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DESIGN AND PERFORMANCE OF A 39cm BALLOON-BORNE TELESCOPE

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ABSTRACT

The U.C.L. MkI gondola incorporates a 39cm telescope of Dall Kirkham configuration. This is stabilized to about 30 arc sec r.m.s. along its line of sight by means of a star sensor driving torque motors on the azimuth and elevation axes. Guide stars from -4 to +4 in magnitude can be used and the star sensor may be offset with respect to the telescope by us to ±5° in elevation and cross elevation to enable parts of the sky containing no suitable guide stars to be viewed. Acquisition of the guide star and setting of the offset coordinates is carried out by ground command and both may be easily changed in flight.

The instrument has been used extensively over the past three years for astronomical observations in the far infra-red and has made 13 flights to date.

INTRODUCTION

In 1969 the Physics Engineering Group at U.C.L., headed by the late H.S. Tomlinson, began the construction of a stabilized balloon-borne telescope. This was designed specifically to meet the requirements of the Infra-Red Astronomy Group under Dr. R.E. Jennings. The following is an account of the design and of the operating experience obtained with the original gondola.

DESIGN CONSIDERATIONS

Whilst a large telescope is desirable, both for reasons of sensitivity and resolution, the financial implications in terms of construction and operating costs limited us, at that time, to a telescope of around 40cm dia. At 100μm the diffraction limit is then about 1 arc min so that a pointing accuracy of this order has been aimed for. A simple biaxial configuration has been chosen with the telescope mounted on an elevation axis within a gondola controlled in azimuth by a motor driving against a reaction wheel. The sensor for the servo system is a star tracker attached to the telescope. This can be offset with respect to the telescope to view areas adjacent to the guide star. Since this will introduce a variable pointing error proportional to the offset angle and to the amplitude of any pendulum motion of the gondola the offset has to be limited to a maximum of ±5° in the elevation and cross elevation directions. A coarse steering mode, controlled by reference to the Earth's magnetic fields and local vertical, is provided to initially direct the star sensor at the chosen guide stat.

An optical system of cassegranian form has been chosen since this enables the masses of the optical components to be conveniently distributed about the elevation axis. It has the further advantage that the final convergent beam can be directed, by means of a 45° flat, out through a hollow elevation shaft to a focus fixed with respect to the gondola frame. This arrangement was originally adopted so that a dewar containing the liquid helium cooled bolometer used for infra-red detection could be mounted in an upright position. It has proved to be a very convenient interface between the telescope and the experimenter's equipment and is free from any major restriction on the size and weight of such equipment.

The main design parameters may be summarized as follows:

Optics:	39cm f/2 f/5.5 Dall Kirkham.
	10 arc sec visible on axis image.
Control axes:	Elevation $0^\circ - 70^\circ$.
	Azimuth $0^\circ - 360^\circ$
Gondola:	size 1.7m x 1.4m x 2.3m height.
	weight 250 kg bare
	500 kg flight ready
	M.O.I. about Azimuth axis 30 kgm^2 bare
	100 kgm^2 flight
	Reaction wheel M.O.I. 1 kgm^2
Guidance:	coarse sensors - flux gate magnetometer + elevation angle pot.
	fine sensor - star tracker with offset drives.
Pointing accuracy:	coarse ± 0.5° pk-pk.
	fine ± 1' pk-pk at zero offset.
Star tracker:	Allowable guide star magnitudes -4 to +4 (Si1 mags).
	noise equivalent angle at null > 20" r.m.s.
	error signal B.W. 10 Hz.
	field of view 2° dia.
	Offset range $\pm 5^\circ$ in elevation and cross elevation.
	Offset drive rate 0.04 to 10 arc min/sec.
Operating equipment:	temperature $+40^\circ$ to -60°C.
	pressure ambient to 2 mb.

CONSTRUCTION

The layout of the gondola is clearly seen in Fig.1. It consists of a rigid rectangular frame in which the telescope is supported by two elevation bearings, one of which houses the elevation drive motor. The main frame is suspended by the azimuth drive unit from the reaction wheel which is, in turn, suspended from the balloon via a trifilar suspension and a swivel coupling. This swivel prevents the suspension winding up and also leaks momentum through from the reaction wheel to the balloon. The main frame is surrounded by an outer protective framework of small aluminium members within which batteries, telemetry, etc. are housed. During flight protective panels, roll bars and crash pads are added as required. (Fig.2).

A section through the main frame, telescope and bearing assembly is shown in Fig.3. For ease of construction and repair, standard aluminium sections are used for the framework and the main frame is of channel sections bolted together with machined brackets. The elevation bearings are mounted in simple pin and bush gimbals so that they are self- aligning and hence not affected by distortions or inaccuracies in the main frame. An Inland T-4036 D.C. torque motor of 2.4 NM rating is used for the elevation drive.

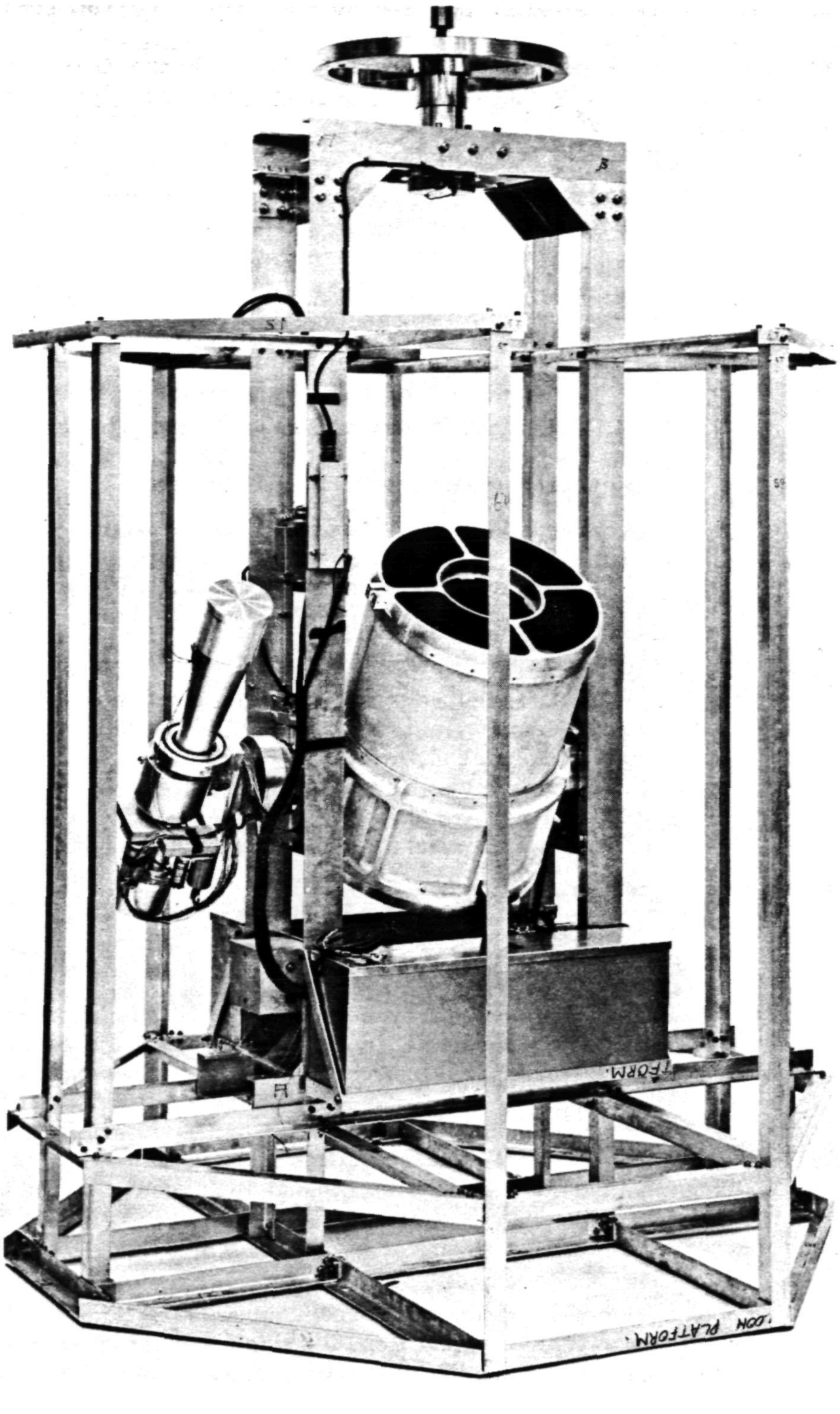

Figure 1. The telescope in the course of construction.

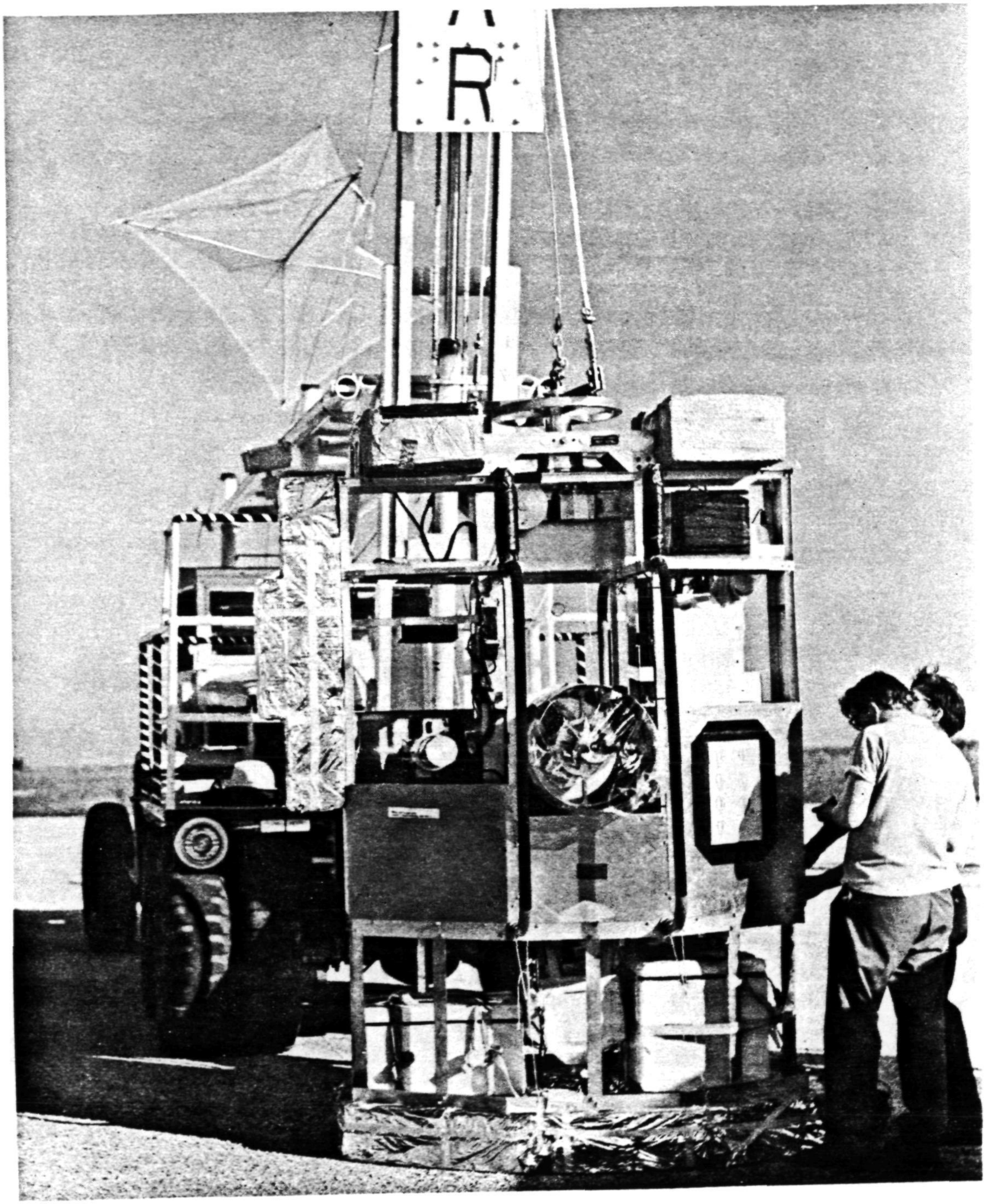

Figure 2. The gondola ready for launch.

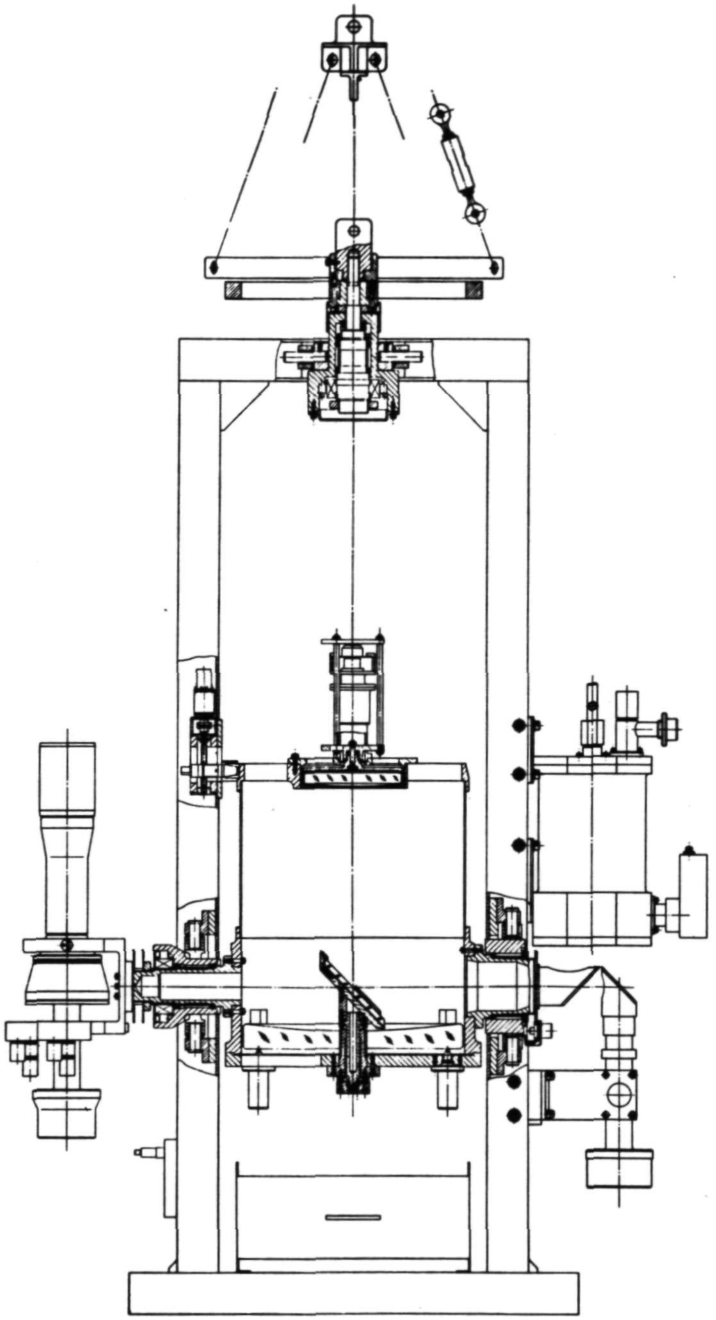

Figure 3. Section through main frame, bearings and telescope.

The azimuth drive unit is also supported in gimbals which take up inaccuracies in the trifilar suspension lengths. The drive motor is an Inland T-5135 of 4 NM rating. When suspended the gondola weight is taken on a low friction thrust race between the bearing housing and the azimuth shaft.

The telescope tube is made from a forged and machined aluminium alloy ring to which the elevation stub axles are bolted. This is connected to the secondary mirror spider by a thin aluminium cylinder. Spigots machined in the strong ring and spider locate and align the primary mirror support plate and the secondary mirror assembly. The primary mirror is centred on the support plate by a stalk which also carries the 45° flat. Three equispaced spring loaded plungers mounted in the support plate push the mirror against teflon stops on the inside of the strong ring with sufficient force to withstand a 4g axial deceleration.

The necessary chopping of radiation to the infra-red detector is achieved by rocking the secondary mirror to shift the effective pointing direction of the telescope. To this end the mirror cell is supported at the spider by a flexible diaphram and can be moved by a rigid shaft fixed to the back of the cell. Two mirror drive mechanisms have been used. In the original a motor and eccentric bearing were used to move the drive shaft in a circular motion so that the focussed image from the telescope was swept in a circular path of about 8 arc min dia. at 13 Hz. This has now been replaced by a mechanism using two solénoids to impart a square wave motion, of similar amplitude and frequency, to the mirror in the cross elevation direction.

CONTROL SYSTEM AND ELECTRONICS

A simplified block diagram of the electronics is shown in Fig.4. There are two control modes.

(i) Coarse Stabilization using error signals from a flux gate magnetometer for azimuth control and from a potentiometer on the elevation axis for the elevation. Both sensors can be rotated about the appropriate axes by ground commanded stepping motor drives to set the telescope to any desired azimuth and elevation. A readoutof the set angles is provided by 10 bit shaft angleencoders mounted on the sensor drive shafts. The overall accuracy in azimuth and elevation settings relative to the magnetic meridian and local vertical is better than $\pm\frac{1}{2}^{\circ}$.

(ii) Fine Stabilization uses error signals from the star tracker to control the azimuth and elevation motors. The servo gain useable is limited in elevation by the star tracker bandwidth and in azimuth by the compliance of the main frame. Under steady conditions with a bright guide star and at low elevation angles a pointing accuracy of ±20 arc sec pk-pk is achieved. This degrades somewhat with elevation angles above 40° and with guide stars dimmer than 3rd mag. A photograph of typical error signals recorded inflight is shown in Fig.5.

The star tracker is mounted in elevation and cross elevation gimbals and can be offset, with respect to the telescope, by up to ±5° in either axis by ground commanded stepping motor drives. The resultant effect, with the sensor locked to the guide star, is to offset the telescope pointing direction from that star. An autoscan drive mode is provided to enable raster scans to be made over the 10° x 10° area or smaller scans can be made under manual control. Offset angle readouts are by 10 bit shaft angle encoders geared to the offset drives. These provide offset coordinates to better than 1 arc min but these are subject to alignment errors (about 1') and thermal distortions (about 1'). A check on the telescope pointing direction is provided by a photomultiplier

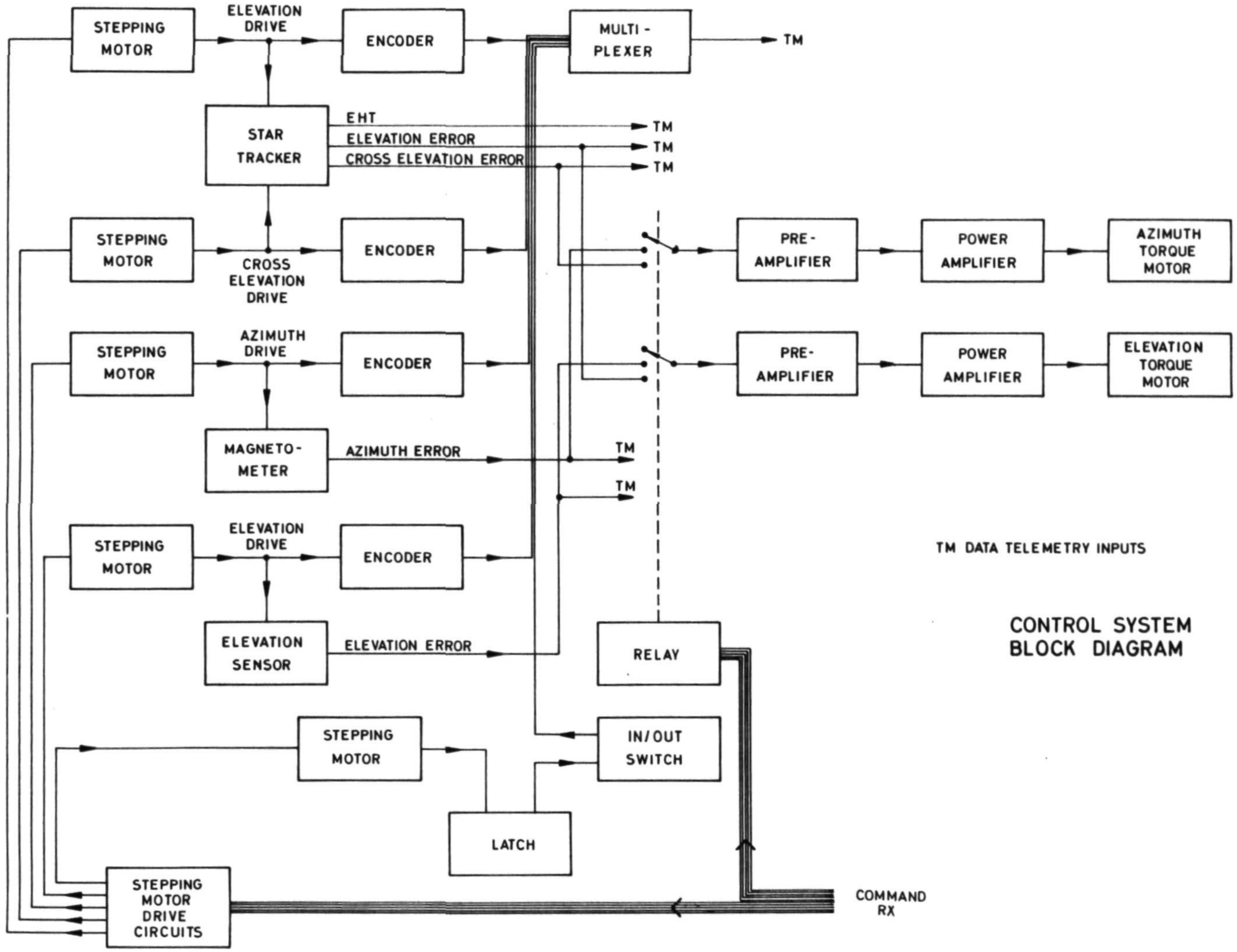

Figure 4. Block diagram of control system.

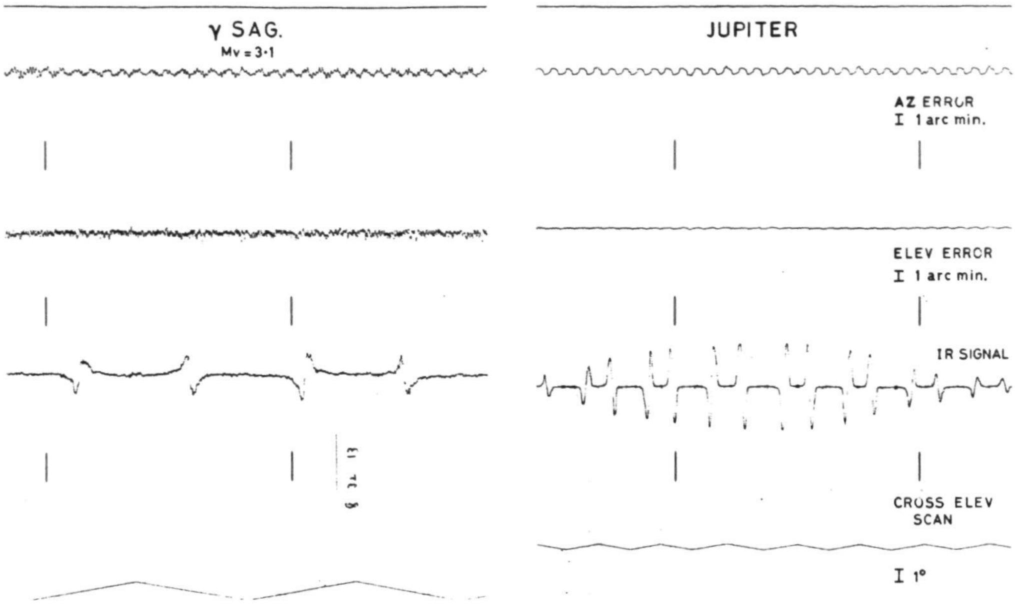

Figure 5. Typical error signal recorded in flight.

monitoring the visible radiation at the telescope focus. This has a 5 arc min dia. field of view and a logarithmic response over the range Mv = 2 to Mv = 8. During scans this signal can be used to build up a picture of the visible star field in the area for comparison and calibration purposes.

In addition to that described above a small amount of electronics is needed to encode the shaft angle outputs into a suitable form for transmission by the data telemetry, to multiplex housekeeping data and to control the latch used to secure the telescope in a vertical position during ascent and descent. The major part of the electronics is housed in a thermally insulated box sited for protection within the main frame.

The overall power consumption of the gondola is about 50 watts in the coarse stabilized mode rising to about 150-200 watts in the star stabilized mode. This is provided by a 24v 120 A.H. pack of silver zinc cells.

The system requires 10 latched commands and 6 I.R.I.G. F.M. data telemetry channels for its effective control.

STAR TRACKER

To enable all parts of the galactic plane to be accessible within the $\pm 5^{\circ}$ offset provided, the star tracker must operate on stars down to 4th Magnitude. In addition, the stability of the guidance servos require the star tracker to have a gain stability of 6db and an error signal bandwidth of 10 Hz. For reasonable transient performance at acquisition a linear characteristic near the null at least ±5 arc min wide is desirable.

The design of the star tracker is fairly conventional and a cross section is shown in Fig.6. A rotating half disc is used to modulate the defocussed image formed by a f/4 lens of 30 cm focal length. Analysis of the amplitude and phase

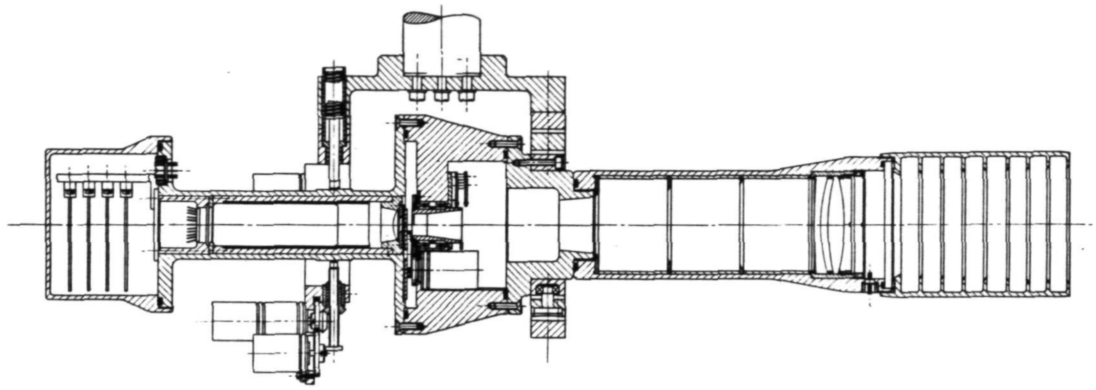

Figure 6. Cross section through Star Tracker.

of the modulated light, as detected by a photomultiplier enables elevation and cross elevation error signals to be derived. This simple arrangement provides no discrimination against sky background radiation which may amount to the equivalent of 1 Mv = +4 star/sq.deg. Accordingly a second chopper wheel with closely spaced spokes (3 arc min) has been added to sweep the entire field of view. This modulates only images with dimensions less than the spoke spacing and so enables (by means of an electrical filter tuned to the spoke frequency) star signals to be differentiated from a diffuse background.

A block diagram of the star tracker electronics is shown in Fig.7. A.G.C. is provided by varying the photomultiplier E.H.T. to maintain a constant level in the chopped signal and the star tracker gain varies negligibly over a range of star magnitudes -4 to +4. Under A.G.C. conditions the E.H.T. level gives a good indication of star magnitude and is useful for guide star confirmation.

The star tracker is mounted in gimbals from a plate fixed to the elevation shaft. At the rear of this plate two motor driven screws drive the end of the sensor to provide the offset facility. The layout of these offset drives can be seen in Fig.8.

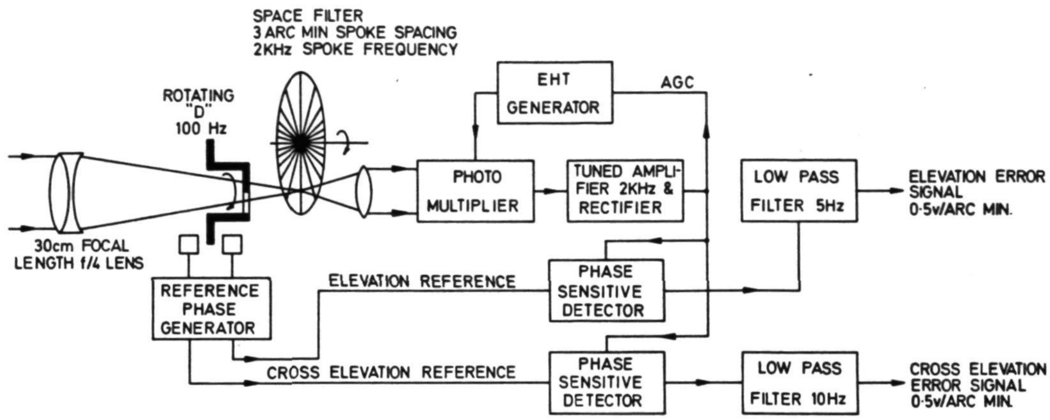

Figure 7. Block diagram of Star Tracker electronics.

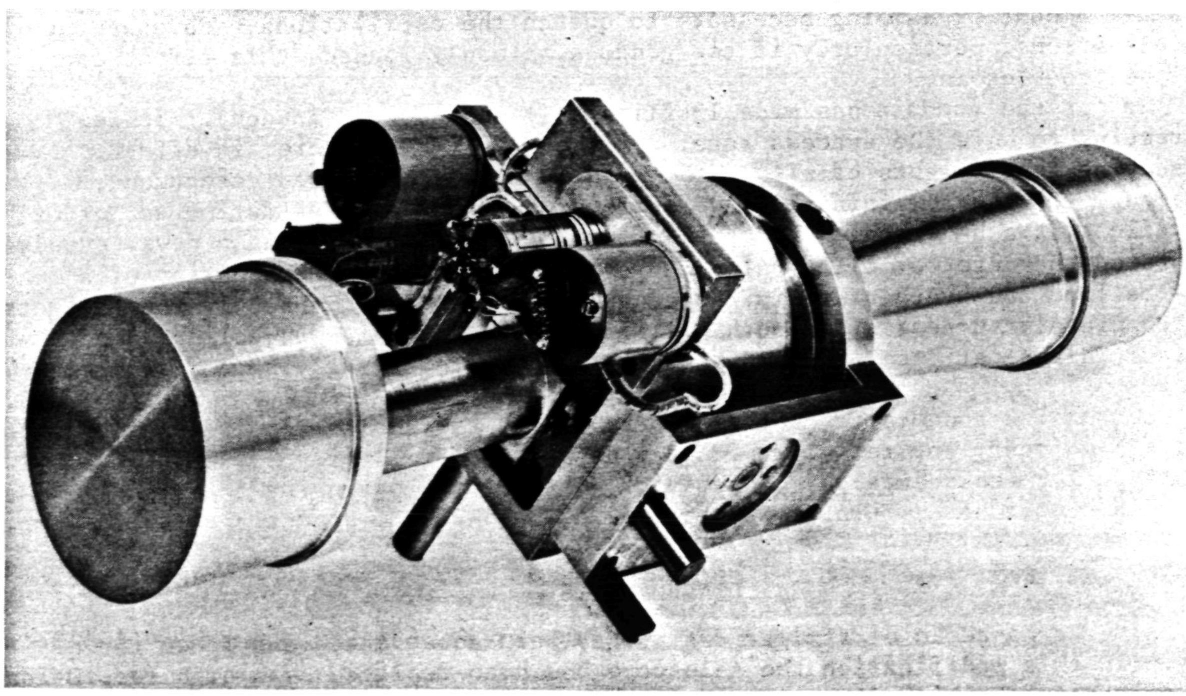

Figure 8. The Star Tracker and offset drives.

OPERATING EXPERIENCE

When the gondola is at altitude a guide star is acquired by following the sequence below.

(i) Unlatch telescope and switch on coarse stabilization. This action also powers the star tracker.

(2) Drive telescope to the coordinates computed for the required guide star at this time.

(3) Check that star tracker is aligned with telescope. If computations and calibrations correct, guide star should appear in star tracker F.O.V. The A.G.C. will then cause the E.H.T. to fall to a level depending on the guide star magnitude.

(4) When guide star is confirmed, control is switched to the star tracker. Once locked on a star the star tracker offsets may be adjusted or scanning commenced.

(5) At the completion of the flight the coarse stabilization is used to drive the telescope into the vertical position where it is relatched and made ready for cut down.

At any time during the flight a new guide star can be acquired by switching back to coarse stabilization and repeating the sequence from step 3. The entire procedure usually takes 5-10 mins and up to 14 different guide stars have been used during the course of a 10 hr flight. Originally our guide star coordinates were precomputed and corrections for small changes in balloon position, declination, etc. were added as required. Now we use an H.P.35 calculator to work out the coordinates on the spot.

In the first flights some difficulty was caused by compound pendulum oscillations of the gondola about its centre of mass. This has been largely cured by the use of a nylon trifilar suspension (seen in Fig.2) which provides the small amount of damping necessary to quench the oscillations. However, at high elevations, particularly if the gondola is badly loaded, this effect can still be troublesome.

So far the gondola has made 13 flights (+ one aborted launch). It is interesting to note the success rate. Of the 13 flights 3 were, in effect, engineering test flights of either the gondola or the infra-red detection equipment. Of the remaining 10, two suffered balloon failures during ascent or early float, two had problems with the command telemetry, one had a power supply failure on the detector electronics and one suffered from a combination of a leaky balloon and overheating in the gondola electronics. Thus only four flights were completely successful, though a limited amount of data was collected on the others. This experience seems in line with that of others flying comparable payloads.

So far the gondola has suffered only superficial damage on landings and has usually been ready for reflying within 4 days. We usually fly about 3 or 4 flights in a 6-week campaign. Reports of work carried out using this gondola have been published by Furniss et al. (1972a & b) and Emerson et al. (1973a & b).

DEVELOPMENTS

A second gondola of similar design has been constructed and flown three times. In this modification the telescope has been replaced by a high resolution U.V. spectrograph which incorporates a secondary guidance system to give 2 arc sec r.m.s. in elevation. A brief description of this instrument and reports of observations made with it have been given by Boksenberg et al. (1972, 1974).

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DISCUSSION SUMMARY — PAPER 2.1

Several questions were asked about hardware and operations. One was concerned with whether the telescope system included a reaction wheel. It does. Another question was about a balloon failure experienced during one flight. It was determined that the balloon leaked during ascent and then failed completely at float altitude. Aside from this failure the University College London Group has had four completely successful flights. The other six have been mixed between partial success and failure.

This group has launched from Australia, France, and the United States (among other places). They have found on occasion that it is less expensive to launch in the U.S. than France.

In order to compensate for temperature changes, the telescope is defocussed in the appropriate direction before launch. This was compared with the Harvard Smithsonian system which used an aluminum frame, aluminum primary, pyrex secondary and an f/13 beam. Refocussing in flight was found unnecessary.

During a discussion of gondola pendulum motion several points were made. One was that it probably depended on time at float, ranging from perhaps 1/2 degree peak-to-peak at first to a few minutes of arc later in the flight. In addition, it was reported that the Ames telescope experienced less than 1/10 degree of pendulum motion during a flight.

The London system has two control axes, azimuth and elevation. The star tracker can be offset in azimuth and cross-elevation. If the gondola balance could be controlled during equipment installation, it would be possible to operate to over 60 degrees with no problems. The main balance problem seems to be associated with properly locating the 300 lbs of ballast on the 800-lb platform.