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No. 109 THE POLARISCOPE BALLOON-BORNE SERVO SYSTEM

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ABSTRACT

This paper describes the stable platform for the Polariscope 71-cm Cassegrain telescope that is mounted in a box-like aluminum gondola (Fig. 1). It is designed to "lock on" certain stars or planets during balloon flights at 36 km altitude and measure the polarization at 2250 and 2850 Angstroms (Coyne and Gehrels 1968).

*1. Stabilization Systems*

The Polariscope telescope is to be pointed in a fixed direction in space but the base, or gondola, is free to move about. The gondola weighs 740 kg at launch — this includes 181 kg of ballast, but not the parachute — and is suspended from 52m long nylon shroud lines (see Fig. 2). The gondola acts as a mass bobbing on an underdamped spring, on a simple pendulum, on a compound pendulum; usually there is a combination of all three. As the gondola moves about it must not drag the telescope with it. This absolutely rules out the use of viscous coupling, such as tachometer feedback, between the gondola and the telescope.

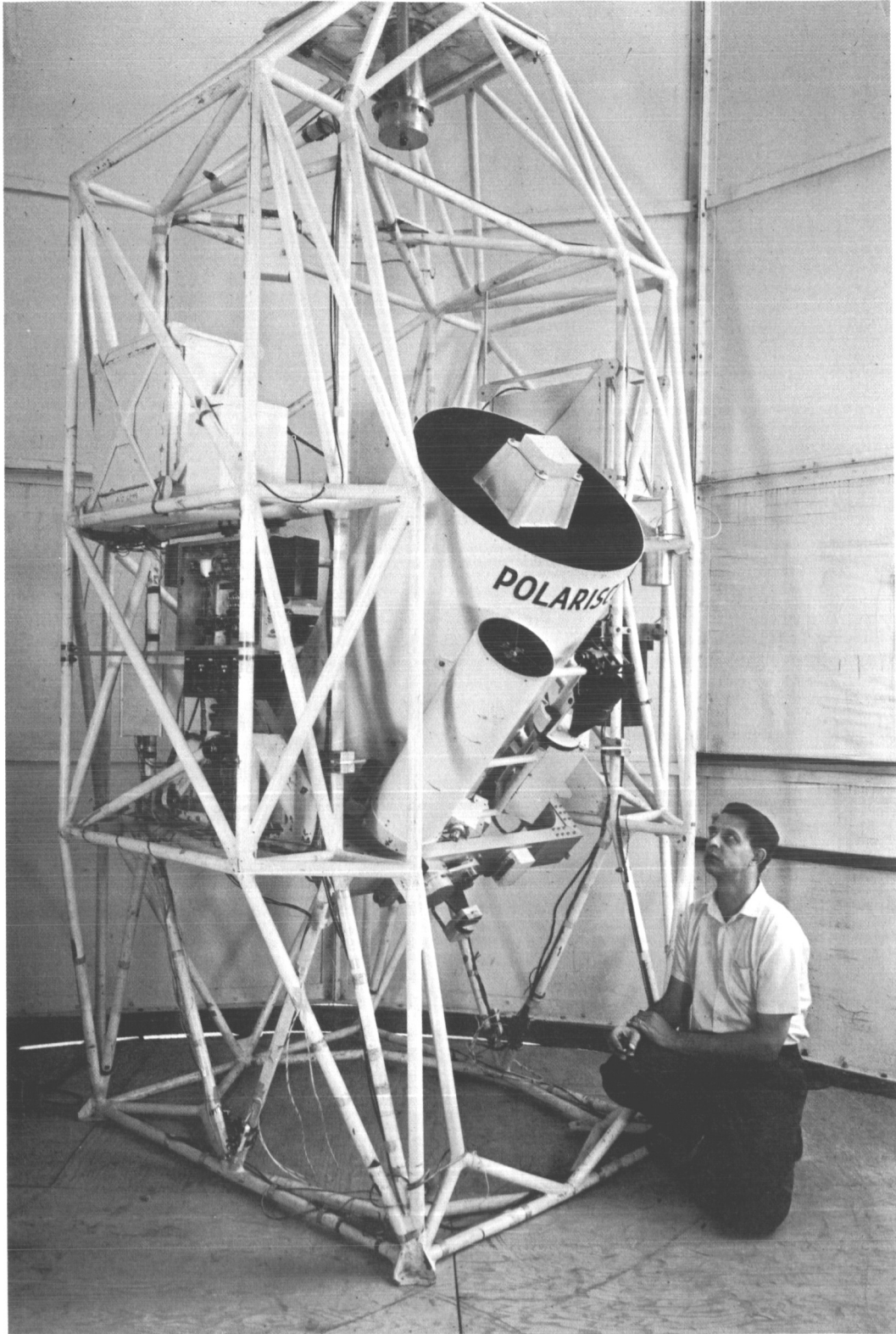
Every movement of the telescope causes a counter-movement of the gondola. If the telescope is moved in elevation the gondola is excited in compound pendulum motion with a decay time of 2 or 3 mins. This oscillation must be damped out. The only damping available is the flexing of the nylon suspension system. If the telescope is moved in azimuth the gondola tries to rotate in the opposite direction. It is then necessary to torque against the balloon through the suspension system to counteract the azimuth motion of the gondola.

There are three natural resonant frequencies in the suspension system. Simple pendulum has a frequency of about 1/20 cps. Torsional pendulum motion is roughly the same. Compound pendulum is close to 1/2 cps. Cross-over frequencies of the servo system must be above these resonant frequencies and below any of the mechanical resonant frequencies of the instrument itself.

*2. Choice of Gimbals*

Three gimbals are used on Polariscope. One gimbal ring is movable in elevation. The axis of the inner gimbal, or telescope proper, is normal to the elevation axis and lies in the plane of the gimbal ring (see Fig. 1). This is called the cross-elevation axis, and the telescope is free to move  $\pm 10^\circ$  in this axis. A third axis, in azimuth, is controlled to keep the gondola opening approximately centered about the telescope. For a true orientation system a fourth axis would be necessary, controlling about a line through the center of the telescope, and it would prevent the image plane from rotating during the observations.

The inner gimbal, or telescope proper, weighs about 140 kg. The outer gimbal ring is a boxlike



*Fig. 1* Polariscope 71-cm telescope, with 20-cm startracker and 7.5 cm vidicon camera lens, within elevation gimbal on gondola frame.

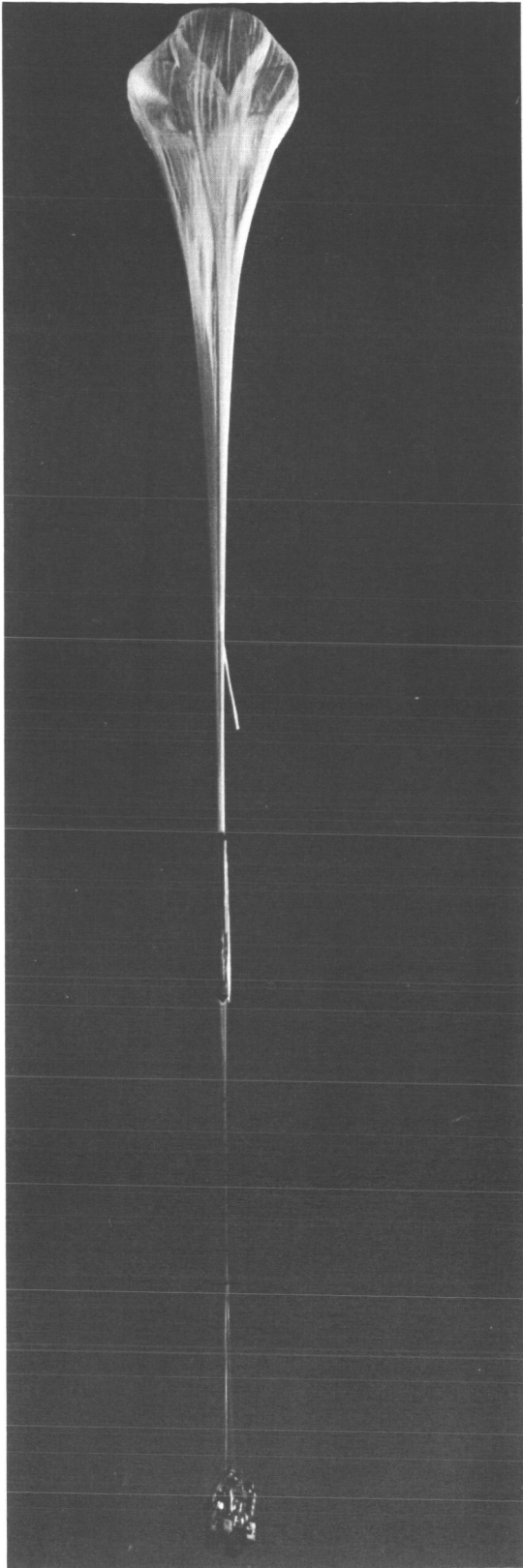


Fig. 2 Polariscope in flight shortly after launch. Photo courtesy D. L. Brumbaugh.

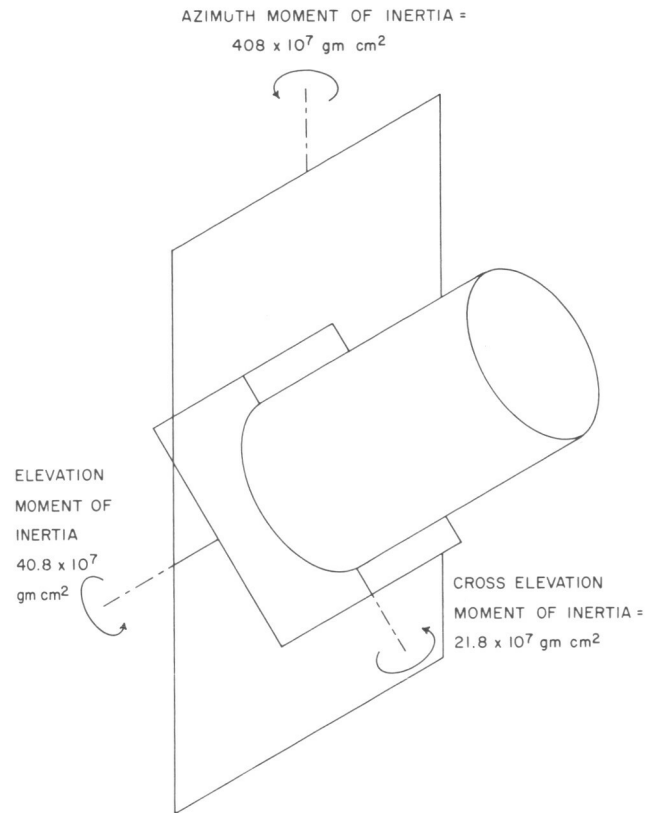


Fig. 3 Gimbal diagram of Polariscope.

structure made of aluminum channel. As such it is quite flexible. To avoid a low resonant frequency between the drive motors and the driven element it was decided to drive the telescope in both axes from two sides rather than from one side of the gimbal ring. This permits a higher servo cross-over frequency than would be possible if the gimbals were driven from one side only. At least  $14 \times 10^7$  dyne cm (10 foot pounds) of peak torque motors made by Inland Motor Corporation of Virginia were selected to be prime movers. Torque motors normally drive their load directly, with no reduction ratio. The most nearly suitable motor built by Inland would be the model 5730, but, used in pairs, these would have required as much as 510 W of peak electrical power to the motors for  $19 \times 10^7$  dyne cm of torque. Smaller motors and a reduction ratio are therefore indicated.

It is difficult to build a servo system that will point to within a few seconds of arc using gear trains with several minutes of arc backlash. We therefore adopted a technique, pioneered for balloon telescopes by G. A. Newkirk of the High Altitude Observatory, that uses gearless reduction ratios involving smooth discs or shafts driving each other, relying

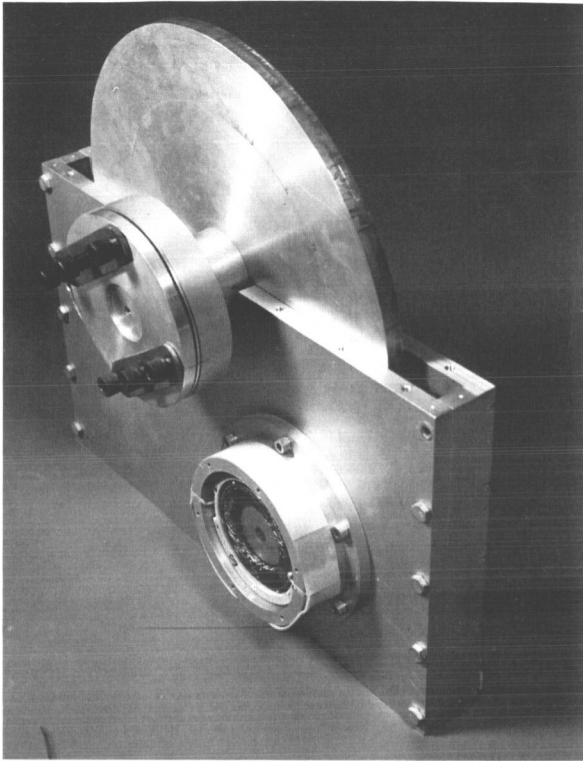


Fig. 4 Elevation motor mount. Idler bearing shaft is concealed by elevation trunnion. Gimbal ring bolts to trunnion with the six Allen head screws. Thrust bearings (not shown) prevent drive disc from touching sides of box.

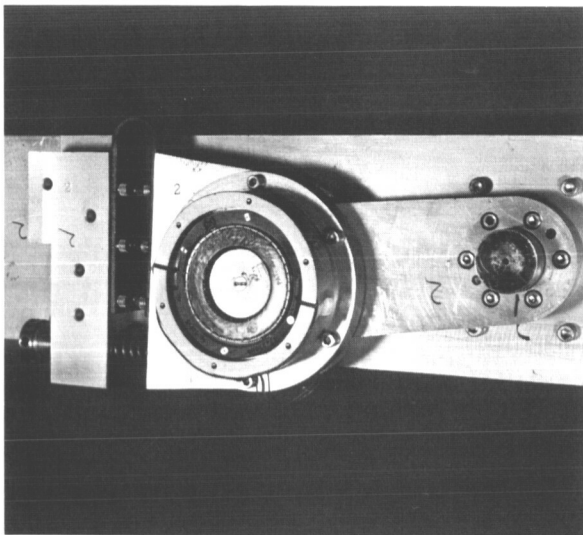


Fig. 5 Cross Elevation motor mount installed on gimbal ring. Hairpin-like steel spring is a flexure bearing; coil spring forces motor shaft against drive disc sector.

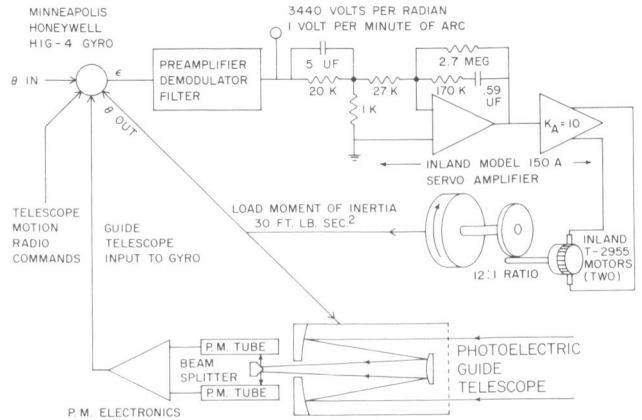


Fig. 6 Block diagram of elevation servo. Photoelectric guide telescope contains a tetrahedral beam splitter at the focal plane of the telescope, and four photomultiplier tubes. If the optical beam is centered on the beam splitter the outputs of the photomultiplier tubes are equal and the precession current to the gyro is zero. If the optical beam is off-axis the outputs of the photomultiplier tubes are unequal and a precession current to the gyro causes the telescope to move toward the star until it is optically centered in the guide telescope.

only on pressure of one member against another to avoid slippage (Hull 1964; as a general reference we used Nidey 1962). Our prime mover (see Figs. 3, 4, 5, and 6) consists of two Inland model 2955 motors per axis; they drive smooth shafts, 2.5 cm in diameter. These in turn drive 32-cm diameter by 1.3-cm thick aluminum discs affixed to the load. The discs are gravity loaded against the motor shafts in elevation. In cross elevation the motor mount is spring loaded against the drive disc sector. This system requires only 150 W of peak electrical power per axis for  $27 \times 10^7$  dyne cm of torque. It has low friction and zero backlash.

A block diagram of the elevation servo electrical system appears in Fig. 6. A Minneapolis-Honeywell HIG-4 gyro is used as the inertial reference element. A good gyro of this type will cause a servo system to point in a fixed direction in space with a small (less than one earth-rate unit) drift caused by the rotation of the earth, which can be trimmed out. Its null position can be changed by electrical precession signals from outside. Its output is a 1600 HZ phase-sensitive error signal. This signal is amplified, demodulated and filtered, being raised to a level where  $K_{\theta} = 1$  V per min of arc, or 3440 V/rad. This is followed by an Inland model 150A servo amplifier consisting of an operational preamplifier whose transfer function is set by external components, feeding a 150 W output power amplifier with a volt-

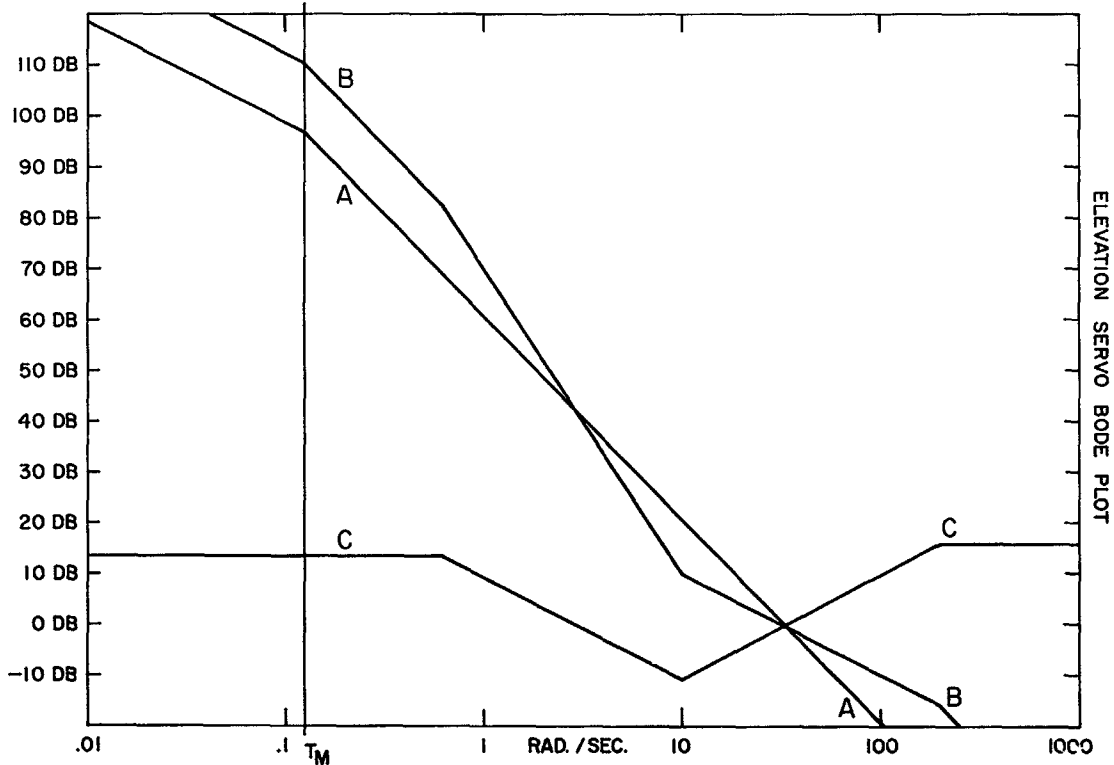


Fig. 7 Bode plot of elevation servo system showing open loop gains vs. frequency.

age gain of 10. The amplifier drives two Inland model 2955 motors, each driving the load moment of inertia of  $41 \times 10^7$  gm cm<sup>2</sup> through 12:1 gearless reduction ratios.

Radio commands for telescope motion are applied as precession currents to the HIG-4 gyros. These signals can control the telescope at rates from 1°/min to 50°/min.

When the telescope is brought to within 5 mins of arc of the desired star the photoelectric guide telescope "sees" the star and generates precession currents with its photomultiplier tubes to correct the gyros constantly, holding the telescope "locked on."

Figure 7 is a Bode plot of the elevation servo (Inland Handbook 1964). Curve A is the uncompensated servo open loop gain assuming that  $K_\theta$  equals 3440 volts per radian, times the power amplifier gain of 10, times the operational amplifier gain arbitrarily assumed set at unity, times the transfer function of the motor and load. Specifically it is a plot of:

$$\text{Open loop gain} = \frac{K_\theta K_A}{K_B} \cdot \frac{1}{S(1+T_M S)}$$

where  $T_M = \frac{J_T}{K_B K_T / R_M}$  and

- $K_\theta$  is Transducer sensitivity, 3440 V/rad;
- $K_A$  is power amplifier gain, 10 V/V;
- $J_T$  is combined motor-load moment of inertia,  $41 \times 10^7$  gm cm<sup>2</sup>;
- $K_B$  is motor winding back EMF constant, 4.08 V/(rad/sec);
- $K_T$  is motor winding torque sensitivity constant,  $4 \times 10^7$  dyne cm/A;
- $R_M$  is motor resist, 3.35 ohms;
- $T_M$  is system mechanical time constant, 8.22 secs.

Curve B is a Bode plot of the compensated servo with a zero decibel cross-over frequency of 5 HZ or 31.5 rad./sec. and  $K_{\theta} K_A / K_B = 40,000$ . This cross-over frequency was chosen as the geometric mean between the compound pendulum frequency and a mechanical resonant frequency that exists in the telescope. Curve C is the difference between curve A and B and is the desired gain-frequency response curve of the operational preamplifier in the Inland servo amplifier. The network values to accomplish this end are shown in Fig. 5. Actually, the 27K resistor is made 33K to compensate for increased servo gain due to cooling off of the torque motors at altitude.

The cross elevation servo is similar to the elevation servo, differing only in moment of inertia and network gain. Pointing accuracy of the elevation and cross-elevation servo is  $\pm 6$  arc sec peak error, or  $\pm 2$  arc sec RMS error.

### 3. Azimuth Servo

The purpose of the azimuth servo is to keep the gondola opening approximately centered about the telescope. The prime mover is a shaft directly driven by a 7 ft. lb. torque motor. It receives its error signal from a precision potentiometer on the cross-elevation axis. Unlike a conventional servo system which torques against a solid mass, this servo system torques against a spring, namely the parachute shroud lines. With 52 m suspension length and 740 kg gondola weight they have a spring function of approximately  $9.5 \times 10^7$  dyne cm for  $30^\circ$  deflection. The electronic network for the system was designed empirically rather than scientifically and will not be discussed here.

### 4. Flight Results

Polariscope flew for the first time with this servo system in March 1967. Performance of the elevation and cross-elevation servo was impeccable throughout the flight. The azimuth shaft bound up once at the beginning of the flight but freed itself and operated properly during the remainder of the flight. This momentary failure has since resulted in the expenditure of considerable effort to improve the azimuth shaft structure and to select the best possible bearing and lubricant. Bearing and motor friction is now  $0.54 \times 10^7$  dyne cm with 726 kg loading the bearing. The second flight with this system occurred in January 1968 and the performance in azimuth was faultless as well as that in elevation and cross-elevation.

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