Far-Infrared Interferometric Telescope Experiment (FITE): Three-Axis Stabilized Attitude Control System

By Asami NAKASHIMA¹⁾, Hiroshi SHIBAI²⁾, Mitsunobu KAWADA¹⁾, Taro MATSUO³⁾, Masanao NARITA⁴⁾,
Eri KATO²⁾, Tetsuo KANO²⁾, Tsunehito KOHYAMA²⁾, Yuka MATSUMOTO¹⁾, Hirono MORISHITA¹⁾,
Toyoki WATABE¹⁾, Kodai YAMAMOTO²⁾, Mitsuhiro TANABE¹⁾, Ryoko KANO¹⁾ and Yusuke ITOH²⁾

¹⁾Division of Particle and Astrophysical Science, Graduate School of Science, Nagoya University, Nagoya, Japan

²⁾Department of Earth and Space Science, Graduate School of Science, Osaka University, Osaka, Japan

³⁾National Astronomical Observatory of Japan, NINS, Mitaka, Japan

⁴⁾The Institute of Space and Astronautical Science, JAXA, Sagami-hara, Japan

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FITE (Far-Infrared Interferometric Telescope Experiment) is a far-infrared balloon-borne interferometer that we have developed. The goal of this project is to achieve a high spatial resolution, 1 arcsecond, at the wavelength of 100 microns with the baseline length of 20 meters. Therefore, it is required that the attitude of FITE gondola should be controlled in the attitude stabilizing accuracy of about 1 arcsecond. In order to meet this requirement, we adopted the three-axis stabilized attitude control. As a result, we will be able to control its attitude stabilizing accuracy in the order of 1 arcsecond, which is 1-2 orders of magnitude better than traditional balloon-borne telescopes.

Key Words: Attitude Control, Infrared Astronomy, Balloon Telescope, Infrared Interferometer

Nomenclature

$\Delta\theta$	: spatial resolution
D	: aperture of telescope
λ	: wavelength
B	: maximum baseline length

1. Introduction

Far-infrared space observations have not improved their spatial resolution compared with the observations at other wavelengths. For example, AKARI, a Japanese infrared space telescope launched in 2006, has the spatial resolution of 30 arcseconds at 100 microns¹⁾, while some optical telescopes achieved sub-arcsecond spatial resolution. Even that of SPICA, a next generation infrared satellite, is planned that its diffraction limit at 100 microns will be 7 arcseconds²⁾.

This is mainly because of two reasons: the high atmospheric absorption and the dependence of diffraction limit on wavelength. Far-infrared radiation from space is not able to reach the ground because of abundant molecular absorption lines. So that we must observe far-infrared radiation in space or at high-altitude site using a satellite, rocket, balloon and so on. But it means that it is difficult to make a large telescope. In addition, diffraction limit, limiting the spatial resolution, is proportional to wavelength as below:

$$\Delta\theta = 1.22\lambda / D. \quad (1)$$

With the same aperture size, longer wavelength means worse spatial resolution. Large apertures would solve this problem, but it is not a realistic way.

In contrast, diffraction limit of interferometer is describable in following equation:

$$\Delta\theta = \lambda / B. \quad (2)$$

Using a interferometer, it is possible to get the high spatial resolution even at longer wavelength with the simple equipment compared with a large single dish.

To overcome two problems mentioned above and achieve spatial resolution in the order of 1 arcsecond at 100 microns,

Fig. 1. The gondola of FITE. The baseline length is 8 m and the total mass is 1600 kg except the ballast.

we have developed FITE, a balloon-borne far-infrared interferometer³⁻⁵⁾. In this project, we plan to make the 20 m-Michelson stellar interferometer in the end. As a prototype of this, we had made an 8 m-interferometer and a 150 microns band detector, with which diffraction limit is 4 arcseconds, and are developing them now (Fig. 1).

If we want to gain spatial resolution in the order of 1 arcsecond, attitude control of FITE gondola, which is united with the telescope, should be required the stabilizing accuracy at comparable level. In the first flight, specifically, it is recommended that the attitude stabilizing accuracy is about 4 arcsecond while an integral time of 10 minutes. This is the goal of attitude control performance for FITE. However, it is difficult to achieve such a high accuracy constantly by the traditional attitude control method, in which the stabilizing accuracy sometimes worsens to 10-100 arcseconds. In order to satisfy this tough requirement, we have developed a new attitude control system which adopts the three-axis stabilized attitude control. The present work can be applied other balloon-borne astronomical telescopes that need precise attitude control.

2. Methods of Attitude Control

Most balloon telescopes in the past controlled their attitudes by using the alt-azimuth mounts. Though, as for FITE gondola, its attitude is controlled by the three-axis stabilized attitude control system and has achieved high attitude stabilizing accuracy. Here, we compare two methods of attitude control.

2.1. Alt-azimuth control system

The alt-azimuth control system is a method in which we change the azimuth of the gondola by rotating the gondola itself around the perpendicular axis and the altitude by moving the telescope up and down around the horizontal axis in the gondola. This method has been adopted for ground-based large telescopes and balloon-borne telescopes because it uses simple structures and control algorithms.

The gravity center of a gondola is low enough from its hanging point to stabilize attitude by gravity force. But, in the case of balloon-borne telescopes, winds blow the balloon and the variation of wind speed or direction induces the balloon-gondola pendulum motion, which causes the attitude accuracy worse. Since the wind around the observational altitude is generally laminar flow, this phenomenon occurs especially when the balloon elevates at the beginning of the observation, so that the observation time may become shorter. Figure 2 shows actual pendulum motion occurred on the alt-azimuth balloon-borne telescope⁶⁾. In this case, the attitude stabilizing accuracy became worse, few dozens of arcseconds to few arcminutes. However, it is shown that we are not able to cancel, virtually, the pendulum motion by attitude control. Therefore it does not suit for FITE.

2.2. Three-axis stabilized attitude control system

It is required that the attitude of FITE gondola is controlled in the accuracy of about 1 arcsecond. To meet this requirement, we adopt the three-axis stabilized attitude control system. In this method, we use a gondola hung at its gravity center, which means the pendulum motion does not affect the

Fig. 2. The pendulum motion of a balloon-borne telescope. This data was recorded at FIRBE observation, our past activity in 2001.

Fig. 3. Concept of two attitude control methods: (left) alt-azimuth control system and (right) three-axis stabilized attitude control system. The rectangles represent the gondola. The pendulum motion affects only the left gondola.

attitude of gondola. Other external force, such as a wind, is empirically negligible small because it is laminar flow and atmospheric pressure at the floating altitude is less than 1 % of that at the ground. Therefore, we can control its attitude with high accuracy in this control system (Fig. 3). Since there is no gravitational restoring force, however, we should control its three-axis attitude, similarly to satellites. In the case of FITE, we use three types of actuators to control its attitude. We note that it needs more difficult control algorithm than the alt-azimuth control system.

2.3. Artifices for three-axis stabilized attitude control system

It is absolutely needed for the three-axis stabilized attitude control system to keep the center of mass at the hanging point. To do so, there are some artifices brought to the gondola.

The hanging point is made by a Universal Joint, a general-purpose industrial product, so that it is capable of bending smoothly to all directions at a point and the hanging point does not shift in any attitude (Fig. 4). The friction of the joint is small enough to be ignored in controlling attitude.

Universal Joint bends over a limited range of ± 5 degrees. When we want to change altitude more widely, we turn the inner part of telescope structure (Fig. 5). In order not to shift the gravity center with its rotation, the partial gravity center of

Fig. 4. Universal Joint and other parts for hanging. It bends smoothly to all directions at the hanging point.

Fig. 5. Changing the direction of the inner part of telescope structure. We define the angle between the inner part of telescope structure and the gondola as the elevation angle. These pictures are when the elevation angle is 90 degrees (upper) and 0 degree (lower).

this part is on the rotational axis located at the center of arm parts.

Balloon-borne telescopes need to drop the ballast while the flight and that reduce the weight of the gondola. There is a risk of affecting weight balance. Thus we locate two ballast boxes filled with tiny iron balls, each maximum total weight reaches 200 kg, symmetrically about the hanging point. In addition, the ballast boxes are hung by springs. Therefore the position of gravity mass does not shift even though the weight of ballast lessens during the observation (Fig. 6).

Fig. 6. The ballast box. It is hung by springs. Another box is located at the counter side across the hanging point.

Fig. 7. The X axis attitude data when the gyro was lying on the floor. We provide raw data (upper) and data using the low pass filter (lower).

3. Instruments for Attitude Control

3.1. Ring laser gyro

FITE has a ring laser gyro for three-axis attitude sensor. The data is refreshed 250 times for every second. By using a low-pass filter, we can know attitude angles in accuracies of 0.2 arcseconds, while the accuracy of raw attitude data is 180 arcseconds (rms) (Fig. 7).

3.2. Reaction wheels

FITE gondola has three reaction wheels (RWs) for each

Fig. 8. The RW and the spindle motion stage for X axis.

Fig. 9. The TWR motor. There is the hanging point above it.

axis angle control. The diameter of RW is 90 cm and its moment of inertia is 4.49 kg m^2 . Based on the principle of conservation of total angular momentum, we can control the attitude angles of the gondola in the accuracy of the order of 1 arcsecond by operating rotational speed of RWs.

3.3. Spindle motion stages

Attitude control with the RWs achieves high attitude accuracy. If we demand them too high rotational speed, however, RW's motors may not be able to satisfy the demand and go out of control. In order to avoid this situation, there are two spindle motion stages which is perpendicular to X or Y axis (Fig. 8). When the spindle weighing 13 kg slide horizontally, the center of gravity is shifted and it gives gravitational torque to the gondola. Using the spindle motion stages as unloaders makes it possible to control the attitude without saturation of RW's rotational speed.

Furthermore, we can use these motion stages to change the attitude angles widely and quickly, without accuracy, when RWs are not operated.

3.4. TWR motor

We adopt the TWR (Twisting-wound rewinding) motor, usually used with alt-azimuth control system, as an unloader of Z axis RW. Similarly to the spindle motion stages, the

Fig. 10. The flow chart of attitude control system.

TWR motor works for rough attitude control.

4. Attitude Control Algorithm

The attitude of the gondola is controlled by independent onboard PC during the observation. Onboard PC sends the data, including attitude angles and status of instruments, to the ground observers. A commander who is monitoring the data sends a command about changing control mode, target attitude angles and value of control parameters. Then, onboard PC rewrites parameters in the program.

We operate attitude control by 250 Hz feedback loop. Figure 10 shows a flow chart of attitude control.

FITE has two modes for attitude control; coarse control mode and fine control mode. Control with RWs needs long response time, though it achieves high accuracy. We choose coarse control mode, which operates only the spindle motion stages and the TWR motor, when we want to change the observed object or recover the attitude of the gondola. At the former mode, the attitude stabilizing accuracies of each axis may come to 10 arcminutes. After that, it should be change to fine control mode for observation. At the latter mode, the three RWs play the main roll of control, while the two spindle motion stages and the TWR motor work as unloaders of X, Y, and Z axis RWs, respectively.

5. Test of Attitude Control

In December 2008, we had planned the first flight of FITE with 8 m baseline to demonstrate the principle of interferometer in Cachoeira Paulista, Brazil. However, the flight was postponed due to the trouble with a part of interferometer optics occurred on the way from Japan. As for the attitude control system, the performance reached to the level required for the first flight through parameter optimization. Here, we report the result of indoor attitude control test on December 13th, 2008.

5.1. Pointing control test

We Operated gondola to rest with fixed target angles. The test started with the target angles of three axes differing from

Table 1. Attitude stabilizing accuracy and control residual of the control test (rms) [arcsecond].

		Attitude stabilizing accuracy			Control residual		
		X axis	Y axis	Z axis	X axis	Y axis	Z axis
Pointing control test	1 minute	1.5	3.4	1.3	16	-37	-16.5
	10 minutes	3.6	28	3.4	16	-37	20
Tracking Test	1 minute	23	2.8	1.1	34	1.1	0.4
	10 minutes	143	47	3.7	87	11	2.9

Fig. 11. The results of the pointing control test. Vertical axis describes difference angle; defined as attitude angle minus target angle. *Upper*: Overview of the control test. *Lower*: Detail of the test.

attitude angles by a few degrees. First, we chose coarse control mode until the movement of the spindle motion stages became less. Then we changed to fine control mode. Figure 11 describes the data of difference angle; attitude angle minus target angle. Additionally, there are values of the attitude stabilizing accuracy and control residual on short and long time scale (a minute and 10 minutes) in the upper part of Table 1.

The stabilizing accuracy of the X axis and the Z axis is better than the diffraction limit of 8 m interferometer, whereas the Y axis attitude control seems to be lack of optimizing. This is because the Y axis moment of inertia is larger than the X axis so that rotational speed of the Y axis RW tends to increase and unloader moves frequently. This problem may be solved by replacing current RWs with ones having larger

Fig. 12. The results of tracking test. Vertical axis describes difference angle; defined as attitude angle minus target angle. *Upper*: Overview of the control test. *Lower*: Detail of the test.

moment of inertia.

5.2. Tracking test

After the pointing control test, target angles were varied as if the direction of telescope tracks diurnal motion of target object. Fine control mode was chosen then. At FITE gondola, the X and the Z axis correspond to the altitude axis and the azimuthal axis, respectively. Therefore, the X and the Z axis target angles of must be shifting with diurnal motion, while target angle of the Y axis is fixed at 0 degree; the direction which arm of interferometer is horizontal. The result of this test is shown in Figure 12 and lower part of Table 1.

The attitude angle of the Z axis is also well under control in the tracking test. This result indicates that attitude control with RW is a good method. However, the stabilizing accuracy of the X axis became worse than that with fixed target angles.

Wide shifting of target angle may have caused great varying of RW's rotational speed, and then unloader moves frequently. We still need to improve the algorithm; to optimize unloading parameters again or to switch the algorithm to tracking target actively using the spindle motion stages.

6. Conclusion

We have developed three-axis stabilized attitude control system for FITE. This attitude control method has been adopted for balloon-borne telescope only twice before in the world^{7,8)}. Furthermore, gravitational unloaders are unprecedented instruments. At the Z axis, we achieved good attitude stabilizing accuracy, meeting the requirement for the first flight, in the attitude control tests on December 2008. The stabilizing accuracy of the Y axis may be better by replacing RWs. It needs more and more test to optimize the motion of instruments for the X axis, but nevertheless we can satisfy the requirement for the first flight by choosing target whose altitude does not shift much during an integration time. Also, if we can gain the stabilizing accuracy of only about 10 arcseconds, except for the worse observation efficiency, we can reconstruct a fringe pattern by being based on attitude data.

Hence, we plan to improve the system to achieve the stabilizing accuracy of below 1 arcsecond for the next challenge of the first flight.

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