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AUTOMATIC BALLAST CONTROL REFERRING TO THE INNER PRESSURE AT THE NADIR OF THE BALLOON

Yoshitaka SAITO[1], Takamasa YAMAGAMI[1] and Jun NISHIMURA[2]

[1] *Institute of Space and Astronautical Science, Sagamihara 229-8510*
[2] *Yamagata Academy of Engineering, Yamagata 993-0021*

Abstract : For long duration balloon flights, when the balloon is outside the tele-command range, it is necessary to control the altitude automatically since the temperature of the lifting gas decreases at sunset. Here, we propose a new method referring to the inner pressure at the nadir of a balloon. The inner pressure is approximately proportional to the amount of descent from the level altitude and to the atmospheric pressure at the level altitude. This method has advantages in its simplicity and does not require prior information of the level altitude.

1. Introduction

Scientific balloons are vehicles to bring payloads up to an altitude of 30-50 km. In comparison with the case of sounding rockets, balloons have capability to lift heavier payloads with less expense ensuring longer observation duration, while the altitude is limited. In addition to these advantages, it also has a merit that balloons flow with the surrounding atmosphere which is useful in performing Lagrange type observations of the atmosphere.

Balloon observations over the polar region started in 1984 with a collaboration of the Institute of Space and Astronautical Science (ISAS) and the National Institute of Polar Research (NIPR). After some test flights, seven experiments using balloons were carried out from the Syowa Station in Antarctica. In 1998, a payload for the cryogenic air sampling was launched and fruitful results were obtained. This air sampling flight included the payload recovery for the first time. It was also the first trial to perform real-time monitoring linking the Syowa Station and NIPR in Tokyo with the international network.

Balloon flight in the polar region is also attractive from technological point of view, since it is able to realize long duration flights in summer season. It is necessary to drop some ballast to maintain the level altitude from which the balloon tends to deviate due to day and night temperature excursion. However, during the summer in the polar region, the sun almost always remain above the horizon and the ballast consumption is smaller than the flight in the medium latitude to enable a long flight duration.

For the long duration flights it is necessary to find a reliable method for automatic ballast control system. It is a rather easy operation to control the altitude of the balloon, while the balloon floats within the tele-command range. However, in the cases like the balloon flights in the Antarctica (the polar patrol balloon) and the long distance balloon flights from Kamchatka to Ural in Russia, balloons are often outside the tele-command range and ballast should be dropped automatically. In this paper, after reviewing the methods used for the past altitude control, we propose a new possible method referring to the inner pressure at the nadir of the balloon.

2. Vertical Motion of the Balloon

Before reviewing the ballast control methods, we summarize the relation between the temperature and the vertical motion of a balloon. Generally, the atmospheric pressure at the level altitude P is determined by the balance between the lift and the total weight W using the gas equation.

$$P=783\left(\frac{T}{230\,\mathrm{K}}\right)^{-1}\left(\frac{W}{1\,\mathrm{kg}}\right)\left(\frac{V}{1\,\mathrm{m}^3}\right)^{-1}\ [\mathrm{hPa}]. \tag{1}$$

Here, T is the temperature of the atmosphere and 230 K is the typical value at an altitude of 30 km.

At night, since the balloon is not radiated by the sun, the lifting gas becomes cool resulting in contraction of the volume and lowering of the altitude. When the temperature decreases by ΔT, the decrease of the balloon volume ΔV is related by,

$$\frac{\Delta V}{V}=\frac{\Delta T}{T}. \tag{2}$$

Since the lift is proportional to the volume V, the balloon descends if the ballast is not dropped. In the case of medium latitude flights, we know $\Delta T/T$ is about 7–10%, it is necessary to drop the ballast by 7–10% of the total weight.

When considering the thermal environment of the balloon, it must not be forgotten that the movement of the balloon also contributes to the temperature of the lifting gas through the adiabatic processes in addition to the thermal inflow and outflow through radiation.

$$\frac{\Delta T}{T}=\frac{\gamma-1}{\gamma}\frac{\Delta P}{P}. \tag{3}$$

Here, γ is the ratio of the specific heat under constant volume and pressure, P and ΔP are the pressure and its difference, respectively. Heat flow from/to the balloon is mainly *via* radiation, and its time scale is approximately a few tenth of minutes. Since the adiabatic process is fast enough, it is also necessary to include this process when solving the heat condition of balloons.

3. Auto Level Control Methods

The altitude of a balloon is usually controlled by dropping ballast by command while it is within the tele-command range. To operate automatically, various methods have been applied. Before introducing our new method, we classify the past methods from referred signal and discuss their merits and demerits.

3.1. Referring to the atmospheric pressure

This method was used for the past polar balloon missions and the long distance flights in Russia. The level atmospheric pressure is set before launch and some amount of ballast is dropped if the measured atmospheric pressure at the balloon altitude sampled every few minutes is lower than the threshold level. This method is quite simple and reliable since only a single pressure sensor is necessary and the hardware to achieve the operation is easy to produce. However, this method has the following drawbacks,

· The precise prediction of the level altitude of a balloon is difficult due to uncertainty in the temperature of the surrounding atmosphere and the real volume of the balloon. It is necessary to set the threshold level to drop the ballast including some margin for safety and this increases the difference between the day and the night altitude.

· After dropping the ballast, the gross weight of the balloon is lighter than before, the day altitude is higher than that of the former day, while the night altitude does not go up with time due to a fixed threshold altitude for dropping the ballast. For most payloads, it is better for the night altitude to follow the increase of the day altitude, while it is not possible by the simple method.

One way to solve these problems is to set the level altitude on board and to drop the ballast if the difference between the level altitude and the current altitude becomes larger than the threshold level determined before launch. While the system becomes complex, ISAS balloon group is developing a device using this method to prepare for the future long duration flights.

3.2. Referring to the vertical motion

In this method, the ballast is dropped when the balloon moves to lower altitude with some descending velocity. In 1980's, ISAS balloon group developed a high-sensitive sensor to monitor the vertical motion and applied this method for the automatic altitude control system (NISHIMURA and HIROSAWA, 1981; FUJII *et al.*, 1983). The weight of the ballast to drop is determined by using the following equation based on an experimental relation for the ballast compensation.

$$\frac{\Delta W}{W} = 0.02\left(\frac{v}{1\ \mathrm{m/s}}\right) + 0.003\left(\frac{\Delta H}{1\mathrm{m}}\right). \tag{4}$$

Here, v is the velocity of vertical motion, and ΔH is the descent altitude from the level altitude obtained by integrating the velocity or being measured by the atmospheric pressure gauge. This system showed nice performance, while it has a demerit that the system requires a complicated hardware or a computer.

3.3. Referring to the temperature of the lifting gas

The decrease of the altitude is due to the cooling of the lifting gas. The altitude control is also achieved by monitoring the gas temperature and dropping the ballast in accordance with eq. (2). This method was used by the balloon group in USA showing nice performance. At a glance, it is expected to work well, while it has a disadvantage.

- As mentioned above, the temperature of the lifting gas is also affected by the vertical motion of the balloon through the adiabatic process. Without other sensors, it is difficult to drop suitable amount of the ballast.

4. New Method—Referring to the Inner Pressure of the Balloon

As the balloon volume decreases, the shape of the balloon is distorted from the shape of zero-pressure balloon as shown in Fig. 1. If there is a reliable sensor to find the distortion, it is also useful for the auto level control.

To detect this deformation, a sensitive pressure gauge can be used to measure the inner pressure (difference of the atmospheric pressure and that of the lifting gas) at the

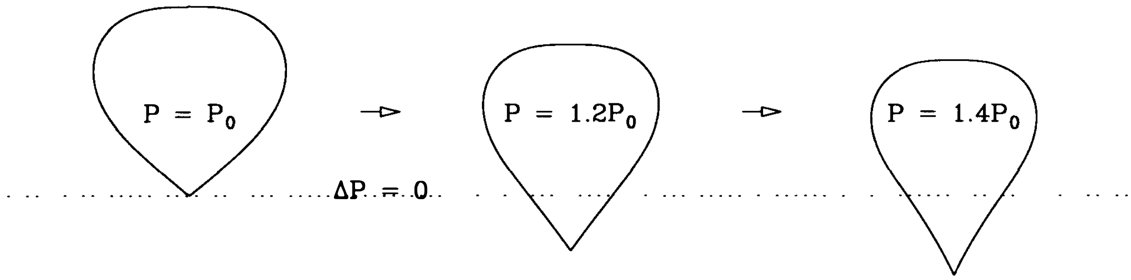

Fig. 1. The shapes of balloon at various altitudes. The dot line shows a height where the inner pressure $\Delta P=0$. The unit of the pressure P is that of the level altitude P_0.

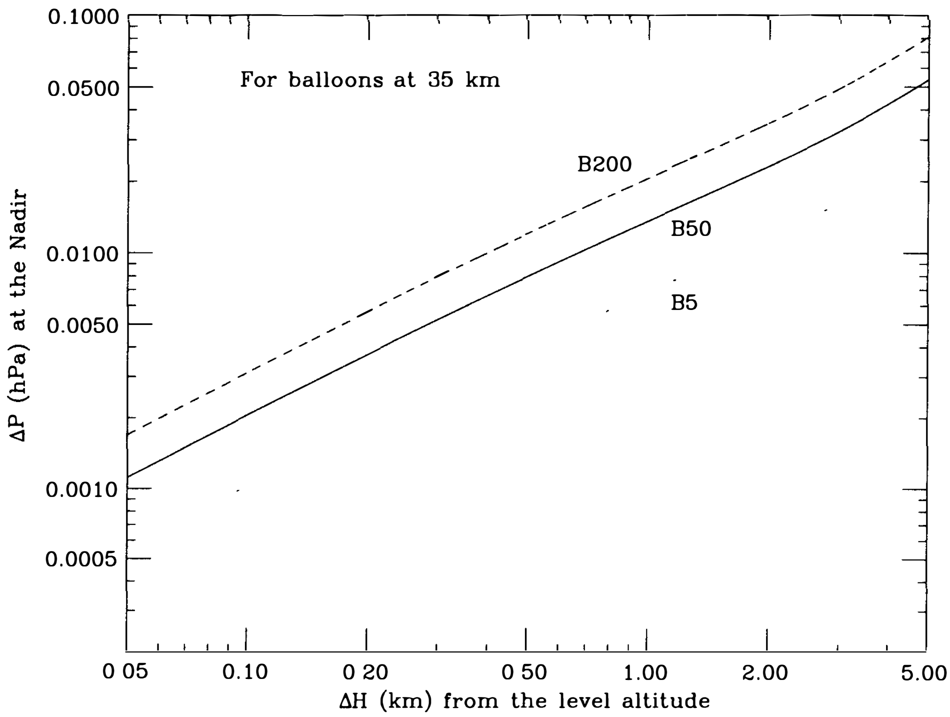

Fig. 2. The descend altitude form 35 km vs. the inner pressure at the nadir for three balloons ; B5: 5000 m^3, B50: 50000 m^3, and B200: 200000 m^3 in volume.

nadir of the balloon where the distortion is maximum. The inside gas pressure is lower than the atmospheric pressure and the difference is approximately proportional to the difference between the level altitude and the current floating altitude as shown below.

The inner pressure at the nadir can be estimated from the equation for the balloon of a natural shape as shown in the Appendix. It is a function of the atmospheric pressure of the level altitude P (or the level altitude H), the decrease of the altitude ΔH, and the volume of the balloon V. Figure 2 shows how the inner pressure at the nadir relates to the descend altitude. We calculated the inner pressures for three balloons (5000 m^3, 50000 m^3, and 200000 m^3 in volume) flowing at the level altitude of 35 km as a function of the descent from the level altitude. The inner pressure is approximately proportional to the amount of descent from the level altitude. If fitted by a straight line at $\Delta H \leq 5$ km,

$$\Delta P = 4.53 \times 10^{-3} \left(\frac{\Delta H}{1\ \text{km}}\right) \left(\frac{V}{5000\ \text{m}^3}\right)^{\frac{1}{3}}\ [\text{hPa}]. \qquad (5)$$

Difference between the model and the curve is less than 5.5×10^{-4} hPa for $V = 5000$ m^3.

Figure 3 shows the relation between the level altitude and the inner pressure at an altitude 1 km below the level. Again, the curves for three balloons (5000 m^3, 50000 m^3, and 200000 m^3 in volume) are shown. Since the inner pressure ΔP is proportional to the atmospheric pressure $P(H)$ (see Appendix), it is generally described by

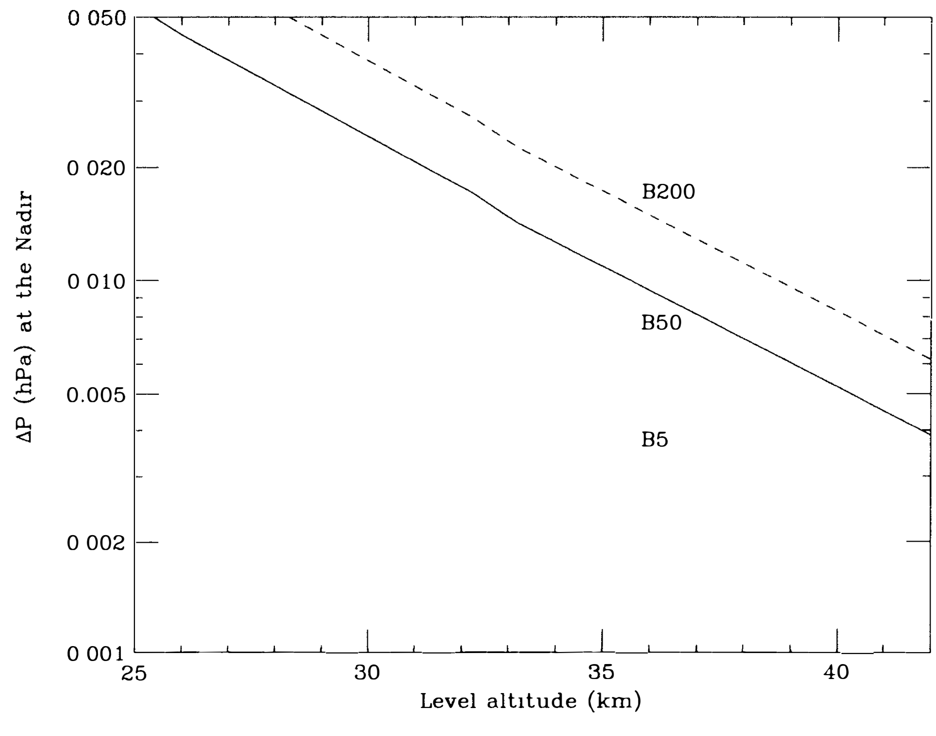

Fig. 3. The level altitude vs. the inner pressure of a balloon descend by 1 km from the level altitude for three balloons ; B 5: 5000 m³, B 50: 50000 m³ and B 200: 200000 m³ in volume.

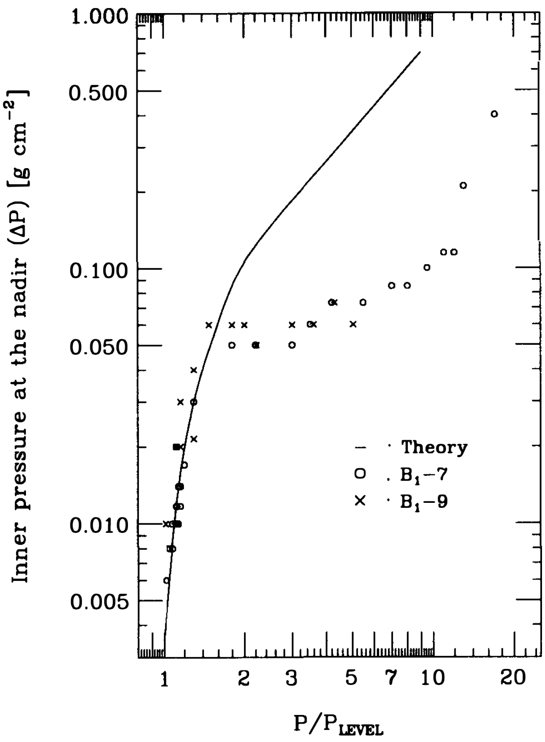

Fig. 4. Comparison of the theoretical curve on the inner pressure at the nadir of a balloon and experiments using balloons with volume of 1000 m³ (NISHIMURA et al., 1968). The vertical axis shows the inner pressure and the horizontal axis shows the atmospheric pressure P normalized by that at the level altitude P_{LEVEL}. Theoretical curve well describes the experiments except at large P/P_{LEVEL}.

$$\Delta P = 4.53\times 10^{-3}\left(\frac{\Delta H}{1\ \mathrm{km}}\right)\left(\frac{V}{5000\ \mathrm{m}^3}\right)^{\frac{1}{3}}\left(\frac{P(H\ \mathrm{km})}{P(35\ \mathrm{km})}\right)\ [\mathrm{hPa}]. \qquad (6)$$

The calculated results at the nadir were confirmed to agree well with the observed data as shown in Fig. 4 (NISHIMURA *et al.*, 1968). The large disagreement for P/P_{LEVEL} above 1.8 is due to the folding of the balloon. It is also important to compare the derived value to the sensitivity of the current pressure gauges. Since the level altitude fluctuates by a few hundred meters (FUJII *et al.*, 1983), it is necessary to set the threshold altitude to be larger than 500 m. From Fig. 2, we found the gauge is required to detect the pressure with an accuracy higher than 2×10^{-3} hPa. The differential gauge used by ISAS balloon group in 1990's (Mano Ace 130 series) has a full scale range of ± 6.4 hPa with the accuracy of 2×10^{-3} hPa. This accuracy is enough for large balloons, while it is close to the threshold level for small balloons. The differential pressure gauge with higher accuracy is now commercially available and it will be better to use accurate sensors for small balloons.

5. Discussion and Summary

We propose a new automatic ballast control method referring to the inner pressure at the nadir. The inner pressure is almost proportional to the amount of descent from the level altitude and it can be measured by commercially available pressure gauges with high sensitivity. This method has the following characteristics.

- It is quite simple and expected to be reliable.
- It is not necessary to know the level altitude precisely before launch.
- The inner pressure at the nadir is not very sensitive to the balloon size and the level altitude. This property is convenient in practice, since the same pressure gauge can be used for various kind of flights.
- The night time altitude also follow the day time altitude increase after dropping the ballast. However, it does not completely follow the increase rate of the day time altitude under the fixed differential pressure between atmosphere and at the nadir of the balloon.

In summary, this method has several merits over the automatic level control methods used in the past. We expect this method to be very useful for a long duration in the future.

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Appendix A. The Natural Shape of A Balloon

The difference of the pressure (inner pressure) between the lifting gas and the surrounding atmosphere at the nadir can be estimated from the equation for the balloon of the natural shape. The natural shape is a shape with the largest volume and the smallest gravitational potential under the fixed gore length. It is also the shape of a normal zero-pressure balloon for which the inner pressure at the nadir is zero. In this paper, we consider the case to use a balloon with the natural shape. The solution of the balloon shape is described by an equation,

$$\frac{\mu}{2\pi}\cdot\frac{\mathrm{d}}{\mathrm{dz}}\left(\frac{\frac{\mathrm{d}r}{\mathrm{dz}}}{\sqrt{1+\left(\frac{\mathrm{d}r}{\mathrm{dz}}\right)^2}}\right)=-rz, \tag{A1}$$

(NISHIMURA and OGITA, 1963), using the cylindrical coordinate described by r and z as shown in Fig. A1. It is also required that the top of the balloon should be flat. This equation is obtained by the variational method solving the shape with the largest volume and the smallest gravitational potential under the the fixed gore length of a weightless balloon, setting μ to be a Lagrangian parameter.

The meaning of the equation is as follows. In the cylindrical coordinate, we know

$$\frac{1}{R}=\frac{\mathrm{d}}{\mathrm{dz}}\left(\frac{\frac{\mathrm{d}r}{\mathrm{dz}}}{\sqrt{1+\left(\frac{\mathrm{d}r}{\mathrm{dz}}\right)^2}}\right), \tag{A2}$$

and,

$$\Delta P=\rho gz, \tag{A3}$$

using ρ as the difference of the density between the lifting gas and the atmosphere at the balloon altitude. Using these equations,the modified eq. (A1) is related to the force balance equation of its gore among the tension T, the inner pressure ΔP, and the curvature R,

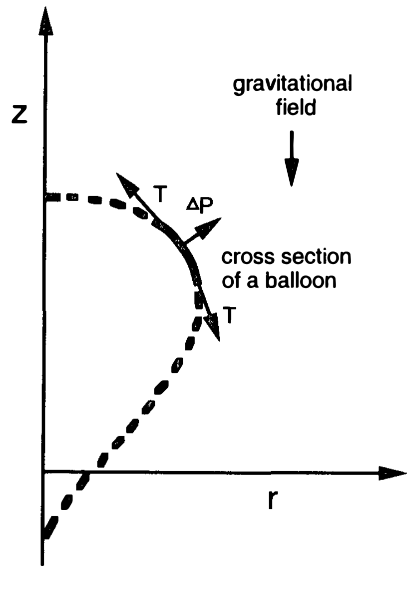

Fig. A1. Definition of the coordinate.

$$\frac{\mathrm{d}}{\mathrm{d}z}\left(\frac{\frac{\mathrm{d}r}{\mathrm{d}z}}{\sqrt{1+\left(\frac{\mathrm{d}r}{\mathrm{d}z}\right)^2}}\right)=-\frac{\rho g z}{\frac{\rho g \mu}{2\pi r}} \Longleftrightarrow \frac{1}{R}=-\frac{\Delta P}{T}, \tag{A4}$$

and one finds a relation,

$$\mu=\frac{2\pi r T}{\rho g}. \tag{A5}$$

The physical meaning of μ is the total tension integrated along the meridional direction normalized by ρg.

Since it is impossible to obtain the analytical solution, we solved it numerically. We, first, solved the equation for various values of μ from the top of the balloon under the initial condition of $r=0$, $\mathrm{d}r/\mathrm{d}z=0$ at $z=a$ (an arbitrary constant) and, then, normalized the resultant shape with its volume or circumferential length. Note, the solution is not directly related to its altitude, but through ρ which does not appear in eq. (A1). Thus, balloons with the same volume and different weight of payload have the same shapes at the level altitudes, while the levels are different. And the shape of a balloon at an arbitrary altitude is a function of ρ normalized by the value at its level altitude.

The inner pressure at the nadir of a balloon was derived as follows. First, we calculated the shape of the balloon with a given volume flowing at its level altitude. We used a condition that the inner pressure at its nadir is zero. Then, we solved shapes of balloons decent from the level altitude. Its circumferential length should match the solution at the level altitude and its volume should be same as that calculated from the decrease of the altitude. Once the solution is obtained, the inner pressure at the nadir is obtained using eq. (A3) setting z to be the value where the solution crosses the z-axis. Figure 2 shows the results. As noted before, the solution is a function of ρ normalized by the value at its level altitude. Since logarithm of ρ is almost proportional to the level altitude H, once ΔH is given, the shape of a balloon becomes the same, while ΔP is different due to the difference in ρ. Thus, one finds logarithm of ΔP is almost proportional to H as shown in Fig. 3.