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A BALLOON-BORNE 1-METER TELESCOPE FOR FAR-INFRARED ASTRONOMY

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ABSTRACT

The Harvard College Observatory, the Smithsonian Astrophysical Observatory, and the University of Arizona have been engaged in a cooperative program to develop a balloon-borne 1-m telescope for infrared astronomy in the wavelength interval 40 to 250 μ. The first successful flight of the telescope occurred in February 1974 from Palestine, Texas. During 5.5 hr at float altitude, the gyro-stabilized telescope mapped the intensity of far-infrared radiation from NGC 7538, Mars, the Orion Nebula, and W3 with a resolution of 1' and from selected regions of these sources with a resolution of 30". Use of an N-slit photometer and a star-field camera will permit absolute positions of the sources to be determined to ≤30". Numerous weak sources were also observed.

The infrared detection system consisted of an array of four gallium-doped germanium bolometers cooled to 1.8 K. Preliminary results indicate that sources with an intensity of 10^3 f.u. were easily detectable.

This paper is concerned primarily with the description of the 1-m telescope and its instrumentation, orientation system, and modes of observation.

INTRODUCTION

In early 1971, a group of scientists at the Harvard College Observatory (HCO) and the Smithsonian Astrophysical Observatory (SAO) initiated a new research program in the promising field of far-infrared astronomy. The primary observational instrument was to be a balloon-borne telescope that could accomplish unique measurements with at least an order-of-magnitude increase in sensitivity and angular resolution over previous experiments in aircraft and high-altitude balloons. The University of Arizona agreed to collaborate and contributed the primary and secondary mirrors and the infrared detectors. Thus, a 1-m balloon-borne far-infrared telescope was designed and constructed that was capable of high-resolution (≤1') mapping in the 40- to 250-μ region and of absolute position determination to ≤30", with at least a factor-of-10 increase in sensitivity (≤10^3 f.u.) over previous experiments.

Telescope Optics

Figure 1 shows the optical arrangement of the f/13.5 Cassegrain telescope. The 1-m primary mirror is spherical (f/2) and constructed of an aluminum alloy, and the 18-cm secondary mirror, made of pyrex, is figured to match the primary mirror. The Cassegrain focus occurs behind the primary mirror, yielding a scale in the focal plane of 15".2/mm. At a wavelength of 100 μ, the diffraction limit of the telescope is 25". Forward of the focal plane, the infrared beam is reflected by a dichroic

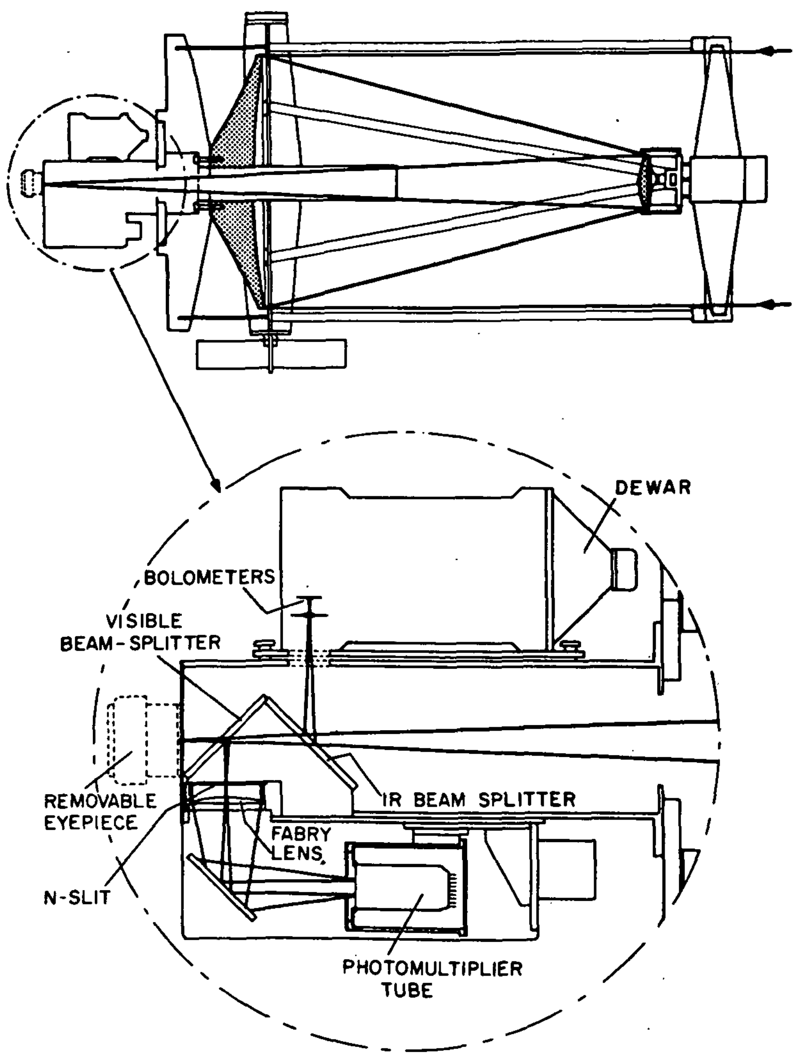

Figure 1. Optical arrangement of the 1-m telescope.

beam splitter that passes visible light. A second beam splitter directs half the optical light onto an N-slit mask at a second focal plane. Light passing through the mask is focused onto a photomultiplier tube. A removable eyepiece, mounted in the focal plane behind the second beam splitter, serves to aid in the optical alignment and testing of the telescope. The secondary mirror is mounted by means of a central bolt to a solenoid-driven chopper mechanism that causes the mirror to oscillate in the azimuthal direction in a square-wave motion of 20-Hz frequency. This beam-switching technique cancels out the background radiation from the sky and the mirror by subtracting the contribution from two fields of view separated by 5'. The chopper mechanism is further mounted on a commandable-focus drive. The whole secondary system is supported by four sheet-metal spiders to the external support ring and then through conventional tubular trusses to the central telescope ring. The weight of the telescope assembly out to the elevation axis, including optics and instrumentation, is ~400 kg.

Infrared Detectors

The infrared detection system consists of four gallium-doped germanium bolometers, cooled to 1.8 K in a liquid helium dewar vented to ambient atmospheric pressure. The ambient pressure at the flight altitude of 29 km is 10.5 torr. As shown in Figure 2, three of the detectors are arranged in a linear array, with each subtending an angle of 1!5 in elevation by 1' in azimuth; the fourth detector, with a circular field of 0!5, is located immediately adjacent to the central detector in the linear

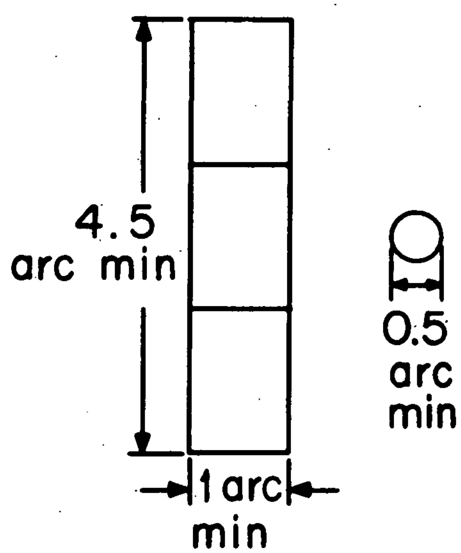

Figure 2. Arrangement of the infrared-detector beams.

array. The cooled optics, all at 1.8 K, consists of a sandwich of 0.86-mm crystalline quartz and 1-mm calcium flouride with one surface coated with diamond dust plus four silicon field lenses. The field of view in the sky is determined by the aperture of the silicon lenses. All the cooled elements are antireflection-coated for maximum transmission at 65 μ. The dewar vacuum window, of 1-mm high-density polyethylene, is coated on the inner surface with diamond dust to reject radiation less than 5 μ and is at a temperature of ~250 K. The passband of the system has a sharp cuton at 40 μ, a peak transmission at 65 μ, and a long wavelength cutoff defined primarily by diffraction. For the three larger detectors, this cutoff is ~250 μ; for the small detector, it is ~125 μ.

Each of the four bolometer signals is amplified by an AC-coupled voltage preamplifier, with a gain of 10^3, followed by postamplifiers with gains of 0.5, 10, and

30. The 12 signal lines are then connected directly to the telemetry system through teflon coaxial cables. The signals are digitized at a sampling rate of 128 s^{-1} and transmitted to the ground station by PCM telemetry. Phase-sensitive demodulation and further processing are done at the ground station by using the telemetered chopper-coil current signal as a phase reference. The onboard signal amplifiers are made immune to external electrical noise by individual batteries and by ground isolation from the gondola.

ORIENTATION OF THE TELESCOPE

Stabilization

The telescope is mounted in a rectangular aluminum-frame gondola (Figures 3 and 4) 5.1 m high and 3.4 × 2.9 m wide. The entire system weighs approximately 1814 kg. Of primary importance are the heavy structural elements used throughout the central portion of the gondola to maintain the integrity of the telescope tube, the elevation and azimuth axes, and the payload electronics. The telescope is stabilized and pointed by means of positional servo controls on the elevation and azimuth axes. The entire gondola moves in azimuth, but the telescope motion in the elevation direction is with respect to the gondola frame. The driving element for each axis is a DC torque motor mounted directly on the axis without gearing. In elevation, the reaction mass is the main frame of the suspended gondola. Reaction forces for the azimuth position control are provided by a large reaction wheel mounted on the gondola center line below the telescope. Complications are introduced, however, by the needs to control the reaction-wheel speed and to isolate the gondola from random and rapid balloon rotations. These needs are met through the use of a "momentum dump" device – a bearing, supporting the shaft passing up to the balloon, whose outer race is driven in sinusoidal excursions of about 2° at a frequency of 5 Hz. Under normal conditions, this motion is symmetrical and yields no net torque, nor momentum transfer, to the balloon, thereby providing some isolation of the payload. If, however, energy accumulates in the reaction wheel so that its angular velocity exceeds 1 rad s^{-1}, the sinusoidal bearing drive is proportionally biased to permit momentum transfer to the balloon. This enables the reaction wheel to slow to a near-zero control speed.

Pointing and Acquisition

Positioning the telescope optical line of sight is accomplished in two modes: first, an acquisition mode, determined with respect to the horizontal component of the earth's magnetic field in azimuth and with respect to the local vertical in elevation, to an accuracy of 0°1; and second, an inertial mode, determined by a two-axis gyroscope system mounted on the telescope tube, which gives stability in inertial space to ~1'. For the acquisition mode, a null magnetometer is mounted on a table and servo-driven in azimuth so as to remain fixed to local magnetic north. The angular position of the magnetometer with respect to the gondola is determined by a 13-bit shaft encoder (smallest bit equals 2'6). An azimuth position command, in the form of a digital word, is transmitted to the gondola and stored in a onboard register. The encoder output is compared with the stored azimuth position command, and the difference signal drives the azimuth servo system. The azimuth position stability is ~6'. In the elevation axis, the telescope angle referenced to the gondola is determined by a potentiometer and compared with the analog equivalent of a 12-bit elevation

Figure 3. Payload just before launch.

command stored in another register. As in azimuth, the difference is used to drive the servo motor. The smallest bit in elevation is 1'.3, and the stability is of the order of 1'.

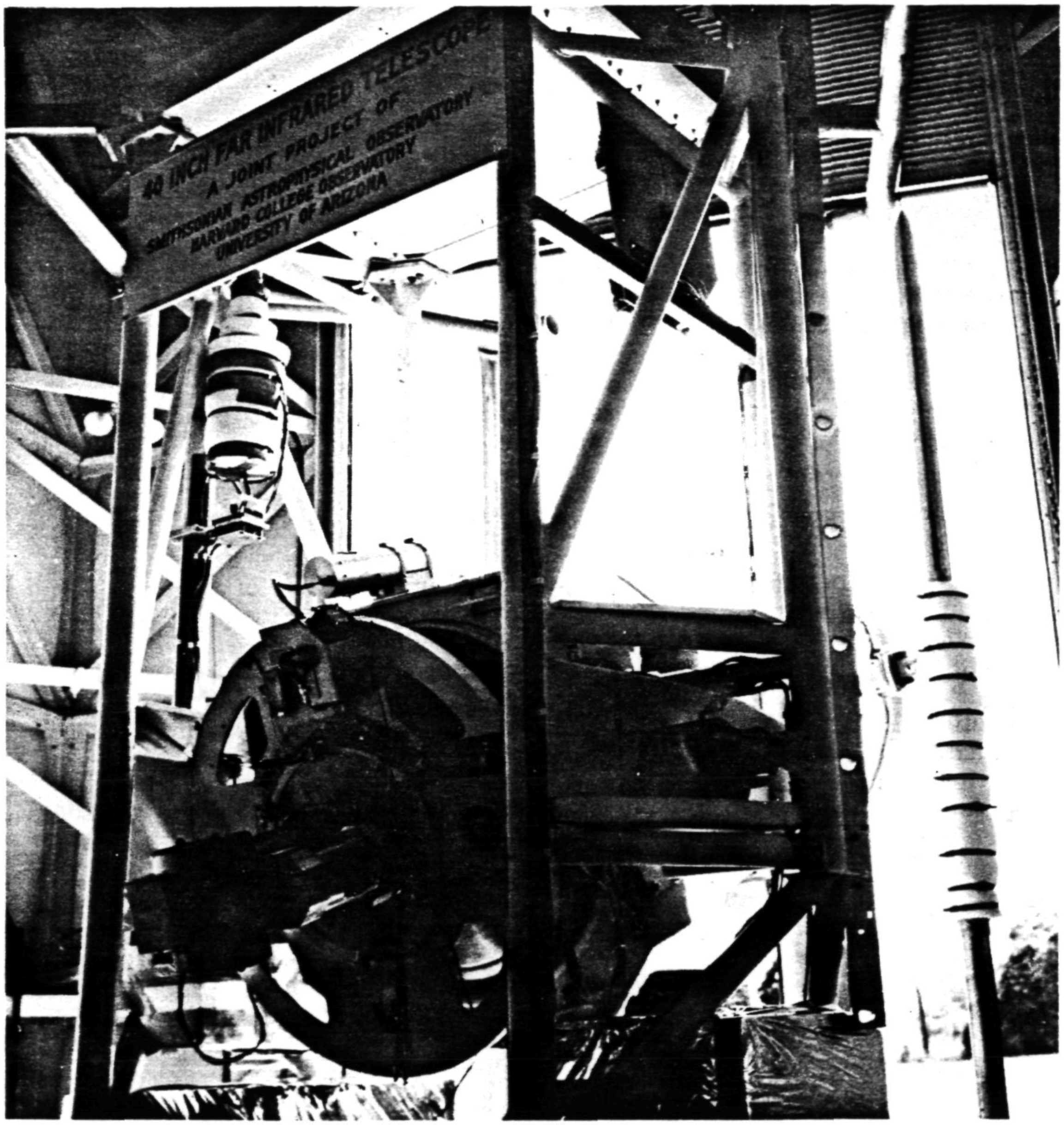

Figure 4. Back assembly of the payload.

To avoid major perturbations in the acquisition pointing mode, the rate of change of position is limited to 0°.5 s^{-1}.

In the inertial pointing mode, position information is obtained from two rate-integrating gyros mounted on the telescope base ring. One senses motions about the elevation axis directly, while the other senses motions about an axis perpendicular to both the elevation axis and the telescope line of sight. In combination with a potentiometer-derived secant function of the elevation angle, this latter output controls the gondola azimuth. At higher elevation angles, the "azimuth" gyro becomes increasingly sensitive to gondola motion about the roll axis, and this places a maximum limit on the useful elevation angle of about 35°. The gyros have random drift rates of the order of 3' hr^{-1}; however, the present electronic circuitry has limited the drift rate to the order of ~0!5 min^{-1}. A much larger drift rate in azimuth was observed during the flight.

By exciting torquing coils on the gyro axes, the gyros can be precessed, and when they are coupled to the pointing control system, controls can, in effect, be imposed on angular rates in azimuth and elevation on the telescope. Provision has been made for "manual" scan rates of ± 1' s^{-1} about both axes; these rates are selected independently from the ground with durations controlled by the operator in real time. Further, and most important, an onboard raster-pattern generator can be commanded to control the gyro torquers so as to produce a raster-like scan of the telescope over a large field of view. Two sizes of raster patterns, each with 32 lines per pattern, are available by command: One set has a line scan rate of 1' s^{-1} and 2!25 spacing between lines, yielding a scanned field of about 30' in azimuth and 1° in elevation in about 18 min; the second set has the above values multiplied by a factor of 3, yielding a 1°5 × 3° field in the same time. The raster scan can be aborted at any time.

OBSERVATIONAL TECHNIQUES DURING FLIGHT

During the payload flight, the observational method consists of a series of operations performed in turn for each object to be observed. First, the expected azimuth and elevation positions for the object are computed on the ground for an appropriate future time and given payload latitude and longitude. An HP9810A programable calculator computes the magnetic deviation and applies corrections from the magnetic azimuth and elevation calibrations. The printed output contains the azimuth and elevation commands to be executed, as well as the expected values of the elevation position potentiometer and the output voltages from a crossed pair of magnetometers on the payload. The azimuth and elevation commands are telemetered in advance to the payload, which, on receipt of an "execute" command, moves the telescope slowly to the desired position and maintains it. At the predetermined time, the gyros are uncaged, activating the inertial mode; the telescope then tracks the point in the sky to which it has been positioned. In most cases, the desired object is not in the field of view – primarily owing to uncertainty in magnetic-azimuth position – and a search pattern must be initiated. The type of search pattern employed depends on the celestial object. For an infrared source without an associated bright object, a large raster scan is initiated. When the source is observed with the infrared detectors, the raster is aborted, the telescope is manually scanned to a new position, and a small raster is initiated to remap the object. If no object is found, the raster goes through 10 lines and then is aborted. A new position in the acquisition mode is calculated and the above process repeated. For an infrared object that is also optically bright, the search mode involves the use of the optical N-slit with a field of 20'; a spiral pattern is generated by manual scans in azimuth and elevation in the inertial mode until the object is found. Typically, an area 3° in azimuth and 1° in elevation can be covered in approximately 4 min. When the object is discovered, the telescope is repositioned and a small raster pattern is initiated. Again, if no object is discovered, the spiral scan is stopped after three azimuth scans and the position reacquired in the acquisition mode.

When an infrared object is being mapped with the telescope in the inertial mode, it is extremely important to know, in real time, the relative position of the telescope axis with respect to the object. Otherwise, valuable time can be lost if it is assumed that the telescope is carrying out a given command when actually the wrong command was sent or the command was not received. To avoid these difficulties, a series of payload-status lights, actuated only by commands received and executed by the payload, are displayed at the ground station. They indicate such functions as inertial mode, azimuth or elevation direction, rastering, and direction of raster line. In addition, the same signals drive an X-Y recorder, which displays the motion of the telescope. Superimposed on the Y axis of the recorder is the output of the N-slit photometer (Figure 5). By observing the X-Y recorder, the telescope can be positioned for mapping by rasters.

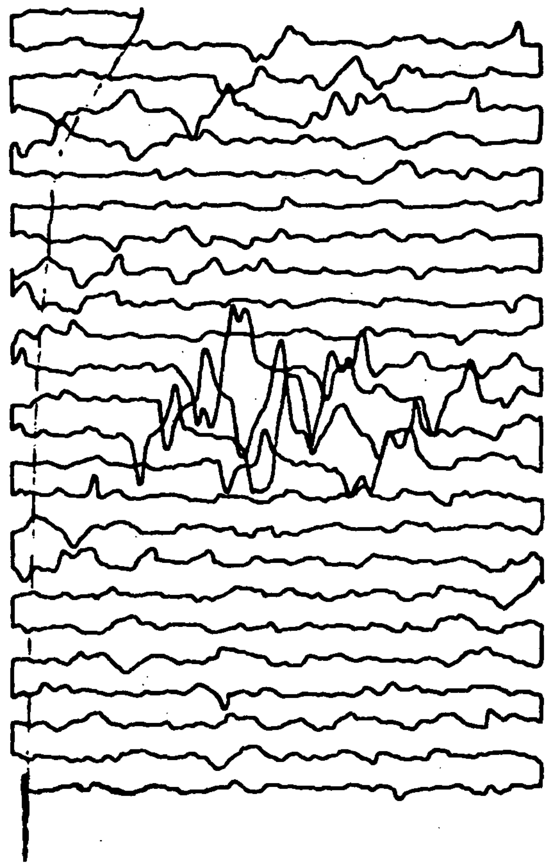

Figure 5. X-Y recorder output during a large raster scan of the telescope. The output of the N-slit optical photometer is added in the Y direction.

A number of other means are also available for calculating the position of the telescope. Some provide data for real-time determination, others, a postflight record.

The pointing control system generates telemetry readouts of the elevation and azimuth positions: In elevation it is an analog voltage, and in azimuth it is an analog voltage indicating the difference between the commanded position and the instantaneous pointed position. Both these readouts provide a sensitivity sufficient to monitor fine-pointing control performance.

An additional determination of magnetic azimuth is provided by a pair of crossed magnetometers mounted on the gondola.

The most useful device for fine-position determination is the N-slit photometer, discussed earlier. Star transits across the three branches of the N mask, telemetered to the ground, indicate with high precision the elevation and azimuth of the optical object with respect to the star field during scanning activities. The photometer output is AC-coupled to reduce its sensitivity to scattered light. The photometer is effective for stars down to 9th magnitude.

An independent device for postflight pointing verification is the star-field camera, a 35-mm-sequence camera mounted on the telescope, which provides an effective field of view of about 15°. The camera photographs star images and records a projected reticle pattern, along with data indicating frame number, time, and status of the payload. In addition to taking pictures on command from the ground, the camera is automatically triggered during the various payload scanning functions.

BACKUP CONTROL SYSTEM

In the event of failure of one or more major systems in the primary operation of the telescope pointing, a simple backup control system can be activated by tone commands. This system serves two functions: automatic stow of the telescope and crude pointing control of the telescope in azimuth and elevation.

The telescope is normally stowed by commanding it to point vertically, placing it in a position such that a commandable motor-driven pin can capture a lug mounted on the telescope for this purpose. Should this primary technique fail owing to loss of battery power or to excessive telemetry range, an independent system, after a preset time and on descent through a particular altitude, will engage the elevation axis and drive the telescope to the vertical position by utilizing its own battery power. In doing so, it also turns off the main payload. Associated with this is a pneumatically actuated capture device that, although locked out during launch, will thereafter retain the telescope in the vertical position on its descent through 9.2-km altitude.

If the primary azimuth or elevation command servo systems should fail, an independent system can be actuated to drive the telescope in elevation by using the same motor as in the emergency stow procedure described above. An independent elevation potentiometer is also provided. The motion in azimuth is achieved by directly driving the motor in the momentum-dump system in either direction. Azimuth position is determined from the cross magnetometers and the N-slit photometer.

POWER, TELEMETRY AND TELECOMMAND

The main power for the payload (except for the telemetry and telecommand systems) is supplied by a silver zinc battery pack with a capacity of 400 amp hr, loaned by NASA Johnson Space Center. The nominal voltage is 28.5 V. With all systems operating, the battery current varies between 17 and 20 amp.

The telemetry system, provided by the National Scientific Balloon Facility (NSBF), consisted of a PCM system with 48 analog inputs and 4 digital words and a bit rate of 40.96 kbits s^{-1}. After decommutation at the ground station, the data were processed by a PDP-11 computer and digitally recorded on tape. Real-time output of the data could also be obtained on a teletypewriter, where all analog and digital words could be printed in sequence or selected words could be printed on command. Thirty digital-to-analog converters were also available. Any 4 of the 12 infrared data lines from the digital-to-analog converters could be switch-selected, processed by the phase-sensitive amplifiers, and displayed on a strip-chart recorder.

Thirteen analog channels of FM/FM telemetry also provide redundancy for the most important data.

The telecommand equipment, supplied by NSBF, comprises a PCM command system, of which 30 momentary commands are used. Because of the number of commands required for this payload, the PCM system is used to address and execute commands within a more elaborate command matrix in the payload. Seven tone commands are also employed.

TESTING AND FLIGHT HISTORY OF THE PAYLOAD

Design of the 1-m telescope began in August 1971, funded from the internal budgets of SAO and HCO, with the hope that the equipment would be ready for flight in a year. Payload construction was completed in August 1972, and the experiment was moved to the NSBF in Palestine, Texas. Operational testing, payload debugging, and other improvements continued into October, at which time the first flight took place. However, it failed shortly after reaching float altitude owing to a short circuit on one of the principal voltage reference lines, probably caused by a spiral metal chip.

A second flight, in April 1973, also failed, this time before reaching float altitude. The failure again occurred in the electronic systems because of a shorted transistor in the elevation motor drive system.

Following the second failure, extensive payload refurbishment was undertaken, particularly in the electronics system, from July through September 1973. Thermal-vacuum tests of the entire payload were then conducted, with assistance from NASA Johnson Space Center. Three simulated flights were performed, by matching temperature and pressure profiles of an actual flight as closely as possible. During the tests, a 3' infrared source was positioned in the chamber, and one wall of the chamber was cooled to 70 K.

The thermal-vacuum tests offered many benefits at relatively low cost. First, the payload design was qualified under conditions it was to experience in flight. Second, valuable data were obtained on the infrared detection system. The sensitivities of the detectors were measured and the noise background evaluated. Third, the differing thermal environments of the three tests provided enough data to allow us to cope with the expected seasonal atmospheric variations for flight at any time of the year. Fourth, the tests gave us the opportunity to build up operational experience with the payload while virtually eliminating any chance of damage that might occur during actual flight and recovery.

A third flight was launched in December 1973, but the balloon burst during ascent. The telescope was stowed while the parachute descended and was recovered with no damage to the payload. For the brief period of ascent, all systems appeared to function properly.

The fourth flight, in February 1974, was a complete success. After an ascent of 2 hr to 28.4 km, the flight lasted 5.5 hr, limited only by telemetry range. The payload was recovered without damage.

PRELIMINARY SCIENTIFIC RESULTS

The data from the February flight are still in an early stage of analysis. However, some preliminary results can be quoted from real-time records.

During the 5.5 hr at float altitude, data were obtained that will permit the generation of infrared maps of NGC 7538, Mars, Orion A, and W3. Angular resolution of 1' was achieved for these maps, and selected scans were accurate to 30" resolution

(Figure 6). The sensitivity was such that sources with an intensity of 10^3 f.u. are easily identifiable. Scans along the galactic plane indicated numerous weak sources. The number of stars detected in the N-slit photometer are sufficient for absolute positions of the infrared sources to be determined.

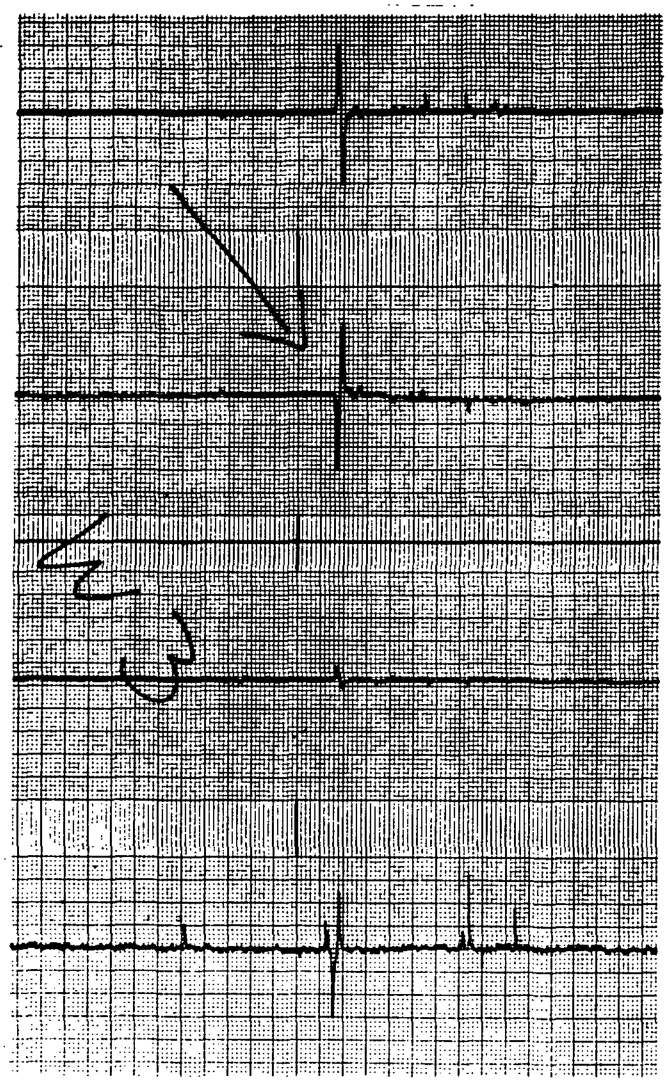

Figure 6. Infrared detector outputs during a raster scan of W3. The top three traces are from the 1' detectors; the bottom trace is from the 30" detector. The chart speed was 0.5 mm s^{-1}, and the telescope scan rate, 3' s^{-1} in azimuth.

The pointing stability of the payload was excellent during the flight.

ACKNOWLEDGMENTS

The payload was designed and constructed by the Solar Satellite Engineering Group, Harvard College Observatory. Details of the payload attitude and command control systems are presented in a paper at this symposium by N. Hazen, L. Coyle, and S. Diamond.

M. Zeilik assisted in the flight preparation.

We had several very valuable suggestions on payload design and construction from Dr. W. Hoffman, University of Arizona.

We are most grateful to NASA Johnson Space Center, Space Environment Test Division and, in particular, to Mr. E. E. Peck, for assistance in the thermal-vacuum tests.

The National Scientific Balloon Facility was responsible for the launch, tracking, and recovery of the experiment and contributed all the onboard telemetry, as well as the data-processing equipment at the ground station. Without their assistance, this flight would have been impossible.

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DISCUSSION SUMMARY — PAPER 1.5

It is expected that it will be possible to fly this system two to four flights each year. There is very little damage to the system on landing. Most of the impact is taken by aluminum rings around the system. They have not experienced misalignment of the gimbals. In order to avoid fouling of motors and bearings, these parts are disassembled and cleaned after each flight. This is the most time-consuming task between launches.

Telemetry is provided by the NCAR system available at Palestine. It provides 48 analog words and four digital words at a 40 kilobit rate. A 350-mile telemetry range has been realized. In addition, the NCAR PDP-11 computer is used to provide digital tapes of the data.

Telescope suspension is through a universal joint to the momentum dump system which includes ball bearings. Stabilization in two axes instead of three was used as a cost savings approach. No problems are encountered for observations below 40°; at 40° oscillations in roll set in.

The primary mirror provided by the University of Arizona is aluminum and weighs 250 pounds. It has a one-arcsecond image when warm and a 15-arcsecond image when cold.