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Geomagnetic Field Observation Using Fluxgate Magnetometer System Onboard Balloons in Antarctica

by

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Abstract

A long-duration experimental program on the use of balloons for polar geophysical observations planned by the Japan National Institute of Polar Research (NIPR) was carried out by the 44th Japanese Antarctic Research Expedition at Syowa Base, Antarctica in January 2003. We have developed a new fluxgate magnetometer system, which was installed in two balloons for the detection of the balloon motion using the geomagnetic field. Detection of the motion is very important because perturbations of the geomagnetic field depend on the magnetometer sensor motion itself. The high-resolution fluxgate magnetometer system developed for balloon experiments is composed of an 8-directional sun pulse sensor, a biaxial inclinometer and a pulse clock counter. Two balloons were launched on 13th January, 2003. The balloons flew 150 km apart from each other and at the same altitude of 31.5 km. We obtained the magnetometer data of the two balloons by using information relayed from satellites for 11 days and 25 days. As a result, the attitude perturbation of the gondola was detected. In this paper, we describe the new magnetometer system and the attitude motion of the large balloons.

Keywords: Fluxgate Magnetometer, Balloon Observation, Attitude Determination, Antarctic Experiment, Sun Pulse Sensor

1. Introduction

The stratospheric wind of Antarctic region in summer is known as a recurrent wind from east around Antarctica about for two weeks period. We had 7 magnetic field experiments in Antarctica, the observational balloon is called Polar Patrol Balloon (PPB) *[1]* launched from Japanese Syowa Station in 1990, 1992 and 2003. PPB will round along 60-70 degrees of south geodetic latitude, and it is corresponding to 50-80 degrees with the invariant geomagnetic latitude. It means that PPB may observe many upper atmospheric phenomena occurred at the area of the plasma pause, auroral belt, plasma sheet boundary layer, polar cup and so on *[2]*.

The first magnetic field observation used a proton magnetometer and measured total force of geomagnetic field boarded on PPB-1 and -2 in 1990 *[3][4][5]*. In 1992, the first vector measurement was succeeded by use of 3-axial fluxgate magnetometer with sun sensors and inclinometers *[6][7]*. Mainstream of magnetic field observation by balloon is a total intensity measurement by a proton magnetometer in France *[8]* and in Russia *[9]* because of difficulty of attitude determination by irregular motion of gondola *[10][11]*. An accurate analysis of sensor attitude is very difficult because, for example, an accuracy of sensor direction should be determined with the accuracy of 0.01 degree for the 1 nT-resolution of geomagnetic field variation. In generally, motion of gondola is thought that a circular oscillation and twist of long rope from balloon are irregularly mixed together.

In January 2003, the 3rd-PPB observation program called Balloon Cluster Project that launches a series of 3 balloons with the same intervals, has planed and carried out by the 44th Japanese Antarctic Research Expedition *[12]*. Each payload instrument was composed with a detector of electromagnetic wave (EMW), a 3-axis double spherical probe for electric field vector detector (EFD), a 3-axial fluxgate magnetometer for geomagnetic field vector measurement (MGF), an auroral X-ray imager (AXI), Dual-frequency GPS satellite signal receiver for total electron content measurement (TEC) *[13]*. The scientific objectives of MGF in the PPB are investigations for a propagation of geomagnetic micro-pulsation, ionospheric current system, geomagnetic field anomaly and attitude determination of balloons that is given as information to other instruments *[14]*.

We have developed a new magnetometer system for vector field measurement *[15]*. In this system, a gondola has to rotate with a regular revolution by use of spin motor. The fluxgate magnetometer system in the 2nd-PPB campaign in 1992 was not successful because the spin of gondola stopped and the data sampling rate was not frequent. We have made an improved vector magnetometer system that consists of 3-axial fluxgate magnetometer, 8-sun pulse sensor and 2-inclinometer with high frequency timer pulse generator for high field resolution measurement and high data sampling rate in this 3rd-PPB project *[16][17]*.

2. Instrumentation

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2.1 Sensors

A schematic PPB system is shown in Fig. 1. A gondola is removed about 100m down from balloon (gas capacity: 50,000m^3) during an ascending flight and the gondola is rotated at 2rpm by a spin motor. An 80cm-length sensor mast of magnetometer system is mounted on the top panel of gondola; the sensor is composed of 3-axial fluxgate magnetometer (MAG), 8-directional sun pulse sensor (SPS) and 2-axial inclinometer (INC). The specification of sensor system is shown in Table 1. The range of magnetic field measurement is ±100,000nT with a resolution of 0.25nT/digit. The inclinometer can measure the inclination from the horizon at the elevation range of ±20.48 degrees with a resolution of 0.3 angular minutes. The sun pulse sensor has 8 directional 0.8 mm-width slits and a signal output is obtained when 3 photodiodes receive a sun light at the same time as shown in Fig. 2.

Table1. Specification of Sensor System

Fluxgate Magnetometer (3-axial)	
Dynamical Range	±100,000 nT/axis
Resolution	0.25 nT/digit
Sun Pulse Sensor (8-directional)	
Dynamical Range	from 0 to +50 deg/dir.
Resolution	0.2 angular minutes/dir.
Clinometer (2-axial)	
Dynamical Range	±20.48 degrees/axis
Resolution	0.3 angular minutes/axis

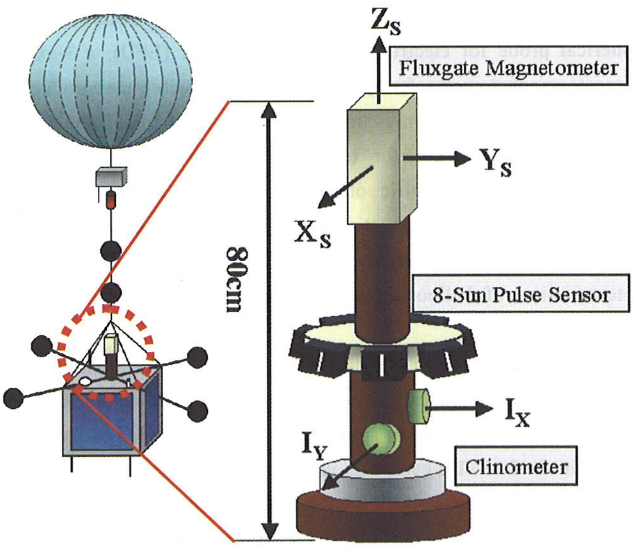

Fig. 1 Sensor mast on the top of gondola

The 4096 Hz clock pulse counter starts by the 1-sec timer signal generator that is corrected each 20 seconds by GPS clock information and the counter stops at a sun light incidence from SPS slit. At the same time of the sun light incidence, magnetometer and clinometer data are synchronously obtained. If the gondola rotates by the spin motor, the counter signal gives an azimuthal attitude angle with the accuracy of 0.2 arc-minutes every 3-4 seconds *[18]*. If the rotation of the gondola stops, magnetometer and clinometer measure at every 1 second by an inner timer automatically. A sample of time sequence is shown in Fig.3. The positioning data of PPB is given by GPS every 20 seconds. Data is transformed through the Iridium Communication Satellite and a telephone circuit. Two ground stations of Syowa Base and Rothera Base in Antarctica received the telemetry data of PPB *[19],[20]*. Table 2 shows comparative characteristics of sensor systems for PPB experiments in 1990, 1993 and 2003. The data sampling of this PPB project was greatly improved to 1 sec-sampling.

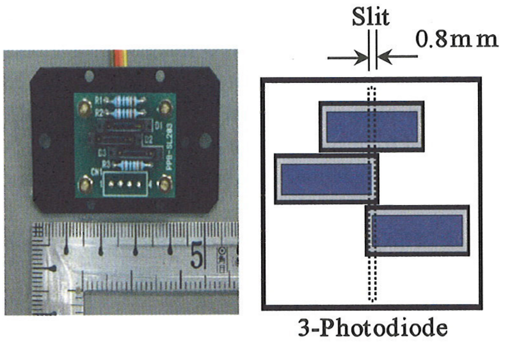

Fig. 2 Sun pulse sensor

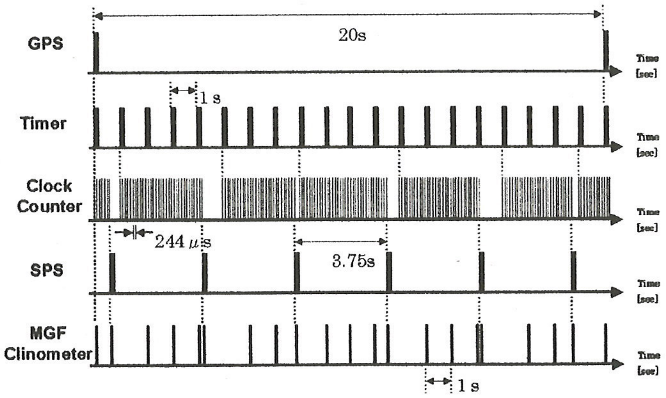

Fig. 3 Data acquisition time sequence

2.2 Ground Calibration Test

The sensitivity, angular alignment of 3 axes and magnetic offsets of the MAG sensors, and the directional alignment of the 8-slits of the SPS and the horizon level of the INC were calibrated at an observatory located at a geomagnetic quiet zone in a mountain valley. In a ground test, the angular alignments of sensors were determined with 20 arc-seconds accuracies. Each instrument was fabricated at the Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA) and tested. The degree of vacuum changed at 700mmHg, 200mmHg, 100mmHg and 3mmHg, respectively and the temperature changed periodically from 0°C to 30°C for two days, and a heating run continued for one week in a vacuum/temperature chamber. In an electromagnetic shield room, magnetic offset was measured for MAG offset and EMC interference.

Table 2 Summary of PPB Magnetometer Systems *[3] [15] [21]*

PPB No (Year)	Sensor	Sensitivity	Data Sampling (sec)	Observation (Days)
#1, 2 (1990)	Proton	1 nT	30	19-23
#3, 4 (1993)	Fluxgate (3-axial)	1 nT	30	9-14
	Proton	1 nT		
	Sun Pulse (2-dir)	0.3 deg		
	Clinometer (2-axial)	0.3 min		
#8, 9, 10 (2003)	Fluxgate (3-axial)	0.25 nT	1	17-24
	Sun Pulse (8-dir)	0.2 min		
	Clinometer (2-axial)	0.3 min		

3. Analysis Method

A typical analysis flow is shown in Fig. 4. The attitude of 3-axial direction is determined by SPS and INC data. The position of the balloon and time are given by GPS and the theoretical geomagnetic field intensity is computed by use of the International Geomagnetic Reference Field (IGRF) coefficients.

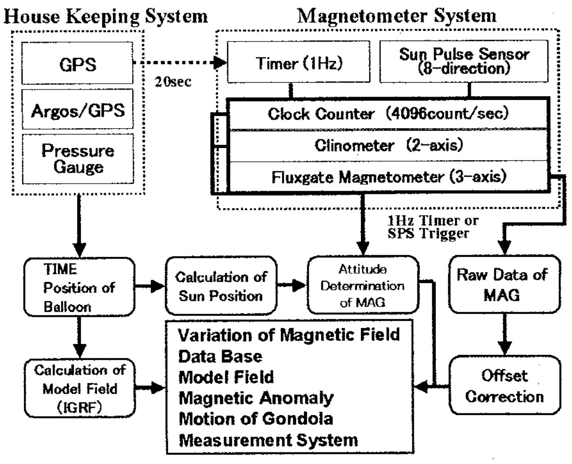

Fig. 4 Analysis Flow Diagram

3.1 Correction for Magnetic Offset

The sensitivities and magnetic offsets of MAG basically change by the temperature and current fluctuations during balloon flight. We determined the sensitivity, magnetic offset and the discrepancy of sensor axial perpendicularity by use of an axis matrix method that had been developed for a correction of satellite MAG sensor. The supposed rectangular magnetic field components, Gx, Gy and Gz are given by multiplication of a transformation matrix and 3-axial output voltages, Vx, Vy and Vz in equation (1). The Bx, By and Bz are axial offsets of MAG sensors and electric circuit. In the matrix, A_{ij} (i=j; x, y, z) shows an axial physical sensitivities (nT/volt) of MAG and A_{ij} (i≠j; x, y, z) shows discrepancy from each perpendicularity among three axes of MAG. The unknown 6-matrix parameters and Bi may be determined by the least square method for equation (2). J is summation of square by a difference between observed total intensity and theoretical reference geomagnetic total field used by IGRF coefficients *[22]*.

$$\begin{bmatrix} G_X \\ G_Y \\ G_Z \end{bmatrix} = \begin{bmatrix} A_{XX} & A_{XY} & 0 \\ A_{YX} & A_{YY} & A_{YZ} \\ 0 & 0 & A_{ZZ} \end{bmatrix} \begin{bmatrix} V_X \\ V_Y \\ V_Z \end{bmatrix} - \begin{bmatrix} B_X \\ B_Y \\ B_Z \end{bmatrix} \qquad (1)$$

$$J = \sum (F_{OBS} - F_{IGRF})^2 \qquad (2)$$

3.2 Coordinate Transformation

A schematic coordinate system of MAG sensor-axis frame (X_M, Y_M, Z_M) and the horizontal topocentric frame (S, E, Z; Southward, Eastward and Zenith, respectively) is shown in Fig. 5. In Fig. 5, A and h are the azimuth and the elevation angles of the sun, and θx and θy show the inclination angles from the horizon that are corresponding to the outputs of x- and y-axial inclinometers. θs is the angle between the X_M direction and the sun meridian plane on the X_M-Y_M plane that is given by the clock generator output. Angle α is the elevation from horizon on the Y_M -Z_M plane and θ is the horizontal azimuth angle from the south to meridian plane including X_M axis. The angle φ is the differential angle between the sun azimuthal direction on the horizon and that on the MAG X_M-Y_M sensor plane. The angle may be negligibly small if the direction of MAG Z_M-sensor coincides with the Zenith. Transformation of two coordinate systems between the MAG sensor (X_M, Y_M, Z_M) frame and the geodetic (S, E, Z) frame is given in equations (3), (4) and (5).

$$\begin{pmatrix} S \\ E \\ Z \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta & 0 \\ \sin\theta & \cos\theta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \cos\theta_x & 0 & \sin\theta_x \\ 0 & 1 & 0 \\ -\sin\theta_x & 0 & \cos\theta_x \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \qquad (3)$$

$$\theta = A - (\theta_S + \phi) \qquad (4)$$

$$\alpha = \sin^{-1}\left(\frac{\sin\theta_y}{\cos\theta_x} \right) \qquad (5)$$

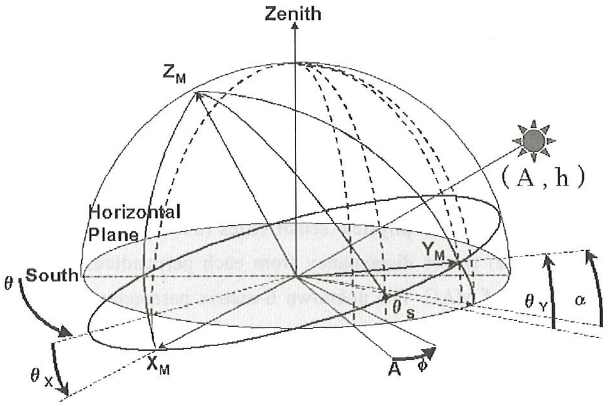

Fig. 5 Coordinate System for MAG

4. Experiment and Preliminary Results

4.1 PPB Launch Experiment

The first balloon, PPB-9 was launched at 07:34 UT on 6 January 2003, but the gondola was fallen down and recovered from the altitude of 15km by a command trouble. PPB-8 and -10 were successfully launched at 06:49 and at 12:16 UT on 13 January 2003, respectively. Both PPBs flied stably at the level of 31.5 km in height and each PPB kept at regular interval distance of 150km. Data acquisition was done by the Iridium Communication Satellite, and Syowa Base (Japan) and Rothera Base (England) stations. PPB-10 and -8 were fallen down at off-shore of Patagonia Islands on 25 January and on 7 February and observed for 11 days and for 25 days, respectively *[23]*. Both PPBs' trajectories are shown in Fig. 6.

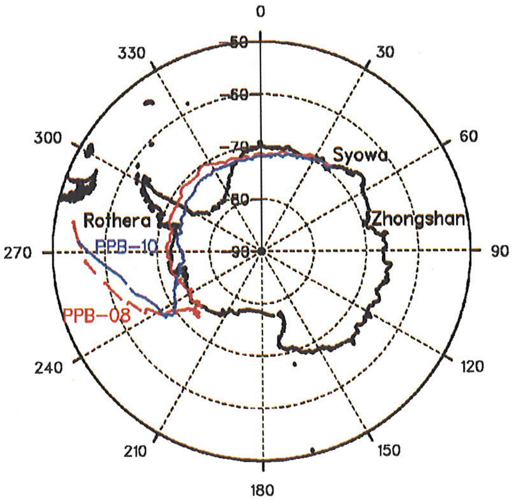

Fig.6 Trajectories of PPB-8 and -10.

4.2 Calibration for MAG Sensor Offset

Azimuthal angles of the gondola X-direction obtained by MAG-X_M and Y_M components data (from 13th 05:32 to14th 14:52[UT]) of PPB-8 are shown in Fig. 7. The azimuthal angle changed with irregular gradients in this figure. It showed that the gondola did not rotate by the spin motor trouble but a twist motion and oscillation caused during all observed time. But a regular rotation showed from 9:03 to 9:10 with the spin period of 33 seconds and the gondola rotated inversely after at 9:13. After then, spin directions turned over every 2 or 3 rotations. We selected a typical duration between at 9:03 and at 9:10 [UT] for analysis of sensor offset determination and the azimuthal angles by MAG coincided with that by SPS as shown in Fig. 8. The change of angle showed a gradual decreased slope and it means clockwise rotation from top view. The obtained offset parameters computed by equations (1) and (2) are shown in Table 3. In Table 3, the sensitivity in flight shows coefficients of magnetic intensity converted from digital output on 3 imaginary rectangular axes that are corresponding to coefficients of *Axx*, *Ayy* and *Azz* in equation (1). The axial angles are computed by coefficients of *Axy*, *Ayx* and *Ayz*. Fig.9 shows 3 kinds of total magnetic field intensities obtained by observed raw data, by the IGRF theoretical data and by the offset parameters. The raw data shows like a sine curve with 130nT peak-to-peak amplitude corresponding to one cycle rotation of the gondola and the corrected total intensity (CAL-Total) reduces to a 5nT-amplitude in Fig.9. This means that the offset parameters were appropriately determined.

Table 3 Magnetometer Sensitivity and Offset Parameters

Offset parameters	Nominal	In Flight
Sensitivity	[nT/bit]	[nT/bit]
X axis	0.25	0.248682
Y	0.25	0.248627
Z	0.25	0.244114
DC Bias field	[nT]	[nT]
X axis	-31	-424
Y	4	19
Z	-162	-862
Axial Angle	[deg]	[deg]
X-Y axes	90	89.90
Y-Z	90	89.96
Z-X	90	90.81

4.3 Motion of the Gondola

We analyzed a simulative motion of the gondola for the 10-minutes data group of PPB-8. Fig.10 shows the angular rotation velocity of the gondola that was analyzed by the geomagnetic angle (MGF) and the sun sensor output (SPS). It shows that the rotational period changes from 33 sec. to 90 sec.

One of simple motions of gondola is a pendulum oscillation about the fulcrum coinciding with the center of gravity in the balloon and also has a rotation around the hanging rope of gondola at the same time. The length of the rope from gondola to the balloon is about 100m, so the calculative period of single vibration is 20 seconds. A horizontal component (MAG X-Y axial plane) intensity of the geomagnetic field shows that a typical period of the gondola's vibration is about 20 seconds as shown in Fig. 11. In this figure, the uncorrected data means analyzed intensity by only MAG offset

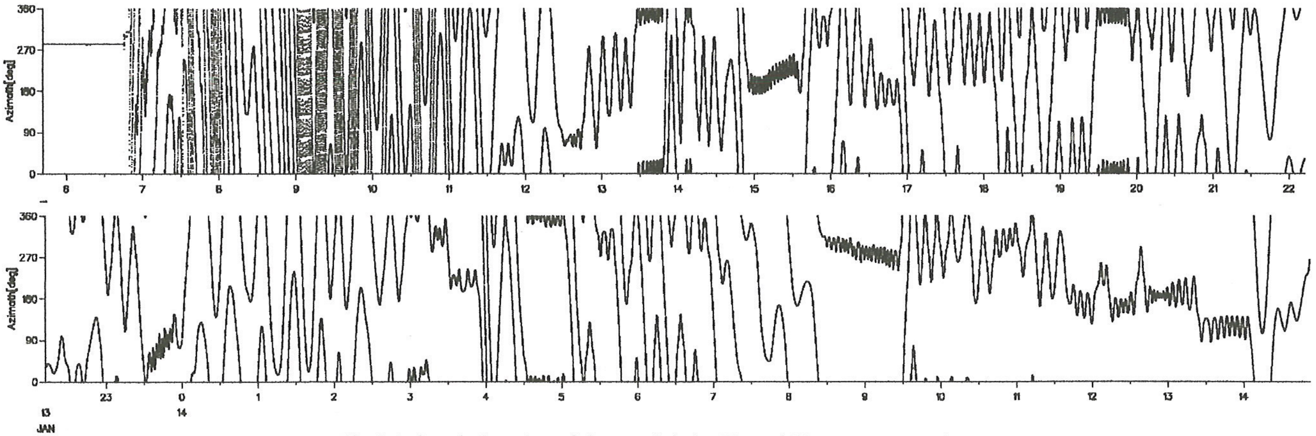

Fig.7 Azimuthal angles of the gondola by X_M and Y_M components data.

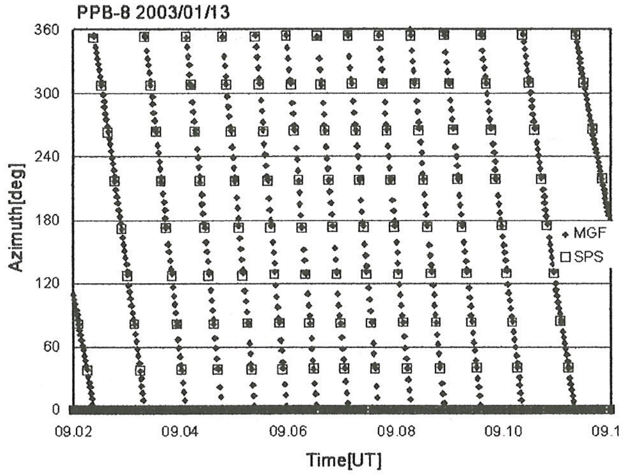

Fig.8 Data sample for gondola's motion analysis.

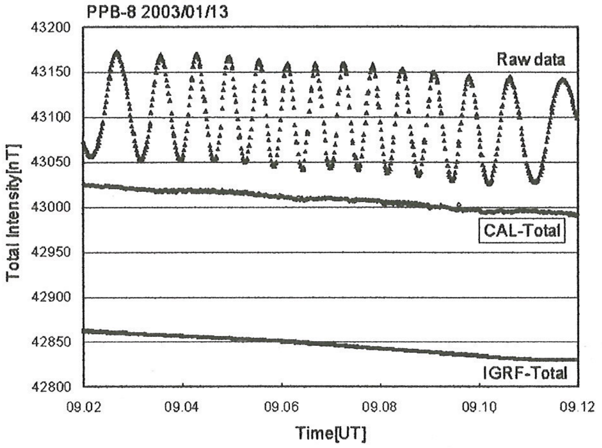

Fig.9 Comparison between 3 kinds total magnetic field

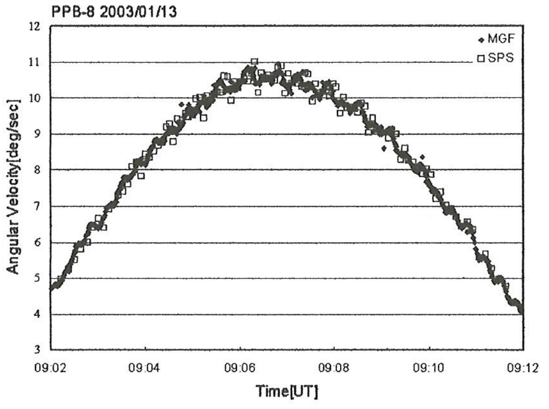

Fig.10 Angular velocity of the gondola

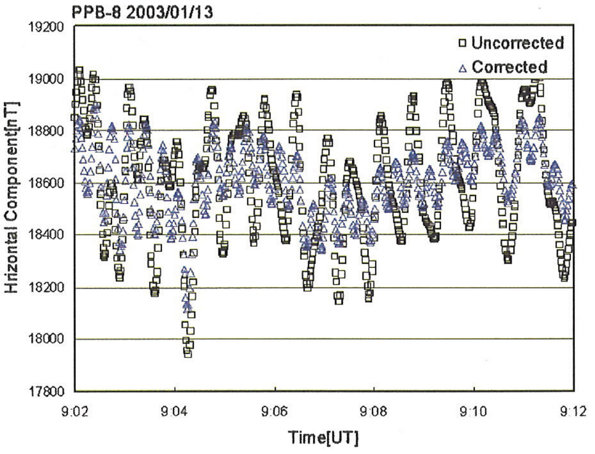

Fig.11 Horizontal component by MGF data.

parameters and the corrected data are calibrated by MAG data and inclinometer data. We assumed by reasonable fitting that the gondola oscillated as a pendulum swing with 0.46 degrees in amplitude with 20 seconds period of the swing. At the same time, the gondola had a spin period of 33 to 90 seconds around the rope and a discrepancy angle was 0.35 degrees between the MAG-Z sensor axis and the hanging rope. A fitting curve used by these motion parameters to the horizontal field intensity of MAG observation data is shown in Fig.12. A schematic motion is shown in Fig.13.

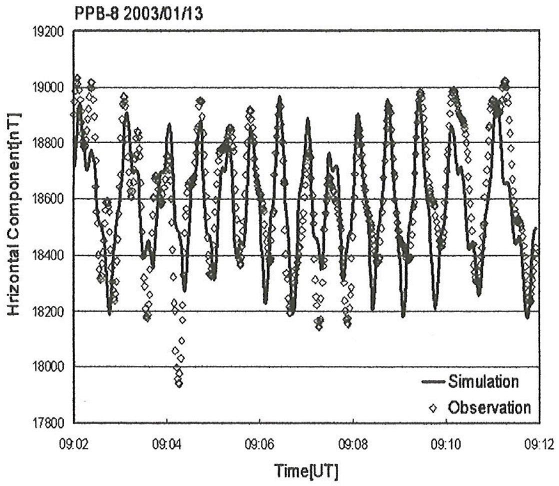

Fig.12 A sample of simulative fitting

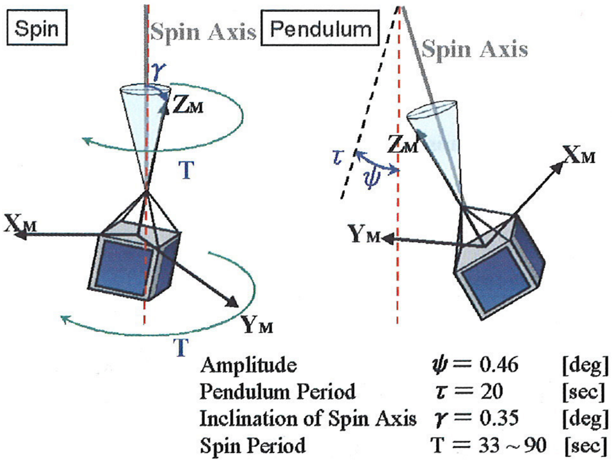

Fig.13 Spin and Pendulum motions

5. Summary

We have developed a new magnetometer system having 8-slits sun sensor and counter clock generator. In this experiment, the magnetometer offset calibration was a useful method and the sensor system is basically useful for a spinning balloon. It is very difficult to get a result of geomagnetic field perturbation because of the spin motor trouble and irregular motions of the gondola. It is better to use a proton magnetometer at the same time for geomagnetic field observation and a remote sensing for the underground anomaly.

Acknowledgements The PPB experimental program was held by the National Institute of Polar Research (NIPR) and PPBs' launch technology was provided by the ISAS/JAXA. PPBs' launches and data acquisition were carried out by the 44-th Japanese Antarctic Research Expedition (JARE) at Syowa Base, Antarctica. We thank greatly to all the persons concerned NIPR, ISAS/JAXA and JARE. The fluxgate magnetometer was assembled by Tierra Tecnica Ltd.

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