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A BALLOON-BORNE FAR-INFRARED TELESCOPE WITH A NEW AZIMUTH STABILIZATION SYSTEM

By

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ABSTRACT

A small telescope control system was developed for balloon-borne far-infrared scanning observations with medium angular resolution. The stabilization of a balloon gondola was performed by a reaction wheel-based servo-mechanical system driven by a torque motor, realizing pointing accuracy better than 0°.1. The method employed in this system is unique in that only the internal frame which the telescope is attached to is stabilized around a vertical axis of the gondola, while the outer gondola being oriented separately by the so-called twist-rewinding servo-system. The performance of the whole system is presented including the three-color far-infrared photometer actually used in the last observation.

I. Introduction

Infrared astronomy has become an important field in observational astrophysics. Especially, balloon-borne experiments could have offered crucial information on the structure of the Galaxy, in terms of distribution of stars, interstellar dust, and star formation regions in the inner galactic region. We have so far developed and used scanning instruments in balloon projects by the use of small infrared telescopes, in which we have utilized the so-called twist-rewinding servo-system with rather crude stabilization capability (Okuda et al. 1977, Oda et al. 1979, Maihara et al. 1979, Maihara et al. 1981).

It was necessary for our latest far-infrared observation to improve stabilization accuracy to the order of 0°.1 because of its finer angular resolution of the detection system. Although we have failed to achieve a planned observvation using this instrument, we have tested and obtained as a whole the aimed performance of the system before launching. So, it may be useful for future extension to report detailed descriptions on the instrumental procedures developed here.

We shall first describe the three-color far-infrared photometric system which was made and flown in the 1980 observation to measure diffuse far-infrared emission from the galactic plane. Then we report the reaction wheel drive mechanism together with the electrical circuitry to implement the fine azimuth control.

II. The Far-Infrared Photometry System

1. Telescope Configuration

We have so far observed far-infrared surface brightness of the galactic plane with a relatively large field of view of abut 0°.7. In these observations we have detected diffusely extended emission at $\lambda_{eff}=150\,\mu m$ (Maihara et al. 1979). The contour map obtained, however, indicates that the most features in the far-infrared map exhibit obvious correlation with H II regions observed at radio frequencies with finer angular resolutions (e.g., Altenhoff et al. 1970). In order to separate such discrete sources from the whole extended emission around the galactic plane, we have designed and constructed a small balloon-borne telescope with higher angular resolution.

The telescope is a newly developed 20 cm Cassegrain telescope with a wobbing secondary mirror. The focal length is about 100 cm, so that the focal aperture of 6 mm in diameter corresponds to a 0°.34 field of view. The beam throw of sky chopping is about 1°.5 which is performed by a pair of push-pull solenoids with a modulation frequency of about 10 Hz. Fig. 1 shows an example of scan profile of the one of the bolometer channels, from which we estimate the FWHM of the beam to be about 0°.33.

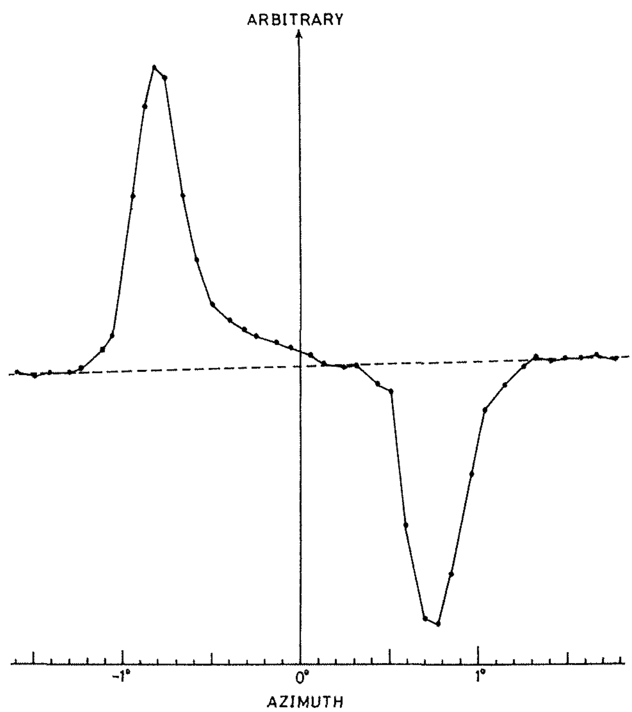

Fig. 1. A typical example of the Az scanning profile for the CH2 bolometer obtained in laboratory experiments.

2. Three-Color Photometric Detection System

A three-color photometric system was designed and fabricated in a helium-cooled cryostat as follows. In the far-infrared region there are two kinds of dichroic wire-mesh filters: an inductive mesh filter and a capacitive mesh filter. The inductive mesh filter transmits short wavelength radiation, and reflect long wavelength waves, while the capacitive filter works reversely. We utilize these as dichroic beam splitters for a simultaneous three-color detection system. Beam channeling of this system on the cold work surface is illustrated in Fig. 2.

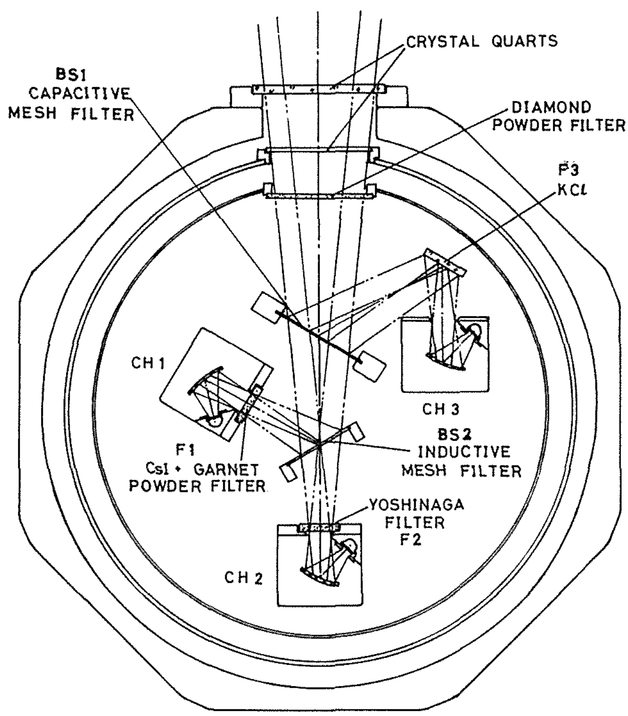

Fig. 2. The optical layout of the three-color far-infrared photometer system installed in an HD-3 type dewar.

The cut-off wavelength of the first capacitive beam splitter BS1 is $\lambda_c \simeq 75\,\mu$m, so the transmitted light contains radiation longer than 75 μm. The second inductive beam splitter BS2 has a cut-off wavelength of about 140 μm. The CH1 in the figure is the longmost wavelength channel whose spectral band is defined by both CsI and garnet-powdered filters F1 at the entrance pupil of the bolometer-installed assembly. The second channel CH2 is defined primarily by the tuned transmission characteristics of the BS2 multiplied by a Yoshinaga filter F2 (BeO+ZnO+NaF+KCl). The CH3 is the shortest wavelength band restricted by a KCl reststrahlen filter F3. In Fig. 3, we summarize the filter curves employed here including some window material.

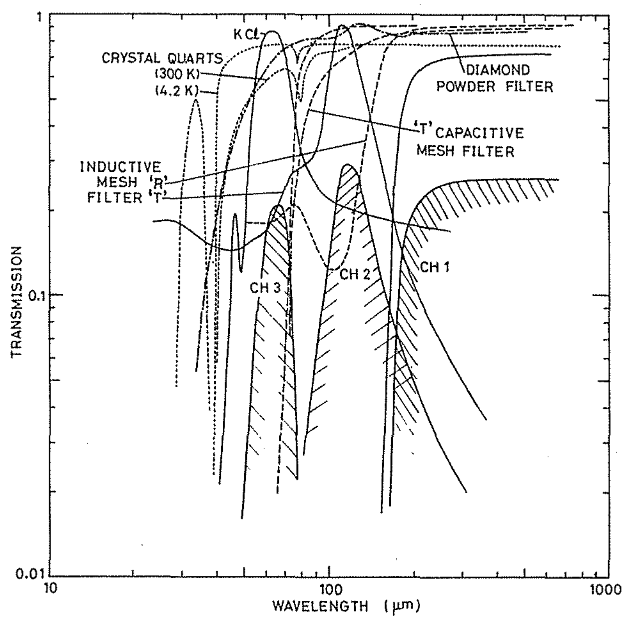

Fig. 3. Filter transmission curves for each bolometer channel. Overall transmission characteristics are shown by hatched areas

Each detector assembly consists of a composite-type Ge:Ga bolometer, an offaxis collecting mirror and a 6-mm diaphragm. The responsivities for these detectors were checked by the use of a conventional black body radiator, and the NEPs were $5.58\cdot10^{-14}$, $1.27\cdot10^{-13}$ and $2.17\cdot10^{-13}$ $WHz^{-1/2}$ for CH1, CH2 and CH3 respectively. The electrical NEPs for these detectors, on the other hand, were proved to be around $3\cdot10^{-14}$ $WHz^{-1/2}$ from I v.s. V curves. The appreciable deficiency of responsivity of CH2 and CH3 could not be clarified completely. But probable are the cases that the optical alignmnt inside the cryostat might not be perfect, and that the tested condition could introduce more background radiation than the balloon-borne condition expected.

III. Attitude Control System

Astronomical observations by the use of balloon-borne telescopes require special attitude control systems capable of pointing and scanning celestial objects in concern. We have so far utilized the so-called twist-rewinding servosystem developed at the Institute of Space and Aeronautical Science, University of Tokyo. The twist-rewinding method attains azimuth atabilization with about one degree RMS fluctuation. To improve this performance we designed an additional azimuth stabilization mechanism within the gondola which is suspended by the similar twist-rewinding system.

The inner gondola frame which accomodates the 20 cm Cassegrain telescope with its elevation drive mechanism is supported on a vertical axis through frictionless ball bearings. A compact reaction wheel drive mechanism is equipped within the inner frame. This twofold stabilizing method is adequate for controlling attitude of a small instrument with relatively less moment of inertia like the present experiment.

In fact the estimated moment of inertia of the inner frame including the telescope and the cryostat assembly is about one fourth of the total moment of the gondola. In Fig. 4 the whole attitude control system is illustrated schematically together with the interconnection wiring between subsystems. A geomagnetic aspect sensor (GA) is also mounted on a small closed-loop servo-system. This subsystem generates instantaneous azimuth signal via a potentiometer linked to the GA axis, which is virtually locked to the direction of null output (i.e., to the south direction). Hence the azimuth read-out is linear over the whole azimuth range.

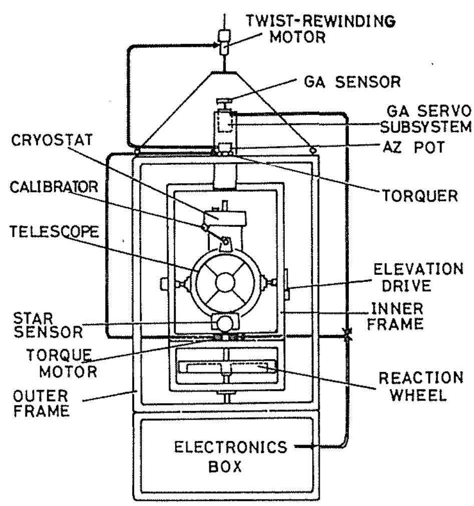

Fig. 4. An illustration of the whole gondola to demonstrate the reaction wheel-based attitude control system.

The moment of inertia of the inner frame including the telescope and the cryostat is estimated to be about 24000 kgw·cm^2. The reaction wheel, on the other hand, is designed to be 3000 kgw·cm^2 (the actual size is 46 cm in diameter, and 10 kg in weight). A torque motor T-2157 of Inland Co. was chosen which has the maximum torque of 2.52 kgw·cm, while the friction torque caused by brushes being 80 gw·cm. Under these parameters we defined servo-electrical constants in a servo-amplifier/driver circuit as follows.

The torque T produced by the torque motor is proportional to the applied current I_{out} which in turn is approximately represented by the output voltage V_{out} of the driver, if the rotation speed is not so high. Then, let the transfer characteristics of the amplifier/driver be expressed by,

$$T(t) = \gamma \cdot V_{out}(t) = -\alpha\theta(t) - \beta\dot{\theta}(t),$$

where $\theta(t)$ is the azimuthal angle at time t, and $\dot{\theta}(t)$ denotes its derivative. Constants γ, α and β must be determined to provide suitable sensitivity and damping characteristics. Note that the torque is responsible for orientation of the telescope. Thus we get an equation of motion for the inner frame with a moment of inertia I as follows.

$$I\ddot{\theta}(t) + \alpha \cdot \theta(t) + \beta \cdot \dot{\theta}(t) = 0 .$$

A general solution obtained under the condition of maximal damping (i.e., the determinant $D=0$, or $\beta^2 - 4\alpha I = 0$) is written as,

$$\theta(t) = (\xi + \eta t) \exp(-\delta t),$$

where $\delta = \beta/2I$. ξ and η should be determined according to an initial condition.

We expect frictional torques introduced by bearings and brushes to be as small as 150 gw·cm in the worst case, which is supposed to hold pointing accuracy better than 0°.1. Accordingly, the terminal torque within which torque remains linear with angular deviation $\theta(t)$ must be set to $\theta_{term} = 0°.8$, since the maximum torque exerted by the motor is responsible (i.e., $T_{max} = 2.5$ kgw·cm). It turns out that $\alpha = 2.5$ kgw·cm·$(0°.8)^{-1} = 1.8 \cdot 10^6$ dyne·cm·rad^{-1}. Adopting $I = 24000$ kgw·cm$^2 = 2.4 \cdot 10^7$ g·cm^2, then $\delta = 2°.7$ sec^{-1}. For instance, if we take $\theta_0 = 0°.8$ and $\dot{\theta}_0 = 0$ at $t=0$, then we get $\xi = 0°.8$ and $\eta = 2°.2$ sec^{-1}. In this case, the telescope is settled to the aimed direction within 0°.1 after 0.8 sec later.

In case that the telescope possesses an initial angular speed at $\theta_0 = 0°.8$ as much as 6° sec^{-1} (equivalent to 1 rpm) for instance, it takes a transient pause at $\theta = -0°.29$ after 0.58 sec later, thereafter it being settled in the same manner as before.

To realize the above response characteristics in the servo-amplifier, we have employed a conventional operational amplifier circuit with a differentiating function shown in Fig. 5. The output signal e_0 of this circuit is expressed by a linear combination of the input signal and its derivative; that is,

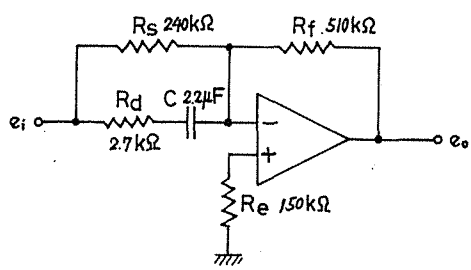

Fig. 5. The servo-electrical stage of the attitude control system.

$$e_0 = -\frac{R_f}{R_s} \cdot e_i - R_f \cdot C \cdot \frac{de_i}{dt} .$$

Here, the input signal e_i represents the azimuth $\theta(t)$ taken from the azimuth potentiometer. Therefore parameters R and C in this equation should be determined so as to make it equivalent to the equation of motion whose coefficients have been specified above. The actual values determined are presented in the figure.

IV. Performance Tests and Discussion

We have intended to make two different modes of observation in a balloon mission by utilizing the telescope control system described here. The one is the slow scan mode, in which the telescope shifts its line of sight direction at a rate of about $0°.1\ \mathrm{sec}^{-1}$ within 5° in azimuth, whereas, in the rapid scan mode, the telescope swings its direction within the same range at a rate of $1°.5\ \mathrm{sec}^{-1}$. In both cases, during the period when the telescope together with the inner frame is moving, the outer gondola frame suffers a compensating torque via the twist-rewinding motor in response to a potentiometric signal: a relative azimuthal angle difference between the inner and the outer frames. In the slow scan mode, the compensating response takes place in a quasi-stationary manner, so that the relative difference could be kept small.

Fig. 6 shows a typical slow scan path along with a curve of rotation speed of the reaction wheel. The ordinate represents instantaneous azimuth signal generated by the GA servo-subsystem. This profile proves to have excellent linearity within the scanning range between $\pm 5°$ in azimuth, indicating a deviation smaller than $\pm 0°.04$.

In the rapid scan mode, the linearity appears to be rather degraded as

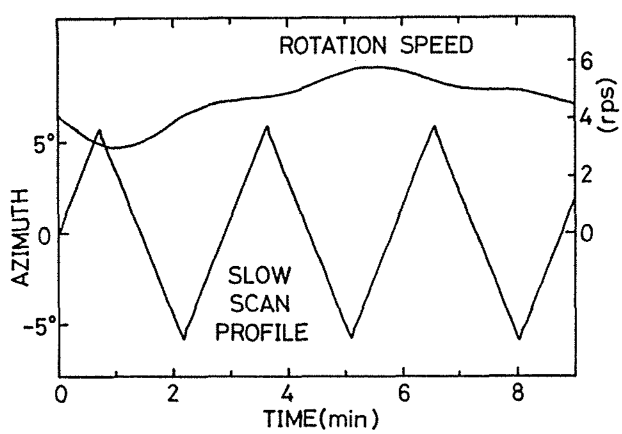

Fig. 6. A typical trace of a sequential scanning path in the slow scan mode. Rotation speed of the reaction wheel is also presented.

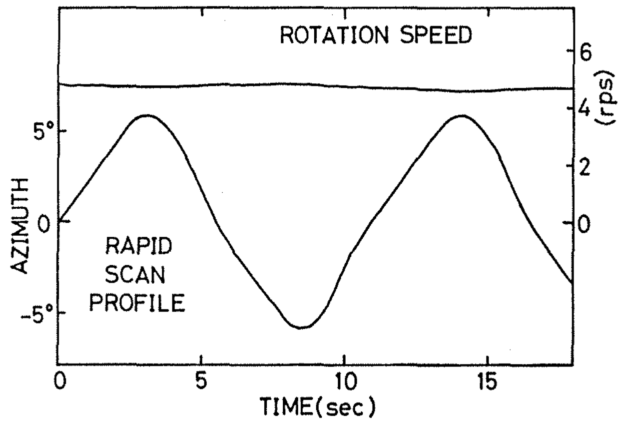

Fig. 7. Same as Fig. 6 but in the rapid scan mode.

shown in Fig. 7. This is because the transient response time at each terminal position of each sweep is limited by the dynamical time constant of this reaction wheel-based system. Another factor of deviation in the curve is attributed to the reactive effect from the outer gondola motion introduced through the compensating torque which is actuated more sharply than in the slow scan mode. The rapid scanning features a complementary observational mode in which surface brightness distributions can be directly observed via DC-coupled amplifier channels instead of the differential chopping method. Hence the correction of the non-linearity of the telescope motion can be applied in a straightforward manner.

Finally we shall summarize several inherent characteristics of this newly developed system for stabilization of a small balloon telescope. 1) The stabilization mechanism presented here is compact, occupying a smaller portion of the whole gondola in terms of weight and power consumption. 2) Relatively quick response of telescope maneuvering is realized, which makes the rapid scan mode possible. 3) The isolation of the balloon rotation motion is simply achieved by the use of the twist-rewinding method, that eliminates a complicated frictionless bearing assembly. 4) The tension of electric leads wired between inner and outer frames seems to contribute to most residual friction torque, especially at a low temperature condition. 5) This system requires rather strict dynamic balance around the azimuthal axis between the frames, because the thereby-caused residual torque could result in the enhancement of rotation speed of the reaction wheel. (To lessen the effect we have equipped with a compensating torque to the axis.)

In this report we have described the new stabilization system for a small infrared balloon telescope including some detailed descriptions on the far-infrared multicolor photometer. Although the system has proved to work well in various ground tests, the actual astronomical observation made in the maiden flight in September 1980 was unsuccessful due to a leakage problem occured in the plastic balloon employed. Nevertheless we feel it necessary to report the unique features of this system for future improvement and extension. In view of the several points listed above as a summary, the present system would be a fairly efficient method in case the rapid scan mode is necessary, because the telescope to be stabilized was small compared with the balloon gondola itself including basic housekeeping facilities. However, it would be more simple and less troublesome to drive the whole gondola by the similar stabilization mechanism incorporated with the twist-rewinding method unless the rapid scanning is crucially needed.

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