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Development of a Reaction Wheel-Based Attitude Control System for Balloon-Borne Infrared Astronomical Observation

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SUMMARY: An attitude control system of a balloon-borne gondola for infrared astronomical observations has been developed by using a reaction wheel-based toquer in conjunction with the twist-rewninding subsystem. The behavior of the coupled system is studied through numerical simulations. In actual balloon experiments the system has proved fine in-flight stability better than one arcmin throughout various observational modes such as pointing and scanning.
Key Word: reaction wheel, balloon-borne instrument, attitude control, stability, servo control circuit, infrared astronomical observation

CONTENTS

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I. INTRODUCTION

The method of observations using stratospheric balloon has extensively been exploited in infrared astronomy. It is expected in future that the balloon technique

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together with a variety of sophisticated instruments for infrared measurements would play important roles to produce a great deal of new astrophysical information.

Fine attitude control of such balloon-borne instruments is more or less essential in astronomical applications. So far in Japan, the suspension rope-twisting servo system developed by Nishimura et al. [*1*] has widely been used for such purposes. This method employs an actuator which exerts twisting torque in the suspension rope to orientate a gondola to a desired azimuthal direction referring to the magnetometer signal. The time constant of the motion in the servo control system is rather long, so that the stability is easily affected by external disturbance. The attained stability ranges from $0.^{\circ}2$ to 2° depending on an actual flight conditions (e.g. Nishimura et al. 1969). Nevertheless, many important observations have been made by the use of this method mostly in the scanning mode with relatively large field of views (Ito et al. [2], Okuda et al. [3], Oda et al. [4], and Maihara et al. [5]).

In the subsequent advanced stage of observations, the requirement on attitude stability tends to be more stringent, since smaller field of views are used and especially polarimetric or spectrometric measurements are undertaken recently. To realize such observations, we have developed a reaction wheel-based attitude control system combined with the twist-rewinding method.

In the earlier development stage, we have built a reaction wheel-based scanning instrument for balloon-borne far-infrared observation (Hiromoto et al. [6]). In this method the orientation of the gondola is primarily achieved by the suspension rope-twisting servo system, while the inner flame on which telescope is mounted is controlled on a gimbal by a reaction wheel. A drawback of this configuration is that the flexure of lead wires has an effect to degrade accuracy of the control. Then we have employed a simple structure with a reaction wheel mechanism as a primary torquer together with the device to rewind the twist of the suspension rope.

In this paper we describe a developed system which was flown in the balloon observations in 1981 and 1982. In these two flights the attitude control performance of about one arcminute stability was realized throughout several observational modes such as rapid and slow scanning, pointing and pseudo-tracking etc.

II. Mechanical Design of the Reaction Wheel System

The gondola used in 1981 and 1982 observations has a moment of inertia of about $16\ \mathrm{kg \cdot m^2}$ consisting of a telescope-photometer assembly, electronic compartment and miscellaneouses. To control azimuthal attitude of the gondola by the reactive torque of a fly wheel, we have designed and built a reaction wheel driving mechanism shown in Fig. 2–1. The fly wheel made of aluminum alloy has a moment of inertia of about $1.7\ \mathrm{kg \cdot m^2}$ with a mass of 22 kg.

The fly wheel sustained by two ball bearings is driven by a DC torque motor (model T–2967 of Inland Co.). The peak torque of this model is nominally $0.706\ \mathrm{N \cdot m}$. The twisting torque by the suspension rope, on the other hand, is about two orders of magnitude smaller than the torque exerted by the torque motor. (For example, the twisting torque expressed by $4\pi^2 I_0/T_0^2$, where I_0 is the gondola's moment and T_0 is

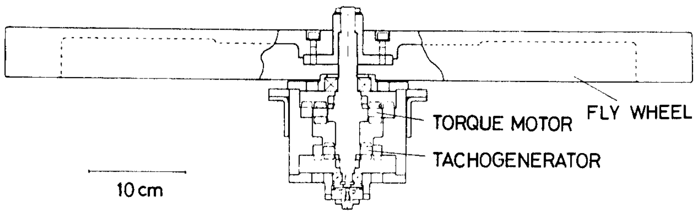


FIG. 2–1. Mechanical structure of the reaction wheel driving system. The wheel has a diameter of 68 cm, a mass of 22 kg and a moment of inertia of 1.7 kg·m^2. The torque motor is a model T-2967 of Inland Co. and the tachogenerator is a model TG-2179B.

TABLE 2–1. Servo Mechanical Components

Components	Specifications
Fly wheel	Moment of inertia: $I_R = 1.7$ kg·m^2
Torque motor	Peak torque: $T_p = 0.71$ N·m
(T-2967)	Torque sensitivity: $K_T = 0.28$ N·m·A^{-1}
	Max. speed: $\omega_{max} = 95$ rad·sec^{-1}
Tachogenerator	Voltage sensitivity: $S_V = 0.61$ V·(rad·sec^{-1})$^{-1}$
(TG-2179B)	Max. speed: $\omega_{\max} = 125$ rad·sec^{-1}
Twisting motor	Speed sensitivity: $K_V = 0.022$ rad·sec^{-1}·V^{-1}
	Max. speed: $\omega_{\max} = 0.26$ rad·sec^{-1}
Suspension rope	Period of oscillation: $T_0 = 60$ sec
Gondola	Moment of inertia: $I_0 = 15.5$ kg·m^2

the period of free rotation, is about 0.01 N·m for a twisting angle of 10°.)

We use a tachogenerator (model TG-2179B of Inland Co.) to detect a rotation speed of the wheel. The signal from this device is utilized to revolve the fly wheel continuously in order to avoid static friction occurring at the null rotation speed. Also the signal is fed to the suspension rope-twisting motor to suppress the monotonic increase of the wheel rotation.

In Table 2–1, we summarize fundamental parameters of the mechanical design of our stabilization system of the gondola.

III. EQUATIONS OF MOTION AND STABILITY CHECK

A. Block Diagram

The servo system, which we have assembled and tested, is presented in a diagram of Fig. 3–1. The azimuthal direction of the gondola is denoted by θ, while θ_0 and θ_e indicate a present value and an error signal respectively. The error signal θ_e is amplified by the servo control circuit ($G_{RW}(s)$), and fed to a drive circuit of the torque motor (torque sensitivity: K_T) to achieve fine aspect control. And moreover the twisting torque by a suspension rope ($-I_0\omega_0^2$), affecting the gondola, brings the reaction of the torque motor driving the wheel. The rotation speed $\dot{\varphi}$ of the reaction wheel is fed to the twist-rewinding motor (the servo control circuit is $G_{TR}(s)$ and the speed sensitivity of the motor is K_v), so as to suppress the increase of the rotation speed and keep the uniformity of it.

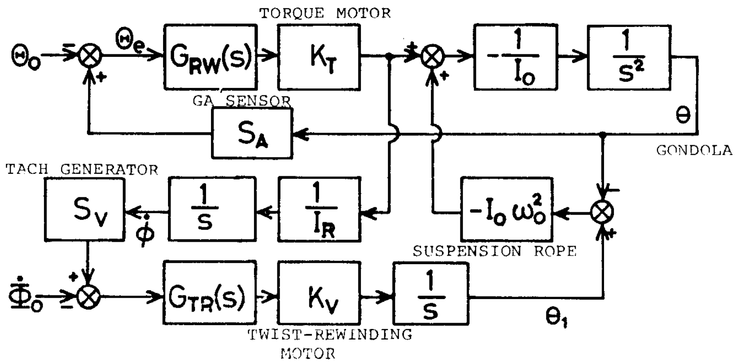


FIG. 3–1. Block diagram of the servo-control system based on the reaction wheel in conjunction with the twist-rewinding motor.

θ: azimuthal angle of the gondola.
$\dot\varphi$: rotation speed of the wheel.
θ_1: twisting angle of the suspension rope.
θ_0: signal of an aimed azimuthal direction.
θ_e: error signal in the azimuthal angle.
$\dot\varphi_0$: signal of a presenting rotation-speed of the wheel.
K_T: torque sensitivity of the torque motor.
K_V: speed sensitivity of the twisting motor.
S_A: sensitivity in the azimuth of the *GA* sensor.
I_0: moment of inertia of the gondola.
ω_0: angular frequency of free rotation of the suspended gondola.
$G_{RW}(s)$: signal modification in a servo-control circuit to drive the torque motor.
$G_{TR}(s)$: signal modification in a servo-control circuit to drive the twist-rewinding motor.
s: variable in the Laplace transform.

B. *Equation of Motion*

The equation of motion of the gondola is written as,

$$\ddot\theta = -J\ddot\varphi - \omega_0^2\cdot(\theta-\theta_1). \tag{3–1}$$

Here J defined by I_R/I_0 is the ratio of the wheel's moment of inertia to the gondola's, and $\omega_0 = 2\pi/T_0$ is the angular frequency of free rotation. Independent variables θ, φ and θ_1 are defined in Fig. 3–2. The first term in Eq. (3–1) means the motor torque to drive the wheel, and the second is the twisting torque of the suspension rope.

The rotation of the wheel is described by,

$$\ddot\varphi = a\dot\theta + b\theta, \tag{3–2}$$

where a and b are constants which are specifically determined in a servo control circuit described later.

For the twisting motor, an equation is written for rotation speed $\dot\theta_1$ rather than θ_1, that is,

$$\dot\theta_1 = -A\ddot\varphi - B\dot\varphi, \tag{3–3}$$

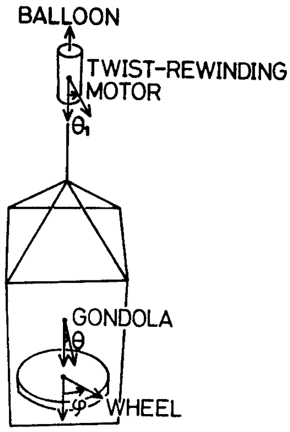


FIG. 3–2. Definition of θ, φ and θ_1 in Eqs. (3–1)–(3–3).

where A and B are coefficients in a servo system to perform the twist-rewinding control.

Nishimura [7] has proposed another form of equation for $\dot{\theta}_1$, that is,

$$\dot{\theta}_1 = -C\theta - B\dot{\varphi}, \tag{3–3}'$$

If $\ddot{\varphi}$ of Eq. (3–3) is replaced by Eq. (3–2), then,

$$\dot{\theta}_1 = -Aa\dot{\theta} - Ab\theta - B\dot{\varphi}, \tag{3–4}$$

which tends to approach to Eq. (3–3)′, because the first term of this equation is ineffective to the motion when $Jb \gg \omega_0^2 Aa$ as in the cases shown in later sections.

C. *Effect of Friction*

The possible effect of friction in the axis of rotation due to motor brushes and bearings is considered here. When the gondola and the wheel are static, Eq. (3–2) is rewritten as,

$$\ddot{\varphi} = b(\theta + f_s \cdot sgn/(b \cdot I_R)) = 0. \tag{3–5}$$

Here we denote the static frictional torque by f_s and *sgn* is the sign of the friction depending on the direction of rotation. The static friction f_s can be enlarged to the maximal static friction f_{SM}. The equation, which should be applied at the instantaneous pause, implies that the accuracy of the attitude control is restricted considerably due to a dead zone of response with a width of $2f_{SM}/(b \cdot I_R)$ in azimuth. If the wheel is controlled around a certain nonzero rotation speed, the term of dynamical friction may only cause an effect of zero shifting in the azimuthal angle.

D. *Stability Check*

From Eqs. (3–1), (3–2) and (3–3), we get an equation for as follows,

$$\ddddot{\theta} + a\dddot{\theta} + (Jb + \omega_0^2 + \omega_0^2 Aa)\ddot{\theta} + \omega_0^2(Ab + Ba)\dot{\theta} + \omega_0^2 Bb\theta = 0. \tag{3–6}$$

Eq. (3–6) turns to be an equation of the fourth degree after the Laplace transform. In an equation of the n-th degree conditions under which roots are stable have been investigated in detail (e.g. Hurwiz [8]). According to the Routh's discrimination, which is a fairly convenient method to discriminate the stability of an equation, we have expressions as follows,

$$Ja>0, \tag{3–7}$$

$$(J^2/\omega_0^2)ab+Ja+JAa^2-Ab-Ba>0, \tag{3–8}$$

$$(J^2/\omega_0^2)Aab+JAab+JBa^2+JA^2a^2b+JABa^3-A^2b^2-2ABab-B^2a^2>0, \tag{3–9}$$

$$Bb\omega_0^2>0. \tag{3–10}$$

Eq. (3–7) demmands $a>0$, a positive damping term. And we set $B>0$ and $b>0$ as consistent with (3–10). Since, in actual cases we have treated, J and ω_0 is small (0.1 and 0.1 $\sec^{-1}$ respectively) and a, $b \gg A$, B (see the following sections), then we get $Ja^2>2b$ and $J>B$ from Eq. (3–9), which are also sufficient conditions of Eq. (3–8). Thus we shall next seek for a set of parameters a, b, A and B satisfying these conditions for the stability.

IV. Determination of Parameters

If the second term of Eq. (3–1), the twisting torque term, is neglected, we get an equation of damping oscillation,

$$\ddot{\theta}=-Ja\dot{\theta}-Jb\theta. \tag{4–1}$$

This equation has a solution of critical damping when $Ja^2=4b$, which also satisfies the sufficient condition for stability stated above. The settling time of this system is characterized by $\tau_1=\pi/(2\sqrt{Jb})$ corresponding to the restoring force and $\tau_2=2/Ja$ signifying the damping time. Since we have demmanded τ_1 and $\tau_2 \simeq 0.1$ sec as a desirable response time, we may adopt $b \simeq 2.5 \cdot 10^3 \sec^{-2}$, and $a \simeq 3 \cdot 10^2 \sec^{-1}$. As, in actual cases, the damping term is generated in an electric circuit by differentiating the signal after considerable amplification, it may become ineffective owing to the electric saturation. So, it would be more practical to choose a larger value of a, for example, $a \simeq 6.6 \cdot 10^3 \sec^{-1}$ as adopted in the present experiment.

Our principle in determining A and B, which relate to the behavior of the twisting motor and the wheel rotation, is to maintain the rotation speed nearly constant by actuating the twisting motor with a much slower response time. To examine the coupled behavior of them, let us consider an azimuth-locked state, i.e., $\ddot{\theta}=0$, and $\theta=0$. Then from Eqs. (3–1) and (3–3) we get,

$$\dddot{\varphi}=-(A\omega_0^2/J)\ddot{\varphi}-(B\omega_0^2/J)\dot{\varphi}, \tag{4–2}$$

also an equation of damping oscillation. The requirement of long time constant of this system compared with the above τ_1 and τ_2 is written as,

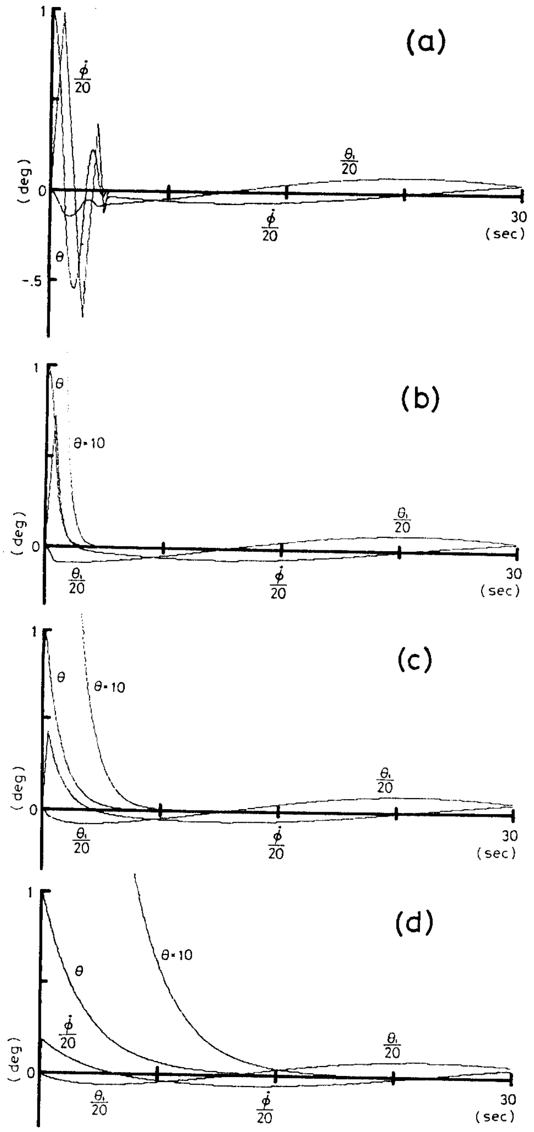


FIG. 4-1

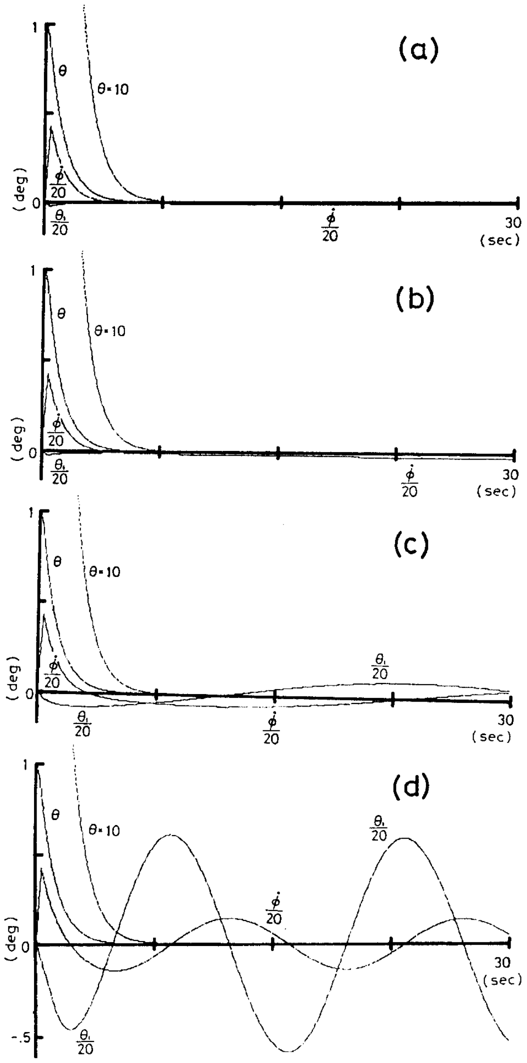


FIG. 4-2

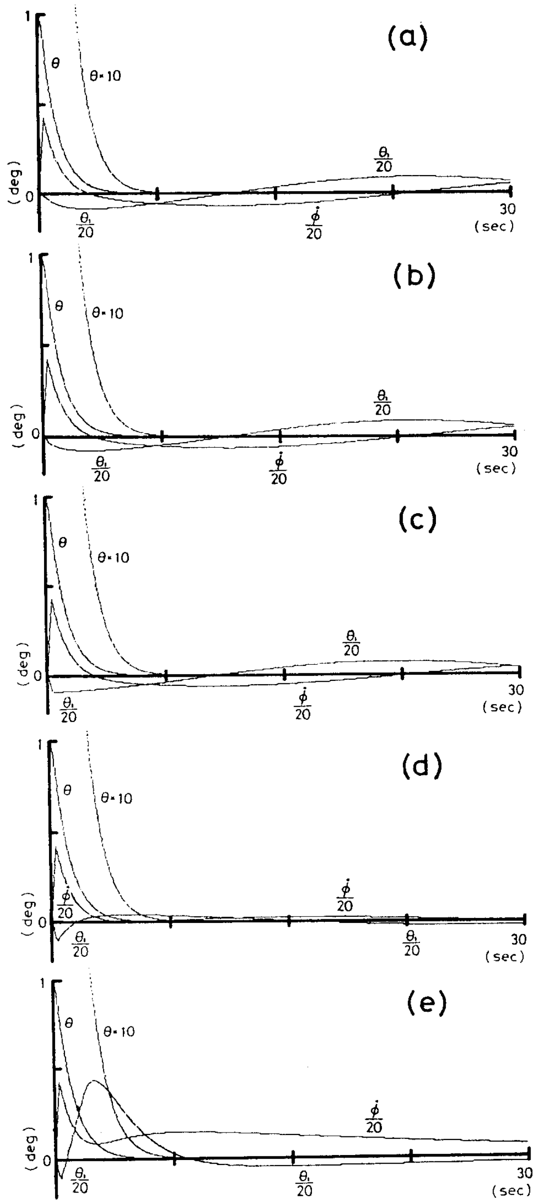
FIG. 4-1. Numerical simulations of the coupled motion expressed in Eqs. (3-1)-(3-3). An initial state of the motion is taken as $\theta=1°$, $\dot{\theta}=0°\ \mathrm{sec}^{-1}$ and $\dot{\varphi}=0°\ \mathrm{sec}^{-1}$. Maximum acceleration of the wheel and maximum speed of the twisting motor due to saturation effect are involved, which are $0.41\ \mathrm{rad \cdot sec^{-2}}$ and $0.2\ \mathrm{rad \cdot sec^{-1}}$ respectively. Parameters of the servo-control are $b=2500\ \mathrm{sec}^{-2}$, $A=0.05$ sec and $B=0.18$. A damping term related to the reaction wheel, a, is taken as follows; (a) $300\ \mathrm{sec}^{-1}$, (b) $1000\ \mathrm{sec}^{-1}$, (c) $2500\ \mathrm{sec}^{-1}$ and (d) $6600\ \mathrm{sec}^{-1}$.

FIG. 4-2. Same as Fig. 4-1, but parameters of the servo-control is $a=2500\ \mathrm{sec}^{-1}$, $b=2500\ \mathrm{sec}^{-2}$ and $A=0.05$ sec. A restoring term related to the twist-rewinding motor, B, is taken as follows; (a) 0.0018, (b) 0.018, (c) 0.18 and (d) 1.8.

$$A \ll (J^2/\omega_0^2)a, \text{ and } B \ll (J^2/\omega_0^2)b. \tag{4-3}$$

Since $J^2/\omega_0^2 \simeq 1$, this leads $A \ll a$, and $B \ll b$.

The actual behavior is hard to predict quantitatively from a simple analysis, we have made numerical computation to determine a suitable set of parameters. In



FIG, 4–3. Same as FIG, 4–1, but parameters of the servo-control is a=2500 sec^{-1}, b=2500 sec^{-2} and B=0.18. A damping term related to the twist-rewinding motor, A, is taken as follows; (a) 0.005 sec, (b) 0.05 sec, (c) 0.18 sec, (d) 0.5 sec and (e) 5.0 sec.

TABLE 4–1. Adopted Parameters

Parameters	adopted values
Restoring term for the reaction wheel	b=2.5×10^3 sec^{-2}
Damping term for the reaction wheel	a=6.6×10^3 sec^{-1}
Restoring term for the twist-rewinding motor	B=0.18
Damping ferm for the twist-rewinding motor	A=0.05 sec

Fig. 4–1, 4–2 and 4–3, results of numerical simulations are presented to examine the consequence of different sets of parameters. As indicated in these figures, the motion of the gondola is basically defined by the parameters a and b, while the coupled behavior of the twisting motor and the wheel rotation being governed by the selection of A and B. In consequence, we have employed a set of parameters tabulated in Table 4–1, by which the actual balloon-borne observations were made.

V. Electric Circuit Design

The signal of azimuthal angle θ is generated by a geomagnetic sensor fixed on the top frame of the gondola. The overall gain of amplification corresponds to the coefficient b. Another term a is yielded through a differentiating circuit made of an operational amplifier similar to the previous paper (Hiromoto e tal. [6]).

We use a simple voltage-to-current coverter based on an operational amplifier, as shown in Fig. 5–1, that has been devised in the present experiment. This is capable of yielding current in proportion to the input voltage independent of the reverse voltage occurring at terminals of the torque motor. If $R_5 \ll R_2+R_4$ and $R_1R_4=R_2R_3$, the relation between output current I_0 and input voltage e_i is expressed as,

$$I_0=-R_3/(R_1\cdot R_5)e_i. \tag{5–1}$$

Several maneuvering modes of azimuth control used in our system are a pointing mode, rapid and slow scanning modes, and a pseudo-tracking mode. Scanning or pseudo-tracking are performed by adding DC voltages varying with respective

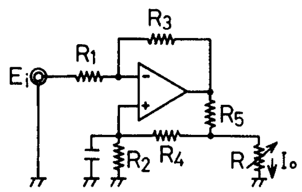


Fig. 5–1. Voltage-to-current converter based on an operational amplifier exploited in this experiment. A register R_4 is introduced for the usage at large current. Resisters are taken as $R_1=60$ k, $R_2=30$ k, $R_3=120$ k, $R_4=60$ k and $R_5=0.5\ \Omega$.

Table 5–1. Maneuvering Modes

Mode	Width	Speed
Azimuthal offsetting		
rapid	$\pm 70^{\circ}$	$1\overset{\circ}{.}6\ \mathrm{sec}^{-1}$
slow	$\pm 70^{\circ}$	$0\overset{\circ}{.}36\ \mathrm{sec}^{-1}$
Scanning		
rapid	$\pm 19^{\circ}$	$0\overset{\circ}{.}26\ \mathrm{sec}^{-1}$
slow	$\pm 6^{\circ}$	$0\overset{\circ}{.}085\ \mathrm{sec}^{-1}$
Pseudo-tracking		$0\overset{\circ}{.}0042\ \mathrm{sec}^{-1}$

rate to the signal from the magnetosensor. The scanning rates are $0^\circ.26\ \mathrm{sec}^{-1}$ for the rapid mode, $0.^\circ 085\ \mathrm{sec}^{-1}$ for the slow mode and $0.^\circ 25\ \mathrm{min}^{-1}$ for pseudo-tracking mode. Coarse setting of the azimuthal attitude of the gendola is also achieved by changing offset voltage in each mode. The specifications of these functions are summarized in Table 5–1.

VI. Flight Performance

The developed attitude control system described here, which comprises the reaction wheel-based azimuthal torquer and the twist-rewinding motor, were flown on June 3, 1981 and May 24, 1982 to make near-infrared polarimetric observations of the Galaxy. The flights were successfully carried out at the Snariku Balloon Center of the Institute of Space and Astronautical Science using a B_{15} (15000 m^3) balloon.

The azimuthal direction of the gondola sensed by a magnetometer of flux gate type was transmitted through a PCM telemetry system, which restricted read-out signal resolution of about 2 arcmin. In Fig. 6–1a the realized attitude data given by the magnetometer is shown for each mode of operation. The time-dependent traces of azimuth presented in the figure appear to have achieved stability better than $\pm 1'$, i.e. fluctuation of the least significant bit(LSB), throughout observations.

The rotation spead of the wheel is also presented in Fig. 6–1a and 6–1b. It is shown that the average speed was maintained at around 4 rpm ± 1.2 rpm with a period of about 55 sec. The period is related to the coupled motion between the reaction wheel and the twisting motor, expressed by $2\pi/\omega_0 \cdot (J/B)^{1/2}$. Though this oscillatory motion has little effect on the performance of gondola control itself, it would be possible to reduce the amplitude of oscillation by choosing a more suitable coefficient A than the present value adopted. Anyway, the instrument, which we have de-

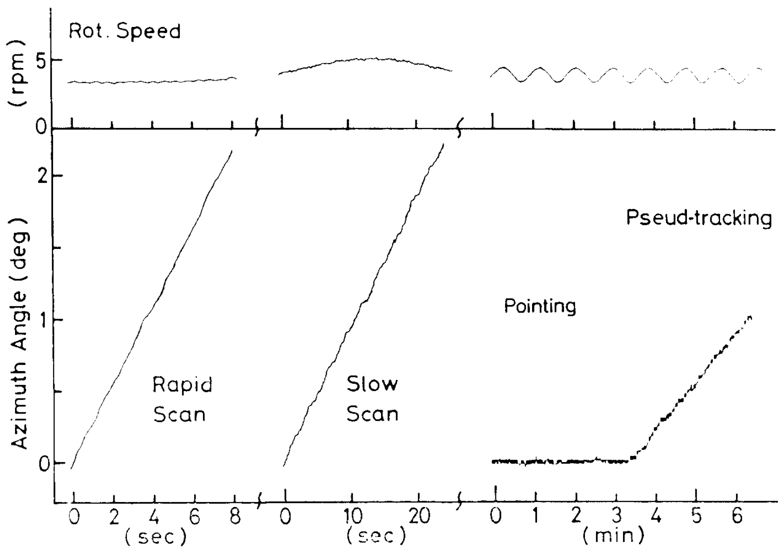


Fig. 6–1a. Profiles of the azimuthal angle of the gondola and the rotation speed of the wheel in the various maneuvering modes at the balloon experiments.

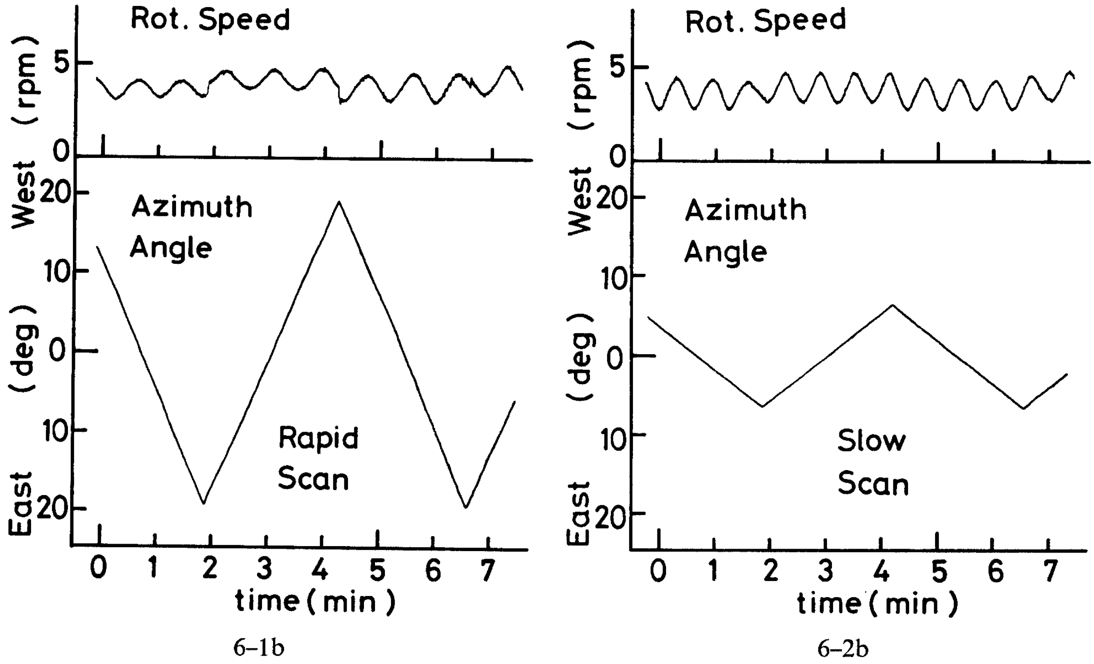


FIG. 6–1, 2b. Scanning profiles in the rapid and the show modes at the balloon experiments.

veloped and reported here, has proved a sufficient performance in each observational mode with an aimed stabilization of 1 arcmin.

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