D-SEND PROJECT FOR LOW SONIC BOOM DESIGN TECHNOLOGY

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Abstract

The D-SEND project aims to demonstrate the feasibility of JAXA's low sonic boom design concept through the balloon drop tests. The project is carried out in two phases (D-SEND#1 and D-SEND#2). The D-SEND#1 drop tests were conducted twice in May 2011. The two different axisymmetric bodies were dropped from the balloon at 30km altitude and the conventional N-type and the shaped sonic booms were successfully captured by microphones at multiple altitudes up to 1km. The D-SEND#2 is scheduled to be conducted in 2013 in the same way as the D-SEND#1. An unmanned experimental supersonic airplane based on the JAXA's low sonic boom design technology is newly designed. The sonic boom intensity of the airplane is designed to be almost as half as the conventional supersonic transport. The airplane autonomously flies over microphones and the shaped sonic booms are measured. In this paper, the balloon drop test method, the test bodies and the aerial sonic boom measurement system with blimps are described. Some test results of the D-SEND#1 are presented as well.

1 Introduction

JAXA (**J**apan **A**erospace E**x**ploration **A**gency) has been promoting a supersonic technology research program since 1997. From 1997 to 2005, the NEXST program had been promoted focusing on the aerodynamic drag reduction technologies. In this program, an unmanned experimental supersonic airplane was developed and flight trial called "NEXST-1 project" was conducted at Woomera Prohibited Area of Australia in 2005[1], [2]. In 2006, a new program called "S3 program" (**S**ilent **S**uper**S**onic research Program) has started as a post program of the NEXST program. The S3 program contains not only basic researches on supersonic aircraft technologies but also flight demonstration project. In this program, JAXA has been focusing on the technology of the computational fluid dynamics such as the aerodynamic drag reduction and sonic boom reduction. In 2010, JAXA launched a new project called "D-SEND (**D**rop test for **S**implified **E**valuation of **N**on-symmetrically **D**istributed sonic boom)" as one of the flight demonstrations, aiming at verifying JAXA's aerial sonic boom measurement system [3] and proprietary low sonic boom design concept [4]. Since the D-SEND project utilizes the high altitude balloon free fall technique to realize a supersonic speed of the test body, a jet engine is not required for the test body. This enables us to develop a small unpowered test body and provides the low development cost and shorter term of the development.

The drop tests are planned to take place at Esrange space center in Sweden. The Esrange space center is supervised by SSC(**S**wedish **S**pace **C**orporation) which has much expertise in the field of balloon operations. In the drop tests, a large stratospheric balloon lifts the test bodies up to an altitude of about 30km. After reaching the ceiling, the drop bodies are released and the sonic booms generated by the bodies are measured by microphones at several altitudes up to 1km. The microphones and the data recording systems are hung along the tether line of a blimp which stays at 1km altitude.

The drop tests sequences of the D-SEND#1 and D-SEND#2 are illustrated together in Fig.1. The sequence starts from the bottom left. The two axisymmetrical bodies of the D-SEND#1 simply free-fall from a high altitude balloon and go through at supersonic speed near the sonic boom measurement system. On the other hand, an unmanned experimental supersonic airplane (S3CM: **S**ilent **S**uper**S**onic **C**oncept **M**odel) flies over the sonic boom measurement system at required flights conditions. JAXA's low sonic boom design technologies will be validated by measuring the shaped sonic booms which S3CM generates. The aerial sonic boom measurement technique and the measured data will contribute to establish a sonic boom acceptance rule for the supersonic transport overland of the International Civil Aviation Organization (ICAO).

In this paper, D-SEND#1 and D-SEND#2 drop test scenarios, the configuration and specifications of test bodies and the aerial sonic boom measurement system are presented. The measured sonic boom data of the D-SEND#1 are also described in details.

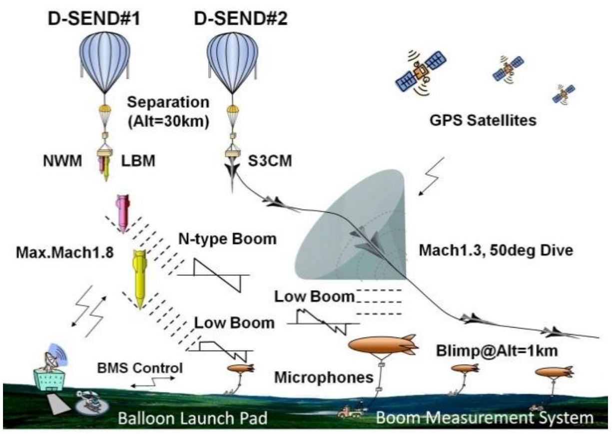

Fig.1 D-SEND#1&#2 Drop Tests Sequences

2 D-SEND#1 Drop Test

The final goal of the D-SEND project is to validate the JAXA's low boom design concept. In order to accomplish the goal, JAXA has planned to drop an experimental supersonic airplane from the balloon and measure the sonic booms from the ground to 1km altitude. However since the balloon drop test method with aerial sonic boom measurement is a new method, a preliminary drop test, namely D-SEND#1, is required before the D-SEND#2 drop test.

The objectives of D-SEND#1 are (1)to confirm the feasibility of measuring the low level sonic booms under actual atmospheric conditions, (2)to establish the aerial sonic boom measurement technology with a blimp and (3)to confirm the operation procedures of the balloon and blimp simultaneously.

2.1 Test Bodies

Since the D-SEND#1 drop test is a preliminary drop test of D-SEND#2, the size of the test bodies for D-SEND#1 should be designed to be equivalent to that of S3CM. At first, LBM (**L**ow **B**oom **M**odel) which generates a flat top shaped sonic boom was designed by the SGD (**S**eebass-**G**eorge-**D**arden) boom minimization theory. The configuration is shown in Fig.2.

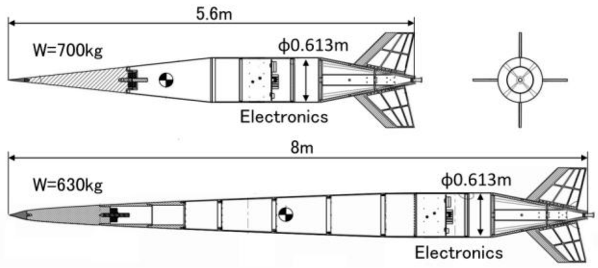

Fig. 2 Test Bodies (NWM & LBM)

The slender part comes from the SGD theory. The cylinder part contains electronics and after-cone has four fins just for aerodynamic static stability. The length of the body is 8m and the diameter is 0.613m. The length of the body is restricted by the height of the crane of the launch vehicle. The weight is 630kg. The weight was designed in order to obtain the terminal Mach number above 1.4 on the ground. Information such as 3-axis accelerations, velocities, positions, angular rates and the GPS time are transmitted to the ground by onboard telemetry system. On the other hand, NWM (**N**-**W**ave **M**odel) which generates a conventional N-type sonic boom signature is designed for the comparison with LBM. The configuration is a cone-cylinder-cone with four fins. The length is 5.6m. The cone-cylinder with four fins is the same as that of LBM. The sonic boom intensity of LBM is designed to be half of NWM. The weight is set to be 700kg in order to make its Mach number profile during the free-fall same as that of LBM. As the aerodynamic drag of NWM is larger than that of LBM, the weight of NWM should be larger. The photo of assembling an actual NWM is shown in Fig.3.

Fig. 3 Assembling of NWM

2.2 Boom Measurement System (BMS)

It is known that sonic boom signatures are often distorted by turbulence in atmospheric boundary layer whose thickness is considered to be about 1km. In order to reduce the influence on the measured sonic boom signature from the turbulence, a tethered blimp which can stay at an altitude of 1km is utilized. Seven low-frequency microphones with a standalone recording system are used for a sonic boom measurement system (BMS). The measurement system is designed so as to have the lower cut-off frequency of 0.2 Hz or lower. Four microphones are installed along the tethered line of the blimp; two at an altitude of 1000m, one each at 750m and 500m. In this case, each altitude means the distance from the ground along the tethered line. Each of three microphones is put on an aluminum plate with 1m sides and located on the ground 3m-5m apart.

In this recording system, the GPS time is used for time synchronization between the test bodies and the BMS. The configuration of a set of BMS is illustrated in Fig.4. The BMS is remotely monitored and controlled via Wi-Fi or satellite phone (back up) from the control center near the launch site. However the signatures are not sent to the control center, because the amount of data is very large.

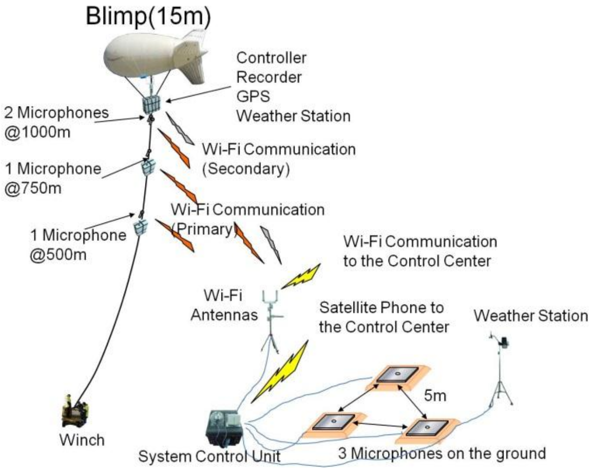

Fig. 4 Boom Measurement System

2.3 Fighter Flight Tests for Prototype BMS

The function tests of a prototype system for measuring sonic-booms above the ground named ABBA (**A**irborne **B**limp **B**oom **A**cquisition) system were conducted at Vidsel test range in Sweden before the D-SEND#1 flight campaign. The prototype system is composed of a blimp, a microphone at an altitude of 1000m, recording and Wi-Fi system. In order to generate N-type sonic boom signatures, Swedish Gripen fighter was used. The flight tests were conducted three times; in 2009[3], 2010[5] and 2011. Through the flight tests, the function of the prototype and the blimp operation procedures were verified. Figure.5 shows the demonstration flight over the ABBA system.

Fig. 5 ABBA Flight Test (Demonstration Flight)

2.4 Drop Zone and BMS Layout

Zone-B at Esrange was selected for the D-SEND project. This area is usually used as the impact area of sounding rockets. The size is roughly 70km wide and 100km long. Figure.6 shows the image of Zone B and the layout of BMSs.

Since the balloon trajectory is significantly dominated by wind directions up to an altitude of 30km and it is very hard to control the balloon trajectory toward a target BMS, the method of sonic boom measurement should correspond to various trajectories in Zone B. But single BMS site has a certain measureable area of sonic booms, because the sonic boom propagates toward a specific direction. In the D-SEND#1, four locations of BMSs are selected to cover the possible trajectories in Zone B as shown in Fig.6. The red solid circles are BMS locations. The red shaded circle is the measureable area. It has a radius of 10km. If the test body is dropped outside of these circles, BMS never hear the sonic boom.

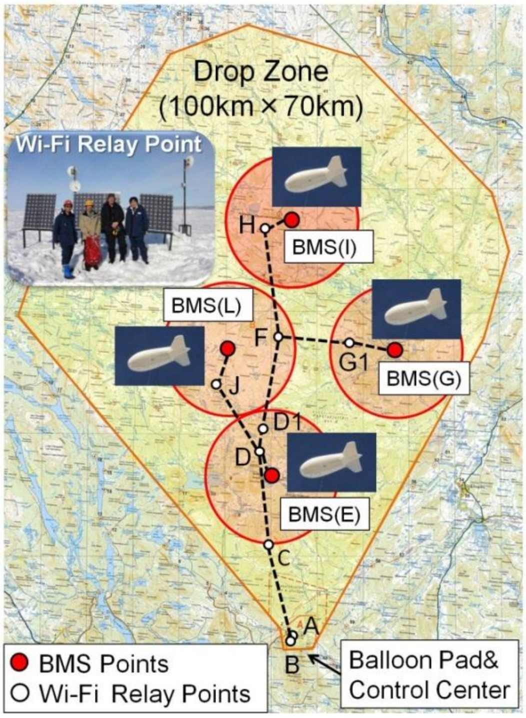

Fig. 6 BMS Layout in Zone B

Since Zone B is very dangerous area during the test, all personnel should evacuate from Zone B. As a result, a remote control system of BMSs operated in the main building near the launch site is required. Thirteen Wi-Fi relay points (Wi-Fi antenna, control system, solar panel and batteries) are set up in Zone B. The Wi-Fi network is also illustrated in Fig.6.

2.5 Balloon System

The balloon system is composed of a large stratospheric balloon, a parachute, some ballast, onboard electronics, a gondola and others. NWM and LBM are connected into the gondola body by a separation mechanism using the pyrotechnical wire cutters. The installation of the test bodies and a whole picture of the balloon system are shown in Fig.7. In a nominal test sequence, LBM is released first from the gondola, and then NWM is released at 10 seconds interval. In order to reduce the disturbances of the reaction of LBM release, LBM is connected on the gravity center line of the whole balloon system. Balance weight is installed at the opposite side of NWM. When the balloon is launched, the gondola with the test bodies is hung to a balloon launch vehicle. The launch vehicle is a very big crane whose arm height is 12m. It can move and align the gondola release direction to the wind direction in the launch site.

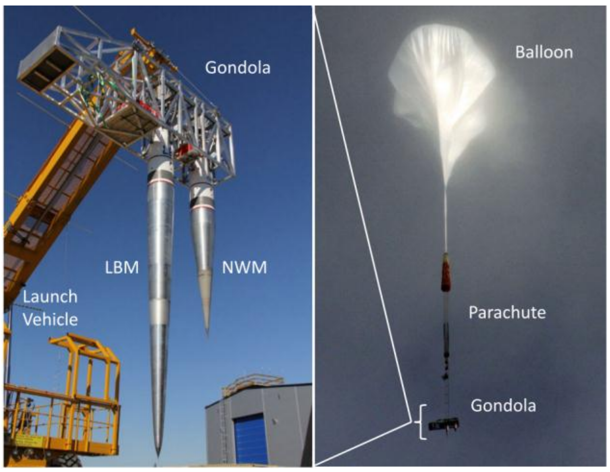

Fig. 7 Balloon System

2.6 Drop Test Results of D-SEND#1

The D-SEND#1 drop tests were conducted twice on May 7th and 16th of 2011. In the both drop tests, the BMSs functioned well as planned.

The N-type and shaped sonic boom signatures were successfully obtained at high resolution on the ground and along the tether line. The photo of the launch preparation is shown in Fig.8.

Fig. 8 Balloon Launch Preparation

2.6.1 First Drop Test

The balloon trajectory is shown in Fig.9. The balloon launch site is located in the middle of the bottom part. The balloon operation center and BMS operation center are located in the main building in this area. The balloon was released from the launch site. The black solid line which moves northward is the planned trajectory of the balloon and the pink is the actual trajectory. The balloon trajectory can be slightly controlled by changing the ascend velocity. The ascend speed becomes faster by dropping the ballast and becomes slower by venting helium gas.

Eventually the balloon successfully entered into BMS(G) circle(r=10km) and LBM was released at an altitude of about 21km and passed through an area with a horizontal distance of about 6km from the BMS(G). Then NWM followed in 10 seconds. The BMS(G) captured sonic booms of LBM and NWM at all altitudes; on the ground, 500m, 750m and 1000m. Each microphones measured four sonic booms; a weak sonic boom at a high altitude, a target sonic boom at a low altitude and two sonic booms caused by each ground reflections (Fig.10). It is interesting that the target sonic boom came first and followed by the high altitude sonic boom. The total number of recorded sonic booms is 34 (22 aerial and 12 ground). The velocity profile with respect to the altitude of LBM is shown in Fig.11. The open circle indicates the generation point of the high altitude sonic boom. The estimated Mach number is 1.06 and the altitude is 15.392km. The solid circle indicates the generation point of the target sonic boom. The estimated Mach number is 1.42 and the altitude is 6.015km. The test conditions are listed in Table.1.

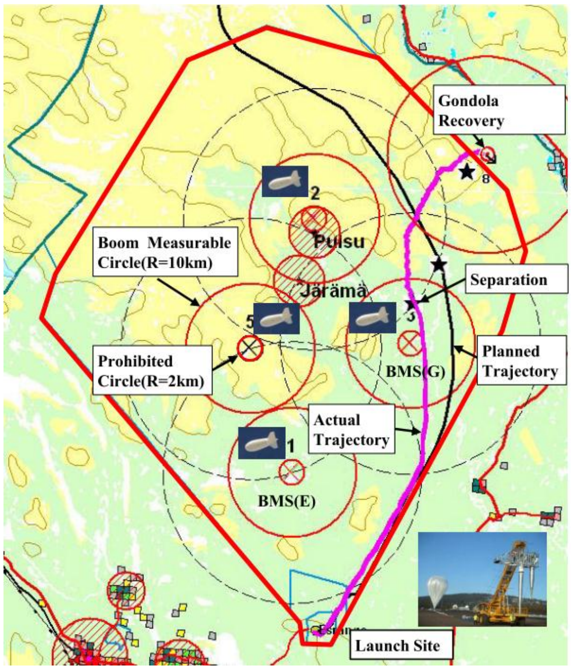

Fig.9 Balloon Trajectory of No.1

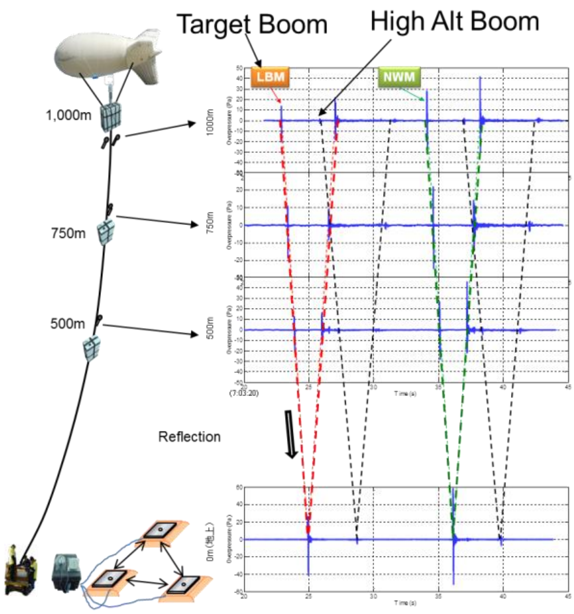

Fig.10 Measured Sonic Booms of No.1

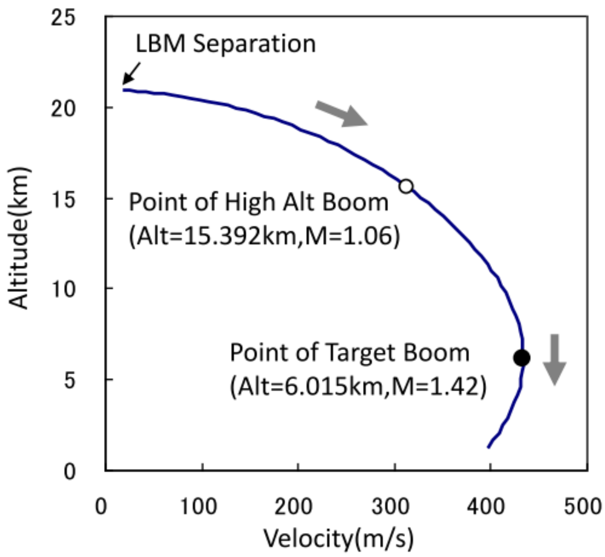

Fig.11 Velocity Profile of LBM

Table.1 Test Condition of No.1

		1st Test	
Balloon Release Time (UTC)		3:44 a.m. on May 7, 2011	
Test Body		LBM	NWM
Electrical Equipment		Mounted	Not Mounted
Separation Altitude		20.874km	20.937km
Maximum Mach Number		1.44	1.45
Condition of Measured Sonic Boom	Altitude	6.015km	6.039km
	Mach Number	1.42	1.43
The Altitude of a Microphone 500m Above the Ground		0.928km	

Note: All altitude is WGS84 ellipsoidal altitude.

The typical sonic boom signature of NWM and LBM compared with the CFD analysis are shown in Fig.12. The sharp N-type of sonic boom signature of NWM was clearly measured. Meanwhile, the shaped sonic boom signature of LBM became half compared with that of NWM as designed. Moreover it is confirmed that the CFD analysis of both bodies by JAXA's design tools agree with the measured data very well.

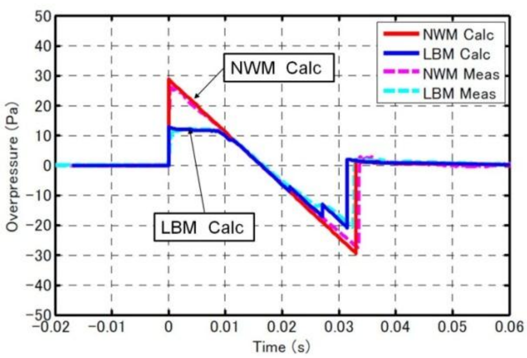

Fig. 12 Sonic Booms at Alt=500m of No.1

2.6.2 Second Drop Test

The second drop test was also successfully conducted and 96 sonic booms (40 aerial, 44 ground and 12 indoor) were captured at BMS(E). NWM was released first and followed by LBM with 60seconds interval due to separation command trouble. Fortunately the flight conditions were not so different each other (Table.2). The separation altitude is about 27km, and the Mach number of the target sonic boom is about 1.6. All the sonic boom data of the first and second drops are reported in ref. [6].

Table.2 Test Condition of No.2

		2nd Test	
Balloon Release Time (UTC)		3:30 a.m. on May 16, 2011	
Test Body		NWM	LBM
Electrical Equipment		Mounted	Mounted
Separation Altitude		26.621km	27.398km
Maximum Mach Number		1.73	1.70
Condition of Measured Sonic Boom	Altitude	4.652km	4.552km
	Mach Number	1.58	1.59
The Altitude of a Microphone 500m Above the Ground		1.033km	

Note: All altitude is WGS84 ellipsoidal altitude.

3 D-SEND#2 Drop Test

3.1 Test Sequence

The test sequence of D-SEND#2 drop test is almost the same as D-SEND#1 (Fig.1). The test body named S3CM which is a new unmanned experimental supersonic airplane is lifted by the balloon up to an altitude of 30km. After the balloon reaches the ceiling, S3CM is separated from the balloon in a proper torus-shape area. If S3CM is released within the torus-shaped area, it can fly over a target BMS under mission required flight conditions. The outer radius of the torus is determined by how far S3CM can fly and the inner radius is by how S3CM can dissipate its energy to fly over the target BMS.

Figure.13 shows the layout of the BMSs and the torus-shape area. Since S3CM can glide a long distance, Zone B can be covered mostly by only two torus-shaped areas. In addition to the two torus-shaped areas, separation limit line (dashed line) is set in 8km inside from Zone B boundary for the flight safety. If the SCM released within the separation line, S3CM does not fly outside Zone B with a termination mode. As a result, the red shaded area called "separation zone" is the allowable area for separation. The actual operation is more complicated. The torus radius changes with respect to the separation altitude. The separation zone should be considered and set to be in three dimensions.

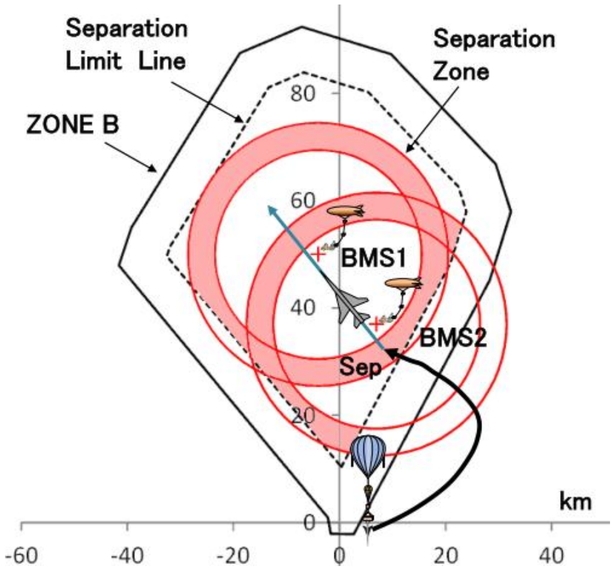

Fig.13 BMS Layout and Torus-shape Area

After S3CM reaches the speed in which flight control by aerodynamic force is possible, it pulls out the position and glides towards the one of BMSs. S3CM goes flying right above the target BMS (an altitude of about 8km) at Mach number 1.3, a flight-path angle of about 50 degrees and a lift coefficient C_L=0.12. Sonic boom propagates from S3CM toward exactly right under with this condition. S3CM goes into autonomous termination mode (spinning motion) after flying over the BMS, and crash onto the ground in Zone B. It is not reusable.

3.2 S3CM

S3CM is newly designed for D-SEND#2 drop test. JAXA's original low sonic boom design concepts such as a non-axisymmetrical nose, a low-drag/low-boom wing shape, and lifting aft-fuselage, are applied to the airplane design utilizing a CFD-based multi-objective optimization technique.

There were two restrictions when the dimension of S3CM is designed due to utilizing the balloon test technique. The total length of the body should be below 8m and the weight should be below 1500kg. Therefore, the S3CM is set to be 16% scale of the JAXA's small supersonic transport as a technical reference airplane[2]. The design condition are (1) Mach number is 1.3, (2) gliding altitude is 8km and (3) C_L=0.12(wing area is 5m^2). The three views drawing of S3CM is shown in Fig.14 and the three dimensional configuration is shown in Fig.15. The weight is 1000kg, the total length is 7.913m and the wing area is 4.891m^2. The designed sonic boom signature is shown in Fig.16 comparing with a reference of N-Type signature. The sonic boom intensity of S3CM is designed almost as half as the reference signature.

The design of S3CM has already finished. Two S3CM are now in production. Final integration test will be finished at the end of May, 2013. The flight campaign is scheduled to be conducted in the summer of 2013.

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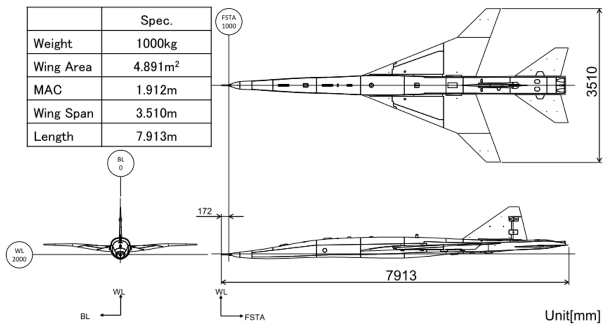

Fig.14 Three View Drawing of S3CM

Fig.15 Three Dimensional Configuration

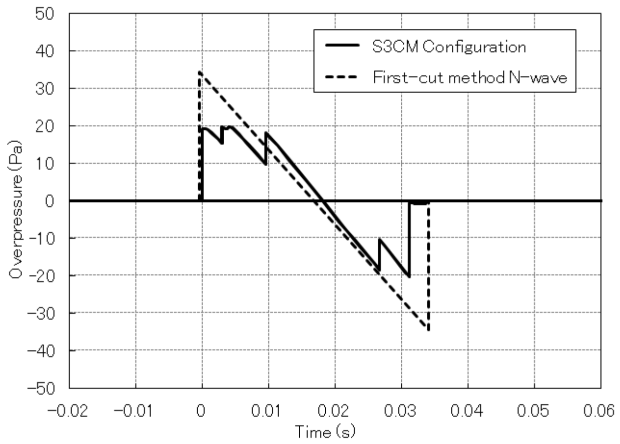

Fig.16 Shaped Sonic Boom Signature of S3CM

4 D-SEND Database

The D-SEND database[7] is a database of the sonic boom signatures obtained from the D-SEND project, such as ABBA Test, D-SEND#1 and D-SEND#2. The aim of the database is to improve the sonic boom prediction tool and low sonic boom design methodology through utilization by Japanese and international sonic boom researchers. The database is composed of the model configuration data, flight trajectories, weather data, and measured sonic boom signatures. At the present, ABBA data and D-SEND#1 data have already been uploaded on the Internet (Fig.17). The D-SEND#2 flight test data is scheduled to be published in 2013.

Fig.17 D-SEND Database Homepage

5 Conclusion

A new sonic boom measurement technology by a stratospheric balloon and an aerial sonic boom measurement system are described. The measured sonic boom data in D-SEND#1 drop test are also presented. Through D-SEND#1 drop test results and experience, the feasibility of measuring a low shaped sonic boom is confirmed and the test procedures are confirmed. Furthermore JAXA's design tools are validated. Now JAXA is manufacturing S3CM and preparing to conduct the D-SEND#2 drop test in the summer of 2013 at Esrange.

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