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ISAS Balloon-Drop Microgravity Experiment System

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Abstract

Scientific balloon flights can provide excellent opportunities for microgravity experiments. A balloon-drop microgravity experiment system, which is aiming for the experiment duration longer than 30 sec, is currently under development in ISAS/JAXA. The first flight of the microgravity experiment system was successfully performed in spring 2006. In this paper, the system configuration and the operation sequence of this system are reviewed. In addition to that, preliminary feasibility of a tethered balloon system for simplified short-term microgravity experiments is also studied. By using the tethered balloon, in exchange for the relatively short experiment duration, the operation cost for an experiment becomes drastically lower than that of a normal scientific balloon flight. The experiment system by using the scientific balloon is very promising for the microgravity experiments in terms of the reasonable cost and the experiment duration.

1. Introduction

The Balloon Project Team[1] of the Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency (ISAS/JAXA) has developed balloon technologies and onboard scientific instruments since 1950's. These scientific balloons, which are made of polyethylene thin-film (≤ 20 μm) and are filled with helium gas, can carry large (≥ 5 m on a side) and heavy (≥ 500 kg) payloads up to an altitude above 40 km The operation cost for an experiment or an observation by the scientific balloon is lower than that of a rocket by one or more orders of magnitudes. Furthermore, the balloon payload containing important scientific data can be recovered without serious damages, and then onboard equipments are reusable with significant upgrades. The scientific balloon is composed of flexible system configurations, so that the development for the balloon experiment system can be of short duration, and the latest knowledge achieved in the experiments can be then reflected to the project progress in short cycle. The scientific balloon can be thus used also as testbed for in-space experiments or observations. Because of the above advantages, balloon flights have been yielded great benefits mainly towards scientific observations of space and stratospheric atmosphere, and also towards experiments for aerospace technology demonstrations. **Figure 1** shows a scientific balloon of launching at Sanriku Balloon Center (SBC).

The scientific balloon flights can also provide excellent opportunities for microgravity experiments on various scientific and technological areas (e.g. Biomedical Science, Material Science, Combustion Science, Fluid Dynamics). Several microgravity experiment systems by balloon-drops have been developed since 1981[2] and an improved system aiming for microgravity down to 10^{-4} G is currently under development in ISAS/JAXA. The first flight of the microgravity experiment system was successfully performed at SBC in spring 2006.

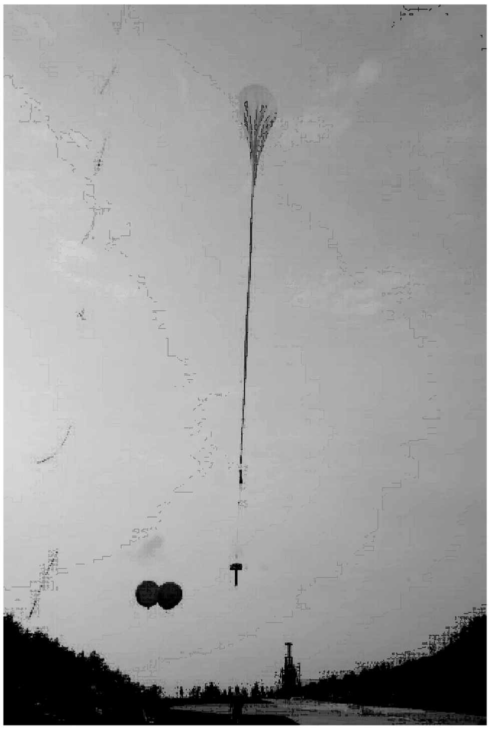

Fig.1 Scientific Balloon of Launching

2. Microgravity Experiment System under Development

There seems to be two prominent types of microgravity experiment systems, those are, low cost and short duration system (e.g. drop tower, parabolic flight by aircraft) and high cost and long duration system (e.g. Space Shuttle, International Space Station (ISS)). The Balloon-based Operation Vehicle (BOV)[3] proposed by ISAS/JAXA is pursuing to develop a microgravity experiment system of moderate cost (< $1000 /sec) and medium duration (> 30 sec). In the balloon-drop experiment, a payload module would not experience excess acceleration, vibration or acoustic condition before the microgravity experiment begins. In some cases, that is a potential advantage of the balloon-drop experiment compared to that by using a rocket or an aircraft. **Figure 2** shows the operation sequence of the balloon-drop microgravity experiment system of ISAS/JAXA.

2.1 System configuration

Figure 3 and **4** show the appearance and the system configuration of BOV#1, respectively. The gondola shown in Fig. 3 contains the House Keeping (HK) system for the balloon flight operation. The size of the BOV#1 is 4 m in length and 0.5 m in diameter. The aeroshell is made of CFRP for weight reduction. The total weight of the vehicle including a microgravity experiment unit is about 210 kg. The spherical microgravity experiment unit of 300 mm diameter is located in the cylindrical airtight vessel at the center of the vehicle as shown in Fig. 4. **Figure 5** shows the microgravity experiment unit. The microgravity experiment unit is absolutely isolated from the main body of the BOV, except for wireless communications with devices on the main body. The three-dimensional position of the microgravity experiment unit is measured by four laser displacement sensors installed at the main body. When the microgravity experiment starts by the separation of the vehicle from the balloon HK gondola, the vehicle attitude is automatically controlled by twelve cold gas jet thrusters and four movable wings to maintain the clearance between the cylindrical vessel and the free-falling experiment unit. However, the BOV#1 is not equipped with the wings, since the expected free-falling experiment in the first flight is short duration, so that the microgravity experiment is terminated before the aerodynamic force significantly affects the vehicle attitude. In the future plan, in order to extend the experiment duration, the BOV will be equipped with a solid motor or an air-breathing engine to cancel the aerodynamic drag force which counteracts the constant acceleration of the vehicle.

2.2 Onboard system

The onboard electronic equipments except for the microgravity experiment unit are installed in another airtight vessel as shown in Fig. 4. All the various technical data, microgravity experiment data and moving image data are saved in each data storage on the vehicle. Some of the data are sent to the ground station via telemetry downlink and can be monitored in real time.

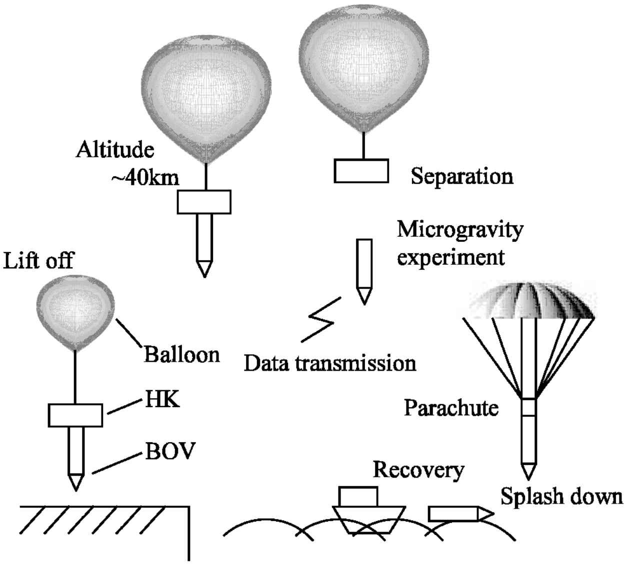

Fig.2 Operation Sequence of Balloon-Drop Microgravity Experiment System

Fig.3 Balloon-based Operation Vehicle (BOV) w/ Balloon HK Gondola

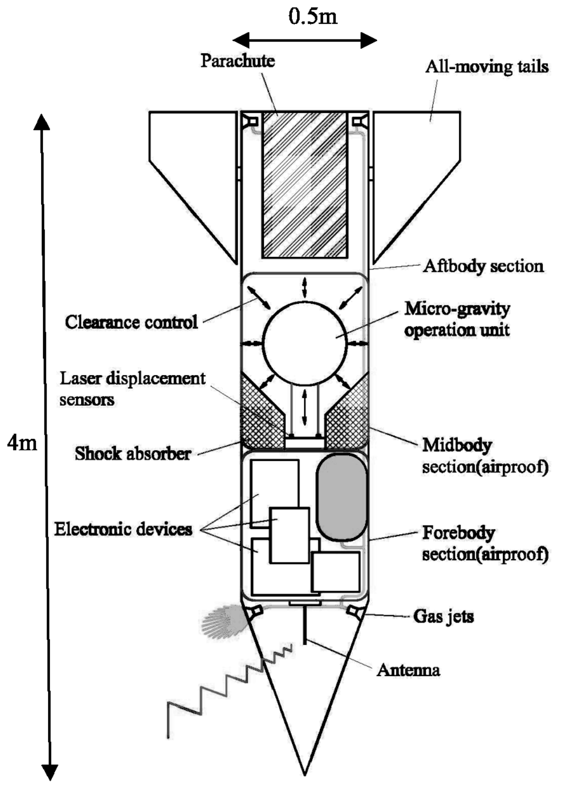

Fig.4 System Configuration of BOV

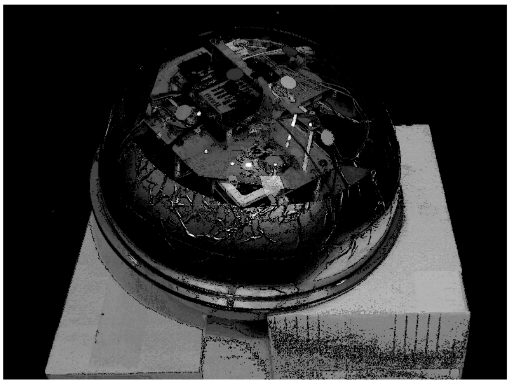

Fig.5 Microgravity Experiment Unit

2.3 Operation sequence

The main objective of the first flight was performance verification of all the operating systems.

By using a balloon of 200,000 m^3 in volume, BOV#1 was launched at SBC on May 27, 2006. About 3 hours later, BOV#1 was separated from the balloon HK gondola at an expected altitude of about 40 km on the Pacific Ocean 50 km off the coast. After 23 sec from the separation, the parachute was successfully deployed according to the automated sequence, and then the vehicle was recovered without unexpected damages. All the experiment data were successfully obtained. The gravity acceleration of the microgravity experiment unit, while the BOV was dropping under control, was on the order of 10^{-3} G. The main objective of the first flight was accomplished. The obtained data are now being analyzed in detail. In two years to come, three flight tests aimed for longer experiment duration are planned in the development project of the balloon-drop microgravity experiment system in ISAS/JAXA.

3. Tethered Balloon System for Simplified Short-Term Microgravity Experiment

In addition to the project of the BOV, preliminary feasibility of a simplified short-term microgravity experiment system by using a tethered balloon is also studied.

The conceptual diagram of the experiment system is shown in **Fig. 6**. The system is composed of a balloon tethered to a winch on the ground. The altitude of the balloon would be a few km due to technical difficulties of the tethered balloon flight operation. The microgravity experiment duration would therefore be shorter than that of the BOV. By using the tethered balloon system, however, the operation cost for the experiment becomes drastically lower than that of the normal scientific balloon flight. Because the one reusable tethered balloon can be launched several times in a day.

3.1 Microgravity experiment condition and balloon altitude

The required microgravity experiment conditions are assumed that the experiment duration is about 10 sec and the vehicle including a microgravity experiment unit is 100 kg in mass and 0.5 m in diameter.

The altitude of the tethered balloon for balloon-drop experiments has to be lower than that of the jet stream for simplicity of the balloon flight operation. Additionally, that has to be sufficiently high to accelerate the vehicle by reasonable mass flow of gas jet thrusters and to deploy a parachute in safety after the microgravity experiment ended.

Figure 7 and **8** show a simulated trajectory profile of the microgravity experiment vehicle dropped from altitude of 5 km. From the drop to x+10 sec, the vehicle is assumed to be constantly accelerated by gravity with help of the gas jet thrusters to cancel the aerodynamic drag force. At x+10 sec, the vehicle altitude and velocity is rightly 4.5 km and 98 m/s, respectively. After the microgravity phase of 10 sec, the vehicle is decelerated by the aerodynamic drag force without help of the acceleration equipment. The drag coefficient of the vehicle is set to be C_D=0.3 based on the results of the wind tunnel test and the numerical simulation of the BOV#1.

Figure 9 shows the peak aerodynamic drag force during the microgravity experiment and the time for the parachute deployment, on various drop altitudes under the same condition as Fig. 7 and Fig. 8. In the case of the drop altitude of 5 km, it is reasonable that the required maximum thrust to counteract the aerodynamic drag is about 220 N. The necessary total mass flow of the gas jet thrusters is thus about 2 kg for the microgravity experiment of 10 sec. In addition, from the end of the microgravity experiment to the landing, sufficient time of about 30 sec is ensured for the parachute deployment as also shown in Fig. 8.

From the above considerations, the tethered balloon altitude for the balloon-drop microgravity experiment is set to be 5 km.

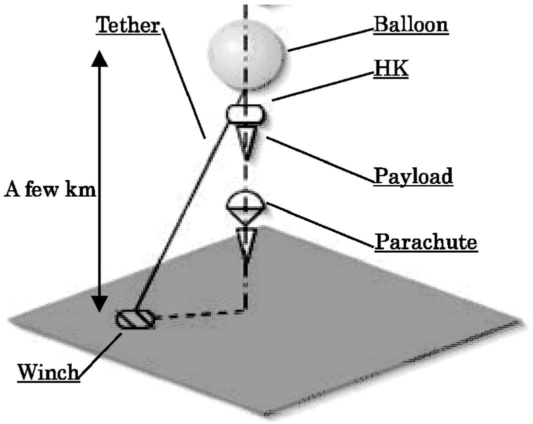

Fig.6 Conceptual Diagram of Tethered Balloon System for Microgravity Experiment

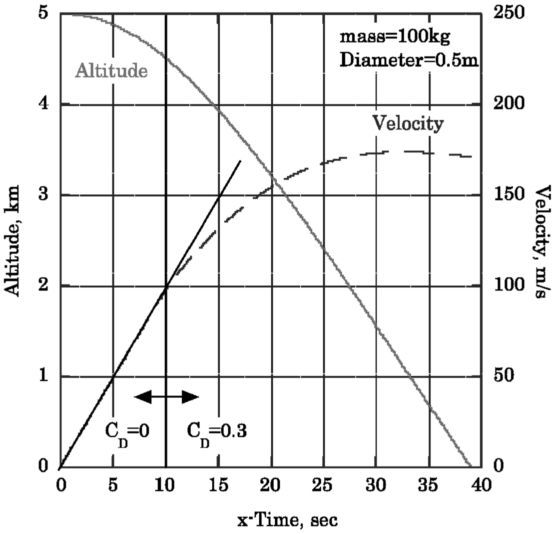

Fig.7 Altitude and Velocity Profile of Microgravity Experiment Vehicle

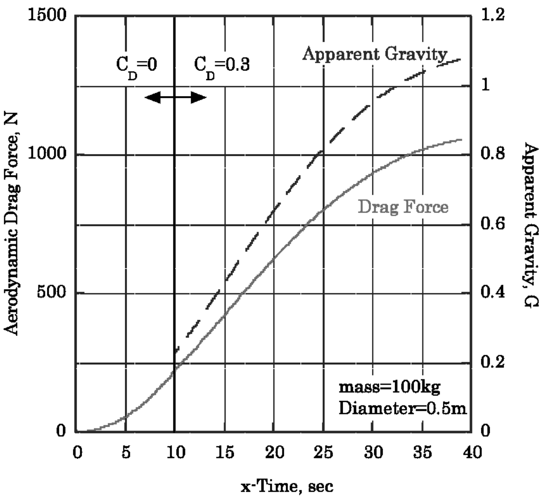

Fig.8 Aerodynamic Drag Force and Apparent Gravity Profile on Microgravity Experiment Vehicle

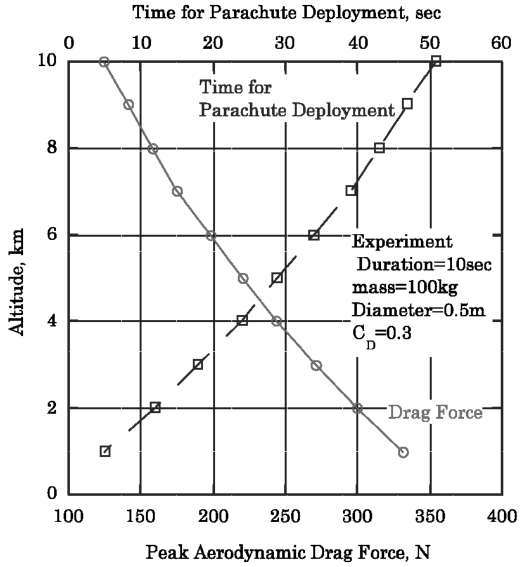

Fig.9 Peak Aerodynamic Drag Force During Microgravity Experiment and Time for Parachute Deployment on Various Drop Altitudes

3.2 Tethered balloon system configuration

Table 1 shows the mass budget of the tethered balloon system.

The mass of the payload and HK system is 100 kg and 50 kg, respectively. The tether under consideration is made of Dyneema®4, which is one of the strongest specific strength tethers at the state-of-the-art. The tether is 6mm in diameter, 21.0 g/m in line density and 1500 kgf in tensile strength. The mass of the tether of 5km is thus 105 kg. The material of the balloon is laminated film of polyethylene and EVAL®5. The area density of the balloon material is assumed to be 100 g/m^2. The balloon is spherically shaped and is constant total volume with a ballonet (a internal variable volume airbag). The ballonet maintains the pressure difference constant as the balloon ascends and the inner He gas expands.

The volume of the tethered balloon has to be determined by required free lift, not to be significantly affected by a crosswind. The total buoyant force F_B of a balloon is given by:

$$F_B = (\rho_{Air} - \rho_{He})gV, \tag{1}$$

where ρ, V is mass density and volume of the balloon, respectively, at a given altitude. g is the gravitational acceleration constant. The free lift of a balloon is difference between the total buoyant force F_B and the total system mass m_{total}. The aerodynamic drag force F_A acting on a balloon is written by:

$$F_A = \frac{1}{2}\rho_{Air} v^2 C_D S, \tag{2}$$

where v is relative velocity of the crosswind with respect to the ground velocity of the balloon. C_D is the drag coefficient assumed to be constant of 0.3 in this case, according to corresponding Reynolds number for a sphere. S is the projected area of the balloon. By considering the balance of the forces, the ideal tether slope θ, when the total system mass is assumed to be a point mass at the balloon position, is written by:

$$tan\theta = \frac{F_B - m_{total}}{F_A}. \tag{3}$$

The ideal horizontal distance D_B from the position of the winch to that of the balloon swept away downwind is therefore given by:

$$D_B = L_{t0}\cos\theta, \tag{4}$$

where L_{t0} is the length of the tether. **Figure 10** shows the variation of the distance D_B and the free lift with respect to the radius of the balloon. The crosswind velocity is assumed to be constant of 5 m/s in Fig. 10. The length and cross section diameter of the tether are also assumed to be constant of 5 km and 6 mm, respectively. The radius of the balloon, that the total buoyant force is balanced with the total system mass, is about 4.5 m. As can be seen in Fig. 10, the most effective radius of the balloon exists for the horizontal balloon swept away distance D_B. In this result, that is the case of the balloon radius of about 6 m. Additionally, in the case of the balloon radius of 6 m, the maximum tensile force acting on the tether, which is summation of the tether weight and the free lift, is about 380 kg. Therefore, the safety factor of about 4 is ensured for the tether strength.

Based on the above considerations, the radius of the tethered balloon is set to be 6 m.

Table 1 Mass Budget of Tethered Balloon System for Microgravity Experiment

Payload	
Diameter	0.5 m
Mass	100 kg
HK System	
Mass	50 kg
Balloon	
Radius	6 m
Volume	905 m^3
Mass	45 kg
Tether	
Length	5000 m
Cross Section Diameter	6 mm
Tensile Strength	1500 kgf
Safety Factor	4
Mass	105 kg
Total System Mass	300 kg
Free Lift	275 kg (92 % of m_{total})
Total Buoyant Force	575 kg

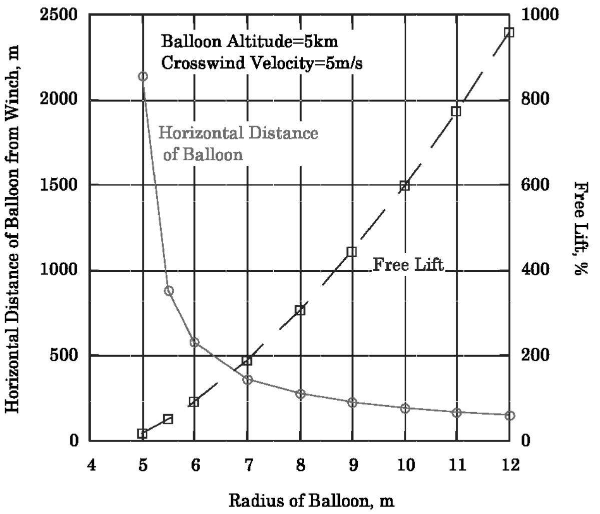

Fig.10 Balloon Radius vs. Balloon Swept away Distance and Free Lift

3.3 Tethered balloon simulation

In order to investigate the effects of actual distributed tether weight and the aerodynamic force acting on the tether, the static tether behavior is numerically simulated.

The tether is modeled by a number of tether nodes (point masses) connected by tether segments (linear-elastic mass-less springs) as shown in **Fig. 11.** m_B is the mass of summation of the balloon, payload and HK system. m_T is the mass of a tether node. F_D and F_L are the aerodynamic forces acting on a tether node. The aerodynamic force perpendicular to the tangent of a tether segment is given by Eq. (2). In this case, C_D in Eq. (2) is assumed to be constant of unity, according to corresponding Reynolds number for a cylinder. The direction of F_D is that of the wind. F_L is in direction perpendicular to F_D. In this simulation, the wind has only horizontal component. T is tensile force of the tether on respective tether segments written by:

$$T = S_T E\varepsilon, \tag{5}$$

where S_T and ε are cross section area and strain of a tether segment, respectively. E is Young's modulus assumed to be 30 GPa based on the tether specification. Poisson's ratio is set to be 0.35.

The tether motion is simulated by numerically integrating the motion equation of respective tether nodes. The motion equation of a tether node is given by:

$$\begin{aligned} m_T\frac{\mathrm{d}^2x_T}{\mathrm{d}t^2} &= T_x^{j+1} - T_x^j + F_D - C\frac{\mathrm{d}x_T}{\mathrm{d}t} \\ m_T\frac{\mathrm{d}^2z_T}{\mathrm{d}t^2} &= T_z^{j+1} - T_z^j - F_L - m_T g - C\frac{\mathrm{d}z_T}{\mathrm{d}t} \end{aligned} \tag{6}$$

The definition of the coordinate system is shown in Fig. 11. In this case, we focus only on the steady solution so that the viscosity term is added in Eq. (6) in order to stabilize the calculation and to obtain a good convergence in small number of time stepping. Similarly to the Eq. (6), the motion equation of the balloon is also given by:

$$m_B\frac{\mathrm{d}^2x_B}{\mathrm{d}t^2}=F_A-T_x-C\frac{\mathrm{d}x_B}{\mathrm{d}t}$$
$$m_B\frac{\mathrm{d}^2z_B}{\mathrm{d}t^2}=F_B-T_z-m_Bg-C\frac{\mathrm{d}z_B}{\mathrm{d}t}\quad .\qquad (7)$$

The other numerical conditions are set according to the previous section.

Figure 12 shows the simulated static tether behavior. The contour on the tether indicates the tensile force on the respective tether segments. The maximum tensile force is about 3766 N at the connecting point with the balloon. The strained tether length is about 5019 m. The elevation angle of the tethered balloon is about 81 deg. The result is in good agreement with the simplified calculation in the previous section. However, the computed horizontal distance of the balloon from the winch is longer than the distance of 576 m calculated in the previous section. The computed distance is about 782 m. Because the slight difference in the elevation angle makes the relatively large difference in the horizontal distance when the elevation angle is large. However, it should be noted that the total aerodynamic force acting on the tether is comparable with that acting on the balloon. Whereas the aerodynamic force has effects to decrease the balloon elevation angle, the distributed tether weight yields increase of the angle. In the case of longer tether, the effects of the aerodynamic force and the distributed tether weight would be relatively increased. Therefore, the numerical simulation is necessary especially for a long-tethered balloon.

If a sufficiently large experiment area will be utilized for safety in light wind, the tethered balloon system would be feasible for microgravity experiments of which is about 10sec duration and 100 kg payload.

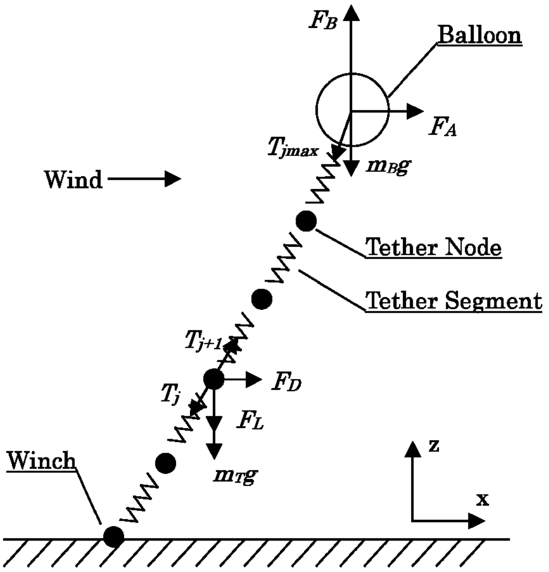

Fig.11 Simulation Model of Tethered Balloon

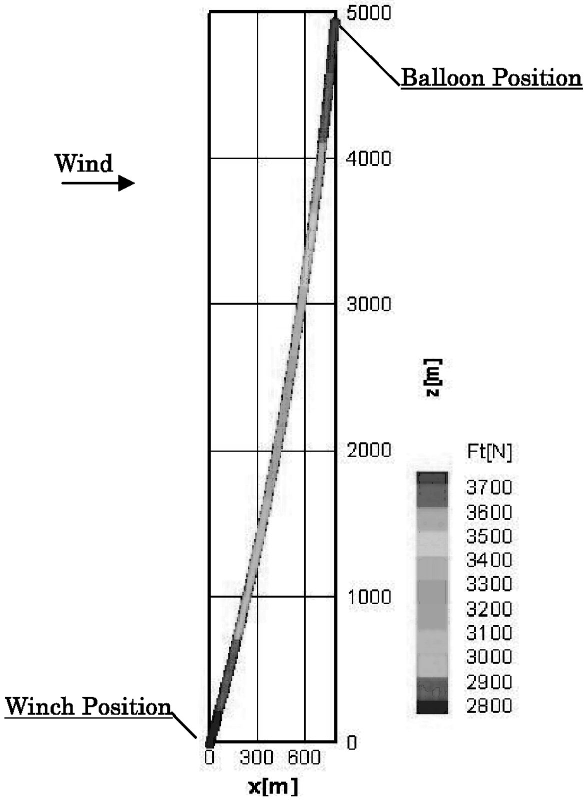

Fig.12 Simulated Static Tether Behavior

4. Summary

The microgravity experiment systems currently under development and under study in ISAS/JAXA are briefly introduced. The experiment system by using the scientific balloon is very promising for the microgravity experiments in terms of the reasonable cost and the experiment duration.

Acknowledgement

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