failure of an H-IIA launcher, an electrical power supply failure to the Earth Observation Satellite MIDORI-II, and the Mars observation probe NOZOMI's failure to enter Martian orbit. These projects were of such importance that their failures greatly impacted Japan's space development efforts. One of the most affected areas is the future launcher program. NASDA and NAL had already experienced a freezing of the H-II Orbiting Plane Experimental (HOPE-X) re-usable spaceplane development program following H-II launch failures in 1998 and 1999, and after the H-IIA failure JAXA has again had to suspend future launcher research programs as well as other space programs in the planning stage. The Japanese space community is now in the recovery phase. The first part of this paper overviews recent Japanese aerospace activities.

The latter part of this paper focuses on the HSFD (High Speed Flight Demonstration) program, for which a Phase I flight experiment campaign was completed in 2002, and a Phase II joint program between NAL/NASDA and the French space organization CNES (Centre National d'Études Spatiales) was completed in 2003. These flight experiments not only demonstrated technological readiness for future entry space vehicle development, but also showed the significance and merits of flight experiments using autonomous unmanned scaled model vehicles that are enabled by advances in modern guidance, navigation and control technology. The paper overviews the HSFD program, presenting a synopsis of previously published reports on vehicle systems and flight test results (Yanagihara *et al.*, 2003, Sarae *et al.,* 2003, Nishizawa *et al.,* 2003) and also describing the characteristics of the guidance, navigation and control systems and lessons learned from the flight experiments.

2. RECENT JAPANESE AEROSPACE HIGHLIGHTS

2.1 Space Transportation Systems

Japan currently operates two launch vehicles: the M-V for scientific space exploration payloads and the H-IIA for Earth-observation and other payloads. Japan is also actively researching re-usable transportation systems.

H-IIA

The H-IIA is Japan's primary heavy launch vehicle, and can launch a two ton-class satellite into 36,000km geostationary orbit. The H-IIA is an evolution of the H-II, with numerous changes to the vehicle structure, engines, and boosters to improve reliability and reduce cost.

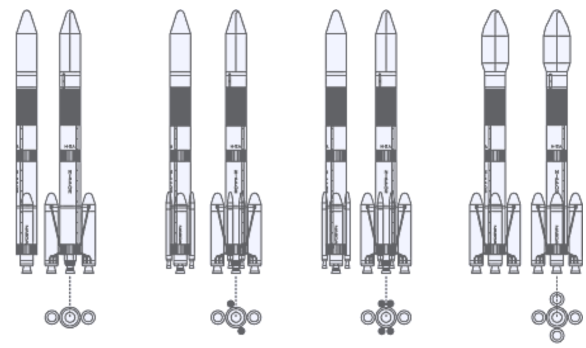
The H-IIA is based on a liquid-fuelled core vehicle approximately 53-meter tall with a diameter of four meters. This is equipped with high-performance engines which use liquid oxygen and liquid hydrogen propellants, and has a total weight of approximately 285 tons when fully loaded with propellants and helium for pressurization. Different configurations shown in Fig. 1 have varying numbers of strap-on solid rocket boosters (SRB) to launch different payload weights. The result is a highly flexible launch vehicle that can launch payloads of various weights into a variety of orbits.

The H-IIA maiden flight, H-IIA F1, on August 26, 2001 verified the vehicle's capability to inject a payload into geostationary transfer orbit with sufficient accuracy. In February 2002 the second H-IIA, which was a more complex configuration with four SRBs attached, was successfully launched. Full-scale mission operations started with the third H-IIA flight, H-IIA F3, which launched the Data Relay Test Satellite (DRTS) and the Unmanned Space Experiment Recovery System (USERS) spacecraft. H-IIA F4 in December 2002 was the first H-IIA polar orbit satellite mission, carrying the approximately 3.7 ton Advanced Earth Observing Satellite-II (ADEOS-II).

After successful launch of Information Gathering satellite #1 (IGS #1) by H-IIA F5 in March 2003, H-IIA F6 launched the information gathering satellite #2 (IGS #2) on November 29, 2003. However, one of the two SRB-As failed to jettison and the vehicle failed to gain sufficient height and speed and was commanded to self-destruct from the ground. The cause of this launch failure is currently under investigation.

M-V

M-V is the fifth generation of the Mu series of rockets for launching scientific spacecraft, which



H-IIA 202 H-IIA 2022 H-IIA 2024 H-IIA 204

Fig. 1 H-IIA versions

have been modified incrementally to respond the growing demands of space science. The M-V is a three-stage solid propellant rocket with a two ton-class payload capability to low Earth orbit. It has a lift-off weight of 130 tons, is 31m in length, and 2.5m in maximum diameter. An optional kick motor stage can be used to insert payloads into high-energy orbits such as for lunar/planetary missions, or highly elliptical Earth orbits.
The first M-V was successfully launched in February 1997 to inject a radio astronomy satellite "HALCA" into its planned orbit. The second M-V launched Japan's first Mars observer "NOZOMI" in July 1998. Although the third M-V launch failed because of a first stage nozzle failure, corrective modifications were made and in May 2003 the asteroid explorer "HAYABUSA" was successfully launched by the fourth M-V. In future, the LUNAR-A lunar penetrator mission, the Japanese fifth X-ray astronomy satellite ASTRO-EII, the ASTRO-F Infrared Imaging Surveyor, and the third solar physics satellite SOLAR-B will be launched by M-V.

Reusable Transportation Systems
Japan has been conducting research into re-usable transportation systems in order to reduce launch costs and eventually make space travel possible for ordinary people. Details of the experiments in this research are described later in this paper.

2.2 Satellite Activities

NASDA/JAXA Practical Satellite Missions
Most Japanese non-scientific satellites have been launched by the former NASDA launchers (H-II and H-IIA). Recent and on-going missions launched by H-IIA are described below.

"Tsubasa" (Mission Demonstration test Satellite 1; MDS-1) was launched into Geostationary Transfer Orbit by H-IIA F2 on February 4, 2002. The objectives of "Tsubasa" are to verify the performance of commercial parts in orbit, to verify component miniaturization technology, and to obtain data on the space environment such as radiation levels. The "Tsubasa" mission ended in September 2003 after twenty months on-orbit, much longer than the scheduled twelve months, having acquired various useful data for the above-mentioned objectives.

"Kodama" (Data Relay Test Satellite; DRTS) was launched on September 10, 2002 by H-IIA F3 and, after several apogee engine firings, was successfully placed in its scheduled geostationary orbit. A data relay satellite relays data between spacecraft in low Earth orbit and ground stations, thereby greatly expanding the area in which real-time communications are possible. In January 2003, "Kodama" completed its initial on-orbit check-out and moved to operation status. "Kodama" is scheduled to relay data to and from the Advanced Land Observing Satellite (ALOS) and the Japanese Experiment Module (JEM) "KIBO" on the International Space Station (ISS), and will be used to broadcast the activities of astronauts.

The Unmanned Space Experiment Recovery System (USERS) was launched by H-IIA F3 as a secondary payload with "Kodama". USERS consists of a re-entry module (REM) that returns to Earth for recovery and a Service Module (SEM) that remains on orbit. The REM was recovered in May 2003 after conducting crystal growth experiments of high-temperature superconductive materials at an altitude of 500km for eight and half months. The SEM remains on orbit to acquire technical data on commercial parts and advanced satellite bus components.

"Midori-II" (Advanced Earth Observing Satellite-II; ADEOS-II) was launched by the H-II F4 in December 2002, in order to elucidate global-scale environmental changes such as abnormal climatic conditions and to monitor the ozone layer. After nine months of observations, however, an anomaly was detected in the satellite power system in October 2003, then all communications with the satellite were lost. Efforts to clarify the cause of the anomaly and to prevent its recurrence in the future satellite programs are on going.

In the near future, MTSAT-1R (Multi-functional Transport Satellite-1R), ALOS (Advanced Land Observing Satellite), ETS-8 (Engineering Test Satellite-8) and SELENE (Selenological and Engineering Explorer) are scheduled to be launched by H-IIA.

ISAS/JAXA Scientific Satellite Missions
Due to historical reasons concerning the development of launch vehicles in Japan, most scientific missions up to now have been launched by Mu-series launch vehicles, and will be for the next several years or more. The most recent and powerful version of the Mu launcher is the M-V.

The first M-V launch put the world's first and scientifically very successful space-based Very Long Base Interferometry (VLBI) mission into orbit in February 1997. The second M-V flight in July 1998 successfully launched the first Japanese Mars orbiter Nozomi ("hope") to study the Martian atmosphere and its interaction with the solar wind. However, due to a technical problem which developed in December 1998, ISAS had to modify the orbital plan en-route to Mars, and then in April 2002 another anomaly occurred that was not recoverable in spite of ISAS' continued efforts. This forced ISAS in December last year to finally abandon the insertion of Nozomi into a circum-Mars orbit. The third M-V flew in February 2000, but the failure of its first stage motor prevented ASTRO-E, the fifth of the Japanese X-ray astronomy observatories that was equipped with highly capable X-ray telescopes, to attain its orbit.

"MUSES-C", the most recent planetary mission, renamed Hayabusa ("falcon") in orbit, was launched by the fourth M-V vehicle on May 9, 2003. The primary goal of this very challenging mission is to develop and demonstrate technologies to obtain and return samples from a small body (1998SF36) in the solar system. If everything goes well from now until the re-entry and recovery on Earth of asteroid samples in 2007 the scientific benefits of the mission, which are considered an additional bonus, are obvious.

Scientific Missions under Development or Budgetary Request

LUNAR-A: A lunar orbiter carries two penetrators to be shot one to three metres into the surface of the moon for seismology studies to learn about the moon's interior structure and for surface temperature measurement. The orbiter collects and relays data from the penetrators to ground stations. Launch is set for the summer–fall time frame of this year.

ASTRO-EII: This is a replacement for the failed ASTRO-E mission, and will carry identical X-ray instruments with the world's highest sensitivity and resolution. The launch of the 1.6 metric ton spacecraft into a 600km circular orbit is slated for January–February of 2005.

ASTRO-F: This infrared astronomy observatory with a cryogenically cooled telescope and focal plane detectors will survey large areas of the sky to study the formation and evolution of galaxies, stars, and planetary systems. The already-delayed launch of this one metric ton spacecraft into a sun-synchronous orbit will take place during Japanese Fiscal Year (JFY) 2005.

SOLAR-B: Based on the very successful 1991–2001 SOLAR-A mission "Yohkoh", this solar observatory will make coordinated measurements of electromagnetic radiation from the optical to X-ray wavelengths in a systematic approach to study the interaction between magnetic fields and high temperature plasma on the surface of the sun. Its launch into a sun-synchronous orbit is scheduled for the summer–fall of 2006.

SELENE: A lunar-orbiting spacecraft with two daughter satellites is to gather relevant scientific data to study the origin and evolution of the moon and also to survey the lunar gravity field. Its launch by H-IIA is tentatively scheduled for JFY 2006.

PLANET-C: A Venus climate orbiter program is requesting the program start to be authorized in JFY 2004, with planned launch in 2008 by M-V rocket.

MMO in BepiColombo Mission: ISAS/JAXA will participate in the European Space Agency's (ESA) Mercury mission by providing the Mercury Magnetospheric Orbiter (MMO). The composite MMO-MPO (Mercury Planetary Orbiter) will be launched by a Soyuz/Fregat launcher in a 2010–2011 window. The program is awaiting approval of the Phase-B start in JFY 2004.

2.3 Aeronautical Activities

R&D by JAXA

Supersonic transport (SST): JAXA set a goal of developing an SST that cruises at a speed of Mach 2.2 with a range in excess of 10,000km with 300 passengers. Basic aerodynamic design with Computational Fluid Dynamics (CFD) technology is currently being conducted along with the development of engines and composite materials. Establishment of system integration technology is another objective of this project. Although a sub-scale flight experiment in the Australian desert in 2002 failed due to premature release of the vehicle from its booster rocket, another trial is planned in the near future.

Stratospheric platform airship system (SPF): SPF is a solar battery-powered airship system capable of long-duration station-keeping flight at a stratospheric altitude of 20km. The objective of this project is to establish technologies required for manufacturing and operating an SPF airship and technologies to utilize the SPF for communication, broadcast and Earth observation. A preliminary flight experiment was successfully completed in 2003 and another experiment is scheduled in 2004.

Flight experiments using MuPAL-α and ε: MuPAL (Multi-Purpose Aviation Laboratory) comprises two flight experiment aircraft for demonstrating advanced aviation technologies associated with, *inter alia*, guidance and control, avionics, man-machine interface, and human factors. MuPAL-α, which can also serves as an in-flight simulator, is a fixed-wing aircraft (Dornier Do.228-200), while MuPAL-ε is a helicopter (MH2000A). Research on dynamically reconfigurable flight control systems to deal with failures and/or adverse weather is under way using MuPAL-α.

Flight simulators: JAXA constructed new flight simulators in 2003, including a full-motion simulator as well as fixed-base ones. These facilities are used for the development of new aircraft and onboard equipments and for research on human factors.

In addition to the above activities, JAXA is carrying out conceptual design of a VTOL jet transport and development of its components such as engines.

Civil aviation

Although the Japanese aircraft industry has not developed an indigenous civil transport since the YS-11 in 1962, it is co-developing regional and business jets with foreign manufacturers. Specifically, Kawasaki Heavy Industries, Ltd. (KHI) joined the development and production of Embraer's ERJ-170, and Mitsubishi Heavy Industries, Ltd. (MHI) will collaborate with Bombardier in the development of its G5000. Japanese manufacturers also fabricate fuselage and wing components of Boeing jet transports such as the 757, 767 and 777, and are also being involved in manufacturing parts of Airbus' A380. The government, aerospace industry, airlines, institutes and academia have been addressing and considering the development of a truly domestic civil aircraft.

The time spent journeying to and from airports can negate some of the benefits of aircraft as a means of transportation, especially for short-range flights, and an aircraft with the convenience of an automobile has long been desired. The "Miracle Vehicle", a single-occupant motor-powered airplane, is an answer. Its compact size and foldable wings allow it to operate from roads like a car. Flight tests have been successfully completed and further development is continuing.

The government is encouraging major hospitals to use Emergency Medical Service (EMS) helicopters, called "Doctor Heli", to transport medical staff to give on-site emergency treatment, and offers financial support.

Military aviation
The Japan self-defense agency (JDA) is developing several new aircraft: an airlift transport aircraft (C-X) with KHI, an anti-submarine warfare patrol aircraft (P-X) also with KHI, and a utility flying boat (US-1A) with Shinmaywa based on the US-1. The amphibious aircraft successfully made its first flight in 2003. The C-X will replace KHI's C-1 and the P-X will take over the missions of the Lockheed P-3C Orion.

MHI has constructed prototypes of the SH-60K patrol helicopter for Japan Maritime Self-Defense Force, and the production model will be finished by 2005. MHI's F-2 support fighter is based on the Lockheed Martin F-16 with greater maneuverability, advanced digital avionics and fly-by-wire flight control system, and a composite wing. The completely indigenous OH-1 observation helicopter newly-developed by KHI has recently entered service. Fuji Heavy Industries Ltd. (FHI) completed prototypes of a primary trainer derived from the T-3 derivative for the Japan Air Self-Defense Force, and the production type has entered service as the T-7.

Unmanned (Uninhabited) Aerial Vehicle (UAV)
Unmanned helicopters have been developed for observation of disaster zones and other dangerous areas, reconnaissance, and crop spraying. Yamaha Hatsudouki produces the R-MAX, Kawada Kougyo the Robocopter, and FHI the RPH-2. These UAVs have been further upgraded to have autonomous flight capability. The Japan Ground Self-Defense Force operates a flying forward observation system (FFOS) which relies on unmanned helicopters to gather information in the combat area.

2.4 University Students' Aerospace Activities

Many student-built space activities have appeared recently in Japan, in the fields of development and launch of micro/nano/pico satellites and sub-orbital rockets. Hands-on training using micro-satellites and rockets provides a unique space education opportunity for university level students, giving them a chance to experience the whole space project cycle from mission creation, satellite design, fabrication, test, launch, operation through to analysis of the results. Even in small-scale projects, students can learn project management, team working, documentation and other important skills which are indispensable for space related projects. In addition, the low cost and rapid development cycle of such activities may provide a new way of space development that is completely different from conventional "government-oriented large project" based space development (Nakasuka, 2000).

In 2002, a university-built satellite "Whale Ecology Observation Satellite System," developed by Chiba Institute of Technology, was launched by H-IIA as a piggyback payload, followed in 2003 by two CubeSat launches by the University of Tokyo and Tokyo Institute of Technology. These have been very successful and have proved the quality of university-built satellites. Currently, Nihon University and Soka University are undertaking their own CubeSat projects, Kyushu university is collaborating with US universities on a tether experiment satellite, and Hokkaido Institute of Technology is collaborating with local industry to develop a remote sensing satellite.

In order to support such student activities, the University Space Engineering Consortium "UNISEC" was founded in 2002 (Kawashima and Nakasuka, 2003) and became a Non-Profit Organization (http://www.unisec.jp). It currently has about 50 regular members and more than 100 student members from 19 universities. Its activities include facilitating information sharing and collaboration among member universities; helping students to use ground test facilities of national laboratories; consulting on political and legal matters; coordinating joint development of equipment and projects; and bridging between university activities and the needs and interests of non-space persons and organizations.

One example of UNISEC's activities is arranging CanSat sub-orbital launch experiments at ARLISS (A Rocket Launch for International Student Satellites) events. CanSat is 350ml juice can-sized pico-satellite. Participating universities each fabricate their own CanSats, which are lifted to about 4 km by high-power amateur rockets in the Nevada desert in the USA (Sako *et al.,* 2001). During descent, which takes about 15–20 minutes using parachute, various experiments such as radio communication, DGPS (differential global positioning system) measurement, tether extension, formation flight and image acquisition are performed. ARLISS events have been held annually since 1999, providing university students with excellent first-step training in satellite development. CubeSat and hybrid rocket projects are briefly described as examples below.

CubeSat Projects
CubeSat is cubic nanosatellite measuring 10cm each side with a weight of 1kg (Heidt *et al.,* 2000). Reflecting the proposals of Professor Robert Twiggs

of Stanford University, more than fifty universities and research institutes have been involved in developing their own CubeSats. In Japan, the University of Tokyo and Tokyo Institute of Technology each began development of CubeSats in 2001 and completed fabrication and ground test in 2002. These two CubeSats were launched into a 820km sun-synchronous orbit on June 30, 2003 from Plesetsk Cosmodrome, Russia using the German-Russian ROCKOT launcher. They are still operating very well even in early 2004, and various pre-planned experiments have been successfully performed, proving the efficacy of the concept. For example, the University of Tokyo's CubeSat XI-IV (Fig.2) captures Earth images from orbit and downlinks them to the ground (Tsuda *et al.,* 2002).

Hybrid Rocket Activities
Several universities have been performing research on hybrid rockets, and have fabricated sub-orbital experimental launchers aiming for orbital launch systems in the future. Hybrid rocket engines have been developed that use a combination of liquid oxygen and acryl, which is comparatively safe yet provides high power and good specific impulse (ISP). Hokkaido University and Tokyo Metropolitan Institute of Technology have performed annual rocket launch experiments up to 1km altitude at Taiki-cho in Hokkaido, including fly-back of the rocket upper stages using a wing or parafoil (Fig. 3). Tokai University has been collaborating with Alaska University of the USA on the development of sub-orbital launchers and has conducted actual launch experiments up to several tens of kilometers in Alaska every two or three years.

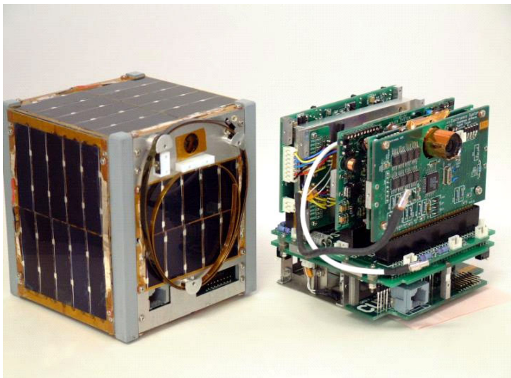


Fig. 2 University of Tokyo's Educational Satellite CubeSat XI-IV launched on June 30, 2003

Fig. 3 Hybrid Rocket Experiment in Hokkaido

3. HIGH SPEED FLIGHT DEMONSTRATION

3.1 HOPE re-entry vehicle research and development program

Japanese future space vehicle research and development has a long history as shown in Fig. 4. NAL and NASDA collaboratively initiated basic research on re-entry vehicles in the eighties, and stepped up to a study for development of a re-usable spaceplane, HOPE (H-II Orbiting PlanE), in the late eighties after the H-II launcher development program started. Following the HOPE system study, three flight experiment programs—OREX in 1994, and HYFLEX and ALFLEX in 1996—were conducted to develop and mature critical technologies such as thermal protection systems, materials, hypersonic aerodynamics and heating, and flight control (Yamamoto *et al.,* 1994, Shirouzu and Yamamoto*,* 1996, Nakayasu and Nagayasu, 1997). Following the success of these experiments, design of the HOPE-X (H-II Orbiting PlanE eXperimental) started in 1996 and continued to 2000 (Tsujimoto and Kouchiyama, 2000). During the design phase, the configuration changed from using wing-tip fins to twin canted fins on the aft fuselage (Ishimoto *et al.,* 2000). It was planned to launch HOPE-X into orbit on an H-IIA launcher from Tanegashima Space Center, complete a single orbit, then land at Aeon airfield, Christmas Island in the Pacific Ocean. HOPE-X had a design empty weight of about 12 tons, and a fuselage length of about 16m.

Following H-II launch mishaps in 1998 and 1999, however, the HOPE-X program was frozen in the middle of 2000. More than one year prior to the freeze of HOPE-X project, NAL and NASDA had started the High Speed Flight Demonstration program to further demonstrate technologies in the transonic speed range around Mach 1. The name "High Speed" indicates the expansion of the low subsonic speed range covered by the ALFLEX experiment to transonic speeds. The HSFD program conducted demonstration flights in 2002 and 2003. These flight tests complete the HOPE program, and a future launcher research program is currently being restructured.

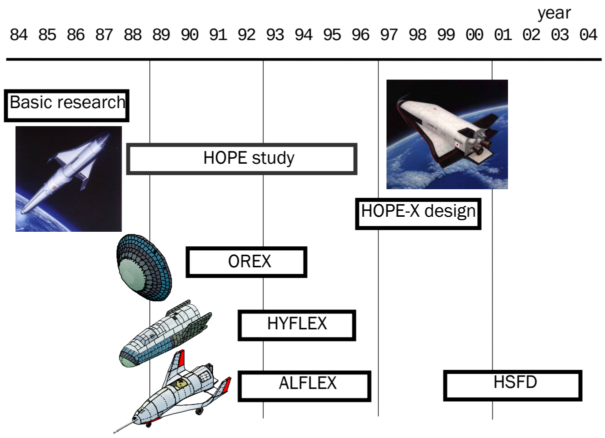


Fig. 4 HOPE reentry research and development

3.2 Objectives of HSFD Phase I and Phase II

The HSFD program consists of two phases, Phases I and II, that have different objectives and experimental methods but use a common core vehicle and systems, based as far as possible on readily available off-the-shelf components. The HSFD Phase I and II experimental vehicles are designed to have as much commonality as possible, which yields efficiencies in development time and cost. Furthermore, it is intended to form the basis of a general-purpose low-cost flight experiment system that will be applicable to the flight tests of other future aerospace plane programs.

Figs. 5 and 6 show schematic mission profiles. The main objective of the HSFD Phase I experiment is to verify approach and landing systems for the terminal phase of the return flight of a winged re-entry vehicle from orbit. The Phase I vehicle is equipped with a jet engine and takes off and lands automatically from a conventional runway. Another objective is the development of autonomous flight technologies essential for future space transportation systems, including take-off and landing.

Phase II, on the other hand, is a drop test in which the vehicle is released from a stratospheric balloon at about 30km altitude, accelerates in free fall, and lands using parachutes and airbags. The main objective of HSFD Phase II is to clarify the transonic aerodynamic characteristics of the HOPE-X vehicle configuration. The aerodynamic data will be used as a reference to evaluate the HOPE-X aerodynamic database to improve wind tunnel testing and CFD technologies. A secondary objective is to establish design technology of a guidance and control system for the transonic speed region.

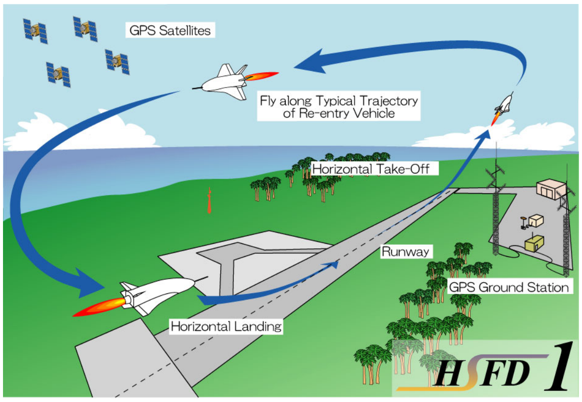


Fig. 5 HSFD Phase I mission profile

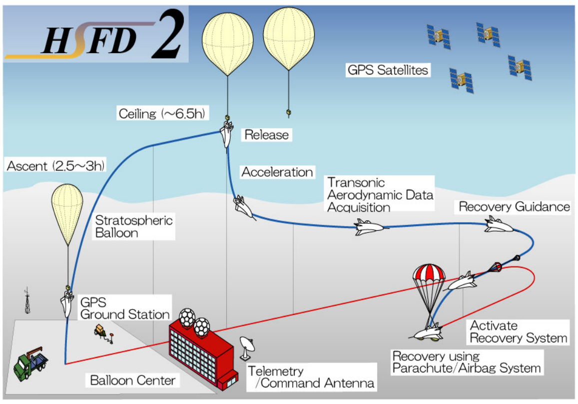


Fig. 6 HSFD Phase II mission profile

4. HSFD Phase I

4.1 Vehicle system development

A three-view diagram of the Phase I vehicle is shown in Fig. 7 and its major characteristics are listed in Table 1. The vehicle's configuration is based on a 25% scaled HOPE-X, with a slightly increased wing area. The vehicle incorporates a small jet engine (Teledyne 382-10) for propulsion and retractable landing gear, and has a fully autonomous flight capability from take-off to landing. The flight profile is preprogrammed as a series of waypoints in the onboard flight control computer (FCC). Path-following capability is specified for the vehicle to allow it to simulate an extremely steep flight path (up to 25 degrees) employed by typical winged re-entry vehicles, and the vehicle has speed brakes on the aft fuselage to enable it to simulate the steep approach flight.

Fig. 8 shows major equipment installed in the vehicle. Off-the-shelf components are used throughout, with

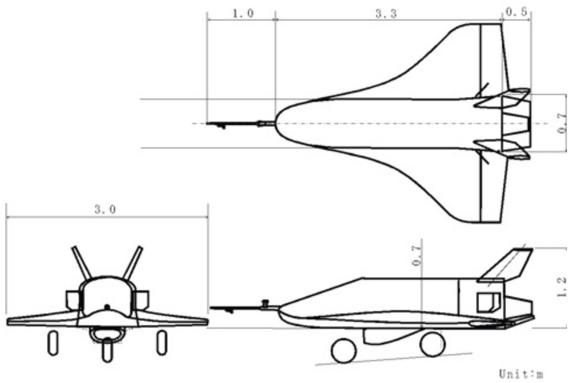


Fig. 7 Phase I vehicle

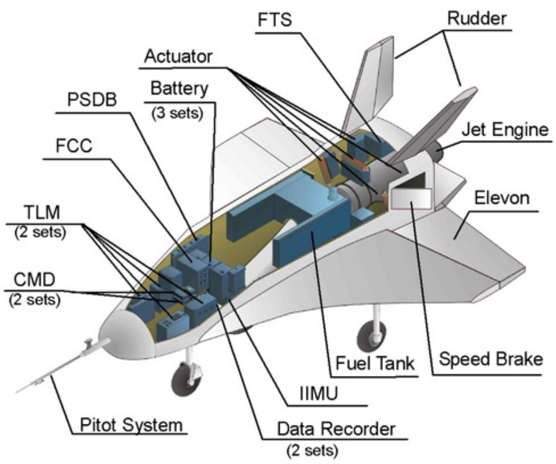


Fig. 8 Phase I vehicle's onboard equipment

the notable exception of the GPS/INS navigation system which was developed by NAL (Harigae *et al.*, 2001). The automatic flight control system is designed to achieve the specified flight performance and to control the vehicle autonomously, and is designed to allow operation in 90% of probable wind conditions at the landing airfield. A ground station monitors the status of the vehicle via telemetry, but remote command from the ground is limited to emergency cases such as a "return to base" command and an emergency flight termination. Since it is experimental, all the vehicle's onboard systems are simplex except for the emergency flight termination system to prevent the vehicle from damaging ground facilities and personnel.

Table 1 Phase I vehicle major characteristics

Design maximum take-off mass	735 kg
Design empty mass	631 kg
Wing Area	4.4 m^2
Runway length and width	1800 m x 30 m
Maximum landing velocity	71 m/s
Maximum dynamic pressure	157 hPa
Maximum aerodynamic load	+2.5 to –1.0
Propulsion system	
engine type	TCMTE 382-10
maximum static thrust (nominal)	4410 N
maximum fuel	104 kg

Fig. 9 Photograph from the first flight of Phase I

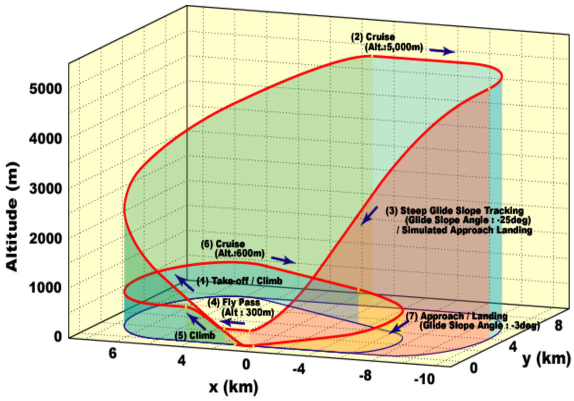


Fig. 10 Flight profile of the third flight

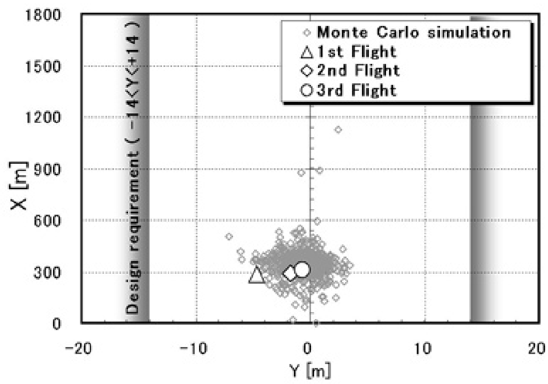
The Phase I experiment was carried out at Aeon airfield on Christmas Island in the Republic of Kiribati, located on the equator in the Pacific Ocean. The airfield has a 1,800m x 30m runway.

4.2 Flight test

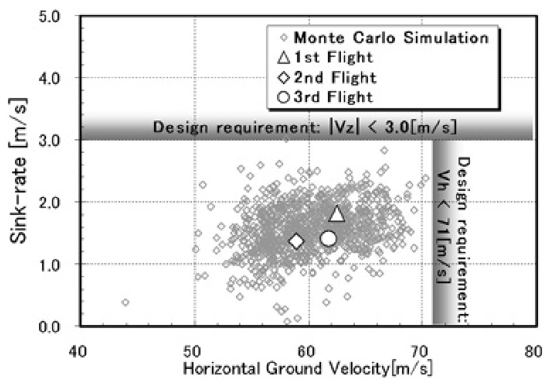
A total of three flights were performed in October and November 2002. The first flight of 9'35" duration was made on October 18, 2002 to verify the vehicle's basic performance, during which the vehicle reached a maximum altitude of 600m and an equivalent air speed (EAS) of 93m/s, and basic autonomous flight performance and the functions of the onboard equipment were confirmed. The photograph in Fig. 9 was taken just after the vehicle stopped after the ground roll at the end of the first flight.

On the second flight on November 5, 2002 of 18'36" duration, the flight envelope was expanded to an altitude of 2,500m, and a simulated steep spiral approach trajectory around the heading alignment cylinder (HAC) was made. The flight path angle of the steep glide slope was –13 degrees, half as steep as the actual winged launch vehicles' glide path. The maximum EAS reached was 95m/s.

The last flight on November 16, 2002, lasting 18'08", achieved the final mission flight profile to verify approach and landing systems on a typical winged re-entry vehicle terminal phase trajectory. The flight envelope was expanded up to 5,000m altitude and a



(a) Touchdown point



(b) Touchdown velocity

Fig. 11 Landing performance

speed of 136m/s EAS, as shown in Fig. 10. It was verified that the Christmas downrange tracking station (XDRS), which is used for monitoring the H-IIA rocket, could also be used to monitor the approach and landing of a winged re-entry vehicle even at altitudes as low as around 100m.

The landing performance of the three flights is shown in Fig. 11 together with the results of 1000 Monte-Carlo flight simulation runs conducted before the flights. The vehicle's touchdown condition coincides with the simulation results and satisfies the design requirements. The vehicle's trajectory tracking performance was also satisfactory. All of three flights were conducted as planned and the Phase I flight experiment was successfully completed.

5. HSFD Phase II

5.1 Vehicle system development

Figure 12 shows a three-view diagram of the experimental vehicle. The vehicle is a 25% scaled version of the 1999 HOPE-X design. Since the Phase II objective is to obtain reference data on transonic HOPE-X aerodynamics, the vehicle's shape is the same as that of HOPE-X except for a nose boom for the air data system. The vehicle's major characteristics are listed in Table 2. The onboard equipment is shown in Fig. 13.

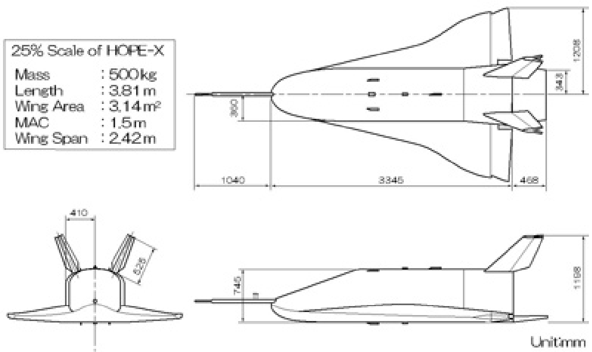


Fig. 12 Phase II vehicle

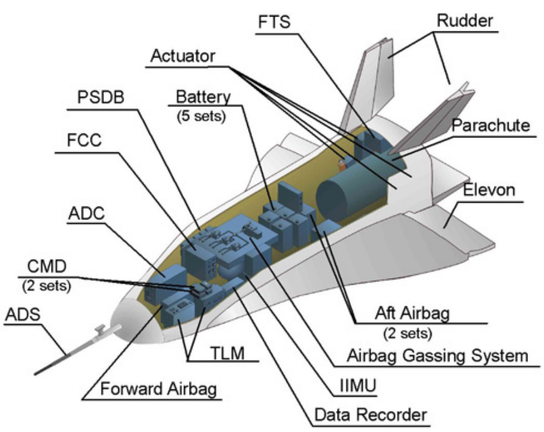


Fig. 13 Phase II vehicle's onboard equipment

As shown in the Phase II mission profile (Fig. 6), the experimental vehicle is lifted by stratospheric balloon to an altitude of 20–30km, depending on the target Mach number, from where it is released into free fall and accelerates to the transonic region. After the vehicle reaches the prescribed Mach number (M0.8, M1.05, or M1.2), it maintains the Mach number with a specified tolerance of ±M0.03 by slowly reducing its angle of attack (AOA) as air density increases with decreasing altitude. The data acquisition phase is therefore similar to the so-called alpha sweep in wind tunnel tests, the rate of AOA change being sufficiently small to allow trimmed flight characteristics to be measured. The pressure distributions on the vehicle's surface and hinge moments of the aerodynamic control surfaces are measured along with air data and position, velocity, acceleration and attitude data.

After data acquisition, the vehicle decelerates and is guided to reach a recovery point at an altitude of 1,300m. When the vehicle reaches the recovery point, a recovery system using parachutes and air bags is activated and the vehicle makes a soft touchdown. Like the Phase I experiment, the flight is fully autonomous and remote command from the ground is limited to emergency recovery and flight termination. NAL/NASDA jointly developed the Phase II flight experiment system in conjunction with CNES, which was chiefly responsible for the high altitude balloon system and ground facilities.

Table 2 Phase II vehicle major characteristics

Design mass	500 kg
Wing area	3.09 m^2
Maximum dynamic pressure	157 hPa
Maximum aerodynamic load	+3.5 –1.0 G
Maximum descent rate before landing	6.2 m/s
Maximum impact acceleration at landing	8 G

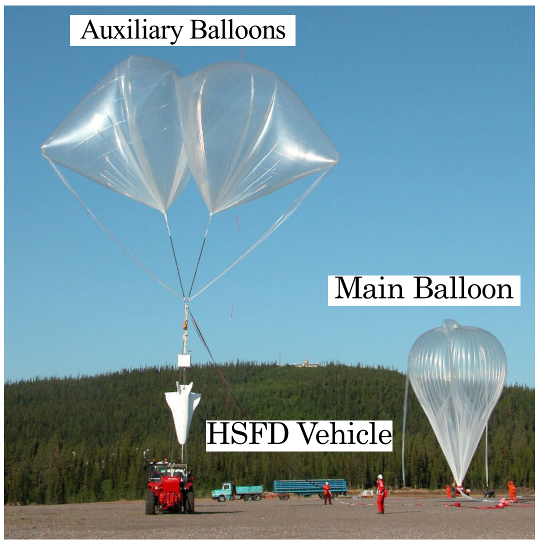


Fig. 14 Photograph of the launch with balloon

5.2 Flight test

The first flight of the planned Phase II campaign was carried out on July 1, 2003 at the Esrange test site in northern Sweden. The target Mach number was set to M0.8. Fig. 14 shows a photograph of the vehicle during the launch operation, and Fig. 15 shows the vehicle's trajectory. The vehicle was launched from the ground under the balloon at 06:03 local time, and was released around the target altitude of 21km at 07:14. Twenty-nine seconds after release, the vehicle reached the target Mach number M0.8, and constant Mach data acquisition was initiated. Mach number was maintained very well at M0.8±0.03 and AOA was reduced from 14 degrees to 2 degrees while sideslip angle was maintained at 0±2 degrees, as shown in Fig. 16. After the data acquisition phase was completed, the vehicle decelerated and was guided to a recovery site. When the vehicle reached the recovery site, the FCC issued recovery system activation commands, but the recovery system did not function as expected and the vehicle was damaged on touchdown.

Although the flight experiment campaign was interrupted due to the damage sustained by the vehicle, valuable data were obtained (Ueno *et al.*, 2004). The vehicle's aerodynamic characteristics at Mach 0.8 were estimated by analyzing the recorded data, and the fully autonomous flight control technologies were demonstrated.

6. HSFD GUIDANCE, NAVIGATION AND CONTROL

6.1 Characteristics of Phase I GNC

Carrier Phase DGPS Integrated Inertial Navigation System

While off-the-shelf components are used throughout the HSFD program, an exception is the Integrated Inertial Measurement Unit (IIMU), a hybrid navigation system that uses a combination of inertial navigation and differential global positioning satellite system (DGPS) positioning, with GPS carrier phase used to enhance accuracy. The navigation system included a mobile ground station to support DGPS positioning, and incorporated a new algorithm proposed by NAL's navigation research group. Although a laser altimeter and barometric altimeter were used for backup altimetry close to the ground, the hybrid DGPS/INS system was proved to give sufficient accuracy for the entire flight from take-off to ground roll stop.

Automatic flight capability including take-off and landing

Fully automatic flight from take-off to ground roll stop is one of the main technical challenges of the Phase I vehicle. The flight is scheduled entirely by readily modifiable onboard data which are programmed before each flight. The flight path consists of straight and curved segments in the horizontal plane which are formed by connecting waypoints with given altitudes. Programmed data include waypoint coordinates, turn center coordinates and radius for curved segments, velocity, and so on.

The flight program data are easily validated by Monte Carlo flight simulation. In fact, Monte Carlo flight simulation has played an important role in the flight control design. The mathematical flight model incorporates about one hundred sources of uncertainty, disturbances and noise, and it is impossible to predict the effects of all combinations of these on flight behavior since their influences are non-linear. A stochastic approach like Monte Carlo simulation is therefore necessary to quantify the effects of these uncertainties, disturbances, and noise. The ease of computational simulation of the closed loop system with automatic flight control makes Monte Carlo simulation a practical design tool. These analyses gave the flight control engineers confidence before the first flight, and enabled them to achieve the final flight mission profile at the third flight.

Lessons learned

The guidance, navigation and control system

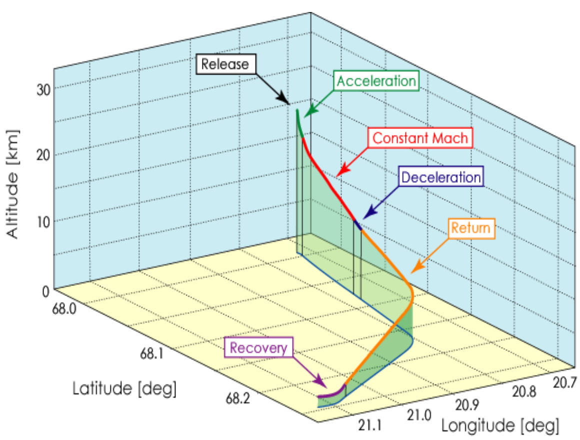


Fig. 15 Flight profile of the Phase II

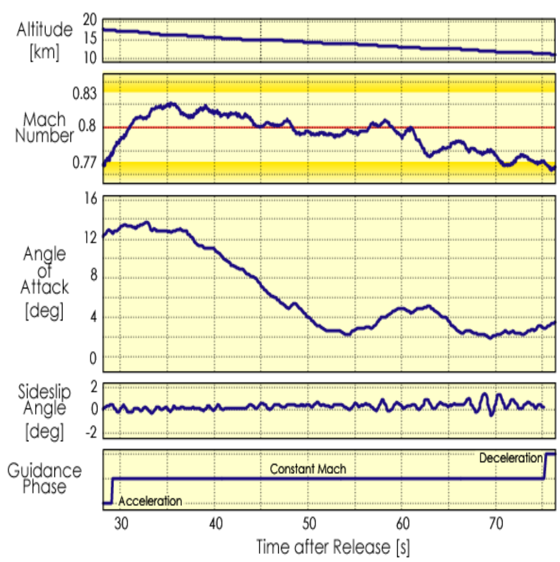


Fig. 16 Flight in the data acquisition phase

performed very well in the flight experiments, and the lessons learned were all minor. Two are as follows.

-Bouncing due to unexpected external force at touch down.
The vehicle experienced bouncing after touchdown on the first flight. This was due to coupling between pitch attitude feedback control and an un-modeled pitching moment disturbance at touchdown. It was resolved by slightly modifying the preprogrammed onboard flight data.

- Minor navigation error due to multi-path effects at the ground GPS station.
Since the location of the ground GPS station was not optimal, differential signals contained slight error due to multi-path effect. The error, however, depends on the locations of GPS satellites, and is therefore repeatable and predictable.

6.2 Characteristics of Phase II GNC

The flight profile of the high-altitude drop test approach posed some technical challenges for the guidance and control of the Phase II vehicle (Tsukamoto, *et al.,* 2004), as described below.

Guidance and control for data acquisition phase
Maintaining a constant Mach number during the data acquisition phase is a key requirement to achieve the flight experiment's aims. The vehicle is released from the balloon and accelerates to transonic speed in free fall. A pull-up maneuver is made after free fall to enter the data acquisition constant Mach phase, and the timing of this maneuver is critical to achieve the target Mach number precisely. Maintaining Mach number at flight path angles of between 70 and 40 degrees depending on the target Mach number is another challenge, as the rate of atmospheric density change due to the high descent rate is significant. The vehicle decreases drag coefficient by decreasing its angle of attack, and a guidance algorithm using a feedback linearization technique was adopted for this purpose.

Attitude control after release
Although the vehicle maintains a constant pitch attitude for about thirty seconds from release to the start of the pull-up maneuver, roll and yaw attitude are controlled after the vehicle reaches a dynamic pressure of 25Pa to control the direction in which the vehicle executes the pull-up maneuver. The low and rapidly changing dynamic pressure during the free-fall acceleration makes attitude control challenging.

Flexible guidance algorithm: uncertain release point including emergency case
The vehicle is recovered using parachutes and airbags, which impose constraints on the surface conditions at the landing site and so limit the number of possible recovery areas in the test range. The vehicle was programmed with the positions of 14 suitable recovery points, priority ranked by terrain and ground conditions. Because of the uncertainty of the vehicle's release position, it is impossible to determine the landing site beforehand, and the vehicle must autonomously select the best reachable recovery area in flight and then fly to the center of the area. The guidance law must be flexible and applicable at any release point in the test range.
Further, the vehicle has an autonomous function to deal with cases of unexpected release altitude—it is able to select the most appropriate target Mach number and continue the flight experiment.

Robust control for transonic flight
Aerodynamic data uncertainties and Mach number measurement error in the transonic speed range are greater than at subsonic and supersonic speeds, making robust flight control design a technical challenge for the transonic speed range. Robust flight control laws were designed using the MDM/MDP (Multiple Delay Model and Multiple Design Point) approach.

Design validation check by Monte Carlo flight simulation
As in the Phase I flight control design, the flight control laws and guidance algorithms were verified by Monte Carlo flight simulation. In the Phase II experiment, the evaluation included guidance to a recovery point and robust flight control. The results of Monte Carlo simulations enable flight control engineers to identify inadequacies in guidance logic and control parameters, can improve the probability of satisfying the requirements, and gives a degree of confidence of successful flight. Monte Carlo flight simulation was essential for the success of the flight experiments.

Lessons learned in Phase II GNC
Lessons learned in the guidance, navigation and control were all minor, except that GPS signals were not properly received during almost the entire flight, so navigation reverted to pure inertial navigation. Consequently there was a position error at the end of the flight of approximately 3km. Other than this position error, the vehicle's attitude, speed, and acceleration had sufficient accuracy for the measurement mission.

7. CONCUDING REMARKS

From the overview of the current status of Japanese aerospace programs, it is understood that the area of guidance, navigation and control plays a key role in research and development. This is in common with the R&D efforts of other aerospace industries as a result of today's revolution in information technology. High performance avionics, digital data communication, digital computers, and software technology have advanced aerospace automatic control capabilities. The HSFD program is a typical case, in which engineers have been reminded of the potential capabilities of digital technology. Automatic flight control technology is now allowing the expansion of the boundaries of flight capability in much the same way as it was explored by human test pilots in the past.

ACKNOWLEDGEMENTS

International collaboration with CNES in the HSFD Phase II program contributed greatly to the development of the flight experiment system and the successful execution of the experiment. The Swedish Space Corporation supported the HSFD Phase II flight experiment at its Esrange site. Japanese aerospace manufacturing company Fuji Heavy Industries, Ltd. participated in the HSFD program as prime contractor. The author acknowledges all the support of the NAL/NASDA HSFD team. Finally, the author thanks the IFAC Japan Section members who provided manuscripts to prepare section 2 of this paper, especially Dr. Nakasuka of the University of Tokyo who arranged all the materials.

REFERENCES

Harigae, M., T. Nishizawa, and H. Tomita (2001). Development of GPS Aided Inertial Navigation System for High Speed Flight Demonstrator. In *Proceedings of the 14th International Technical Meeting ION GPS 2001*, pp. 2665 – 2675.

Heidt, H., J. Puig-Suari, A. Moor, S. Nakasuka and R. Twiggs (2000). CubeSat: A New Generation of Pico-satellite for Education and Industry Low-Cost Space Experimentation. In *14th Annual AIAA/USU Conference on Small Satellites,* Logan, Utah.

Ishimoto, S., M. Shirouzu and J. Kouchiyama (2000). Modification of HOPE-X Aerodynamics Configuration. In *22nd International Symposium on Space Technology and Science*, Morioka, (2000-e-42).

Kawashima, R. and S. Nakasuka (2003). Unique Space Education Organization - Challenges of University Space Engineering Consortium (UNISEC). In *54th International Astronautical Congess*, Bremen, (IAC-03-P.2.04).

Nakasuka, S. (2000). Micro Satellite and Space Education. In *Journal of Space Technology and Science*, Vol. 16, No. 1, pp. 1-8.

Nakayasu, H., and M. Nagayasu (1997). On the Automatic Landing Flight Experiment (ALFLEX). In *Proceedings of the ALFLEX Symposium*, University of New South Wales, Sydney, also published as NAL SP-39T, National Aerospace Laboratory, Tokyo.

Nishizawa, T., W. Sarae, T. Munenaga, K. Fujii, M. Yanagihara and S. Venel (2003). Overview of High Speed Flight Demonstration Project. In *12th AIAA International Space Planes and Hypersonic Systems and Technologies*, Norfolk, Virginia, (AIAA-2003-6980).

Sako, S., Y. Tsuda, S. Ota, T. Eishima, T. Yamamoto, I. Ikeda, H. Ii, H. Yamamoto, H. Tanaka, A. Tanaka and S. Nakasuka (2001). CanSat Suborbital Launch Experiment - University Educational Space Program Using Can Sized Pico-Satellite. In *Acta Astronautica*, Vol. 48, No. 5-12, pp.767-776.

Sarae, W., T. Nishizawa, M. Sagisaka, T. Akimoto, M. Yanagihara, Y. Miyazawa, S. Venel, S. Guedron and J.C. Cretenet (2003). An Overview of The High Speed Flight Demonstration Project. In *54th International Astronautical Congess*, Bremen, (IAC-03-V.6.07).

Shirouzu, M. and M. Yamamoto (1996). Overview of the HYFLEX Project. In *7th AIAA International Space Planes and Hypersonic Systems and Technologies Conference*, Norfolk, Virginia, (AIAA 96-4524).

Tsuda, Y., N. Sako, T. Eishima, T. Ito, Y. Arikawa, N. Miyamura, K. Kanairo, S. Ukawa, S. Ogasawara, S. Ishikawa and S. Nakasuka (2002) Educational Pico-Satellite Project CUBESAT - University of Tokyo's CUBESAT XI and its Operation Plan," In *53rd International Astronautical Congess and World Space Congress*, Houston, (IAC P-1-02).

Tsujimoto, T. and J. Kouchiyama (2000). Current Status of the H-II Orbiting Plane-Experimental (HOPE-X) Development. In *22nd International Symposium on Space Technology and Science*, Morioka, (2000-g-06).

Tsukamoto, T., H. Suzuki, T. Ninomiya and T. Nishizawa (2004). Guidance and Control for the High Speed Flight Demonstration Phase II. In *AIAA Atmospheric Flight Mechanics Conference*, Providence, Rhode Island, to be presented.

Ueno, M., W. Sarae, T. Tsujimoto, M. Yanagihara, T. Hirotani and S. Venel (2004). Estimating Aerodynamic Characteristics of the High Speed Flight Demonstrator using Flight Test Data. In *AIAA Atmospheric Flight Mechanics Conference*, Providence, Rhode Island, to be presented.

Yamamoto, M., T. Akimoto, K. Yamawaki, M. Inaba, T. Shimoda and Y. Inoue (1994). Outline of Orbital Re-Entry Experiment, (in Japanese). In *HOPE/OREX Workshop*, Tokyo, also published as NAL SP-24, National Aerospace Laboratory, Tokyo.

Yanagihara, M., Y. Miyazawa, T. Akimoto, M. Sagisaka, S. Venel and S. Guedron (2003). Current Status of HSFD Project Phase II. In *3rd International Symposium, Atmospheric Reentry Vehicles and Systems,* Arcachon.