

ULTRAVIOLET TELEVISION DATA FROM THE
ORBITING ASTRONOMICAL OBSERVATORY.

I. INSTRUMENTATION AND ANALYSIS TECHNIQUES
FOR THE CELESCOPE EXPERIMENT

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ABSTRACT

The Celelescope Experiment consists of two major sub-assemblies installed in OAO-2: an optical package containing four 12-inch Schwarzschild telescopes using Westinghouse Uvicons to produce television pictures (2° square) of star fields; and an electronics package, installed in OAO Bay E-4, to control the operation of the Uvicons and to encode the television pictures into digital signals for transmission to the spacecraft and thence to the ground. The only significant failure during 16 months of orbital operation was destruction of one of the four Uvicons by overexposure to daylight during two different types of operation. The other three cameras obtained more than 7400 scientifically useful pictures and provided useful ultraviolet data on more than 5000 stars. Sensitivity decreased significantly during our 16 months of operation (see Figure 8); this decrease was our primary reason for discontinuing operation of the Celelescope experiment in April 1970.

Our data-analysis system consists of a combination of computer programs and manual reviews. The system required extensive modification after launch in order to compensate for differences between our pre-launch expectations and the actual data. The final data-analysis system not only transforms the incoming tele-

vision pictures into identifications, positions and ultraviolet brightnesses for the observed stars but also provides an improved set of calibration tables and an accurate curve of sensitivity change for use in that transformation.

This paper describes the Telescope instrumentation and data-analysis system, summarizes the major problems that we encountered during orbital operation, and lists a few major problems that we anticipated but did not encounter.

I. INTRODUCTION

This description of the Telescope experiment is an abridgment of two more detailed discussions: Performance Evaluation of the Telescope Experiment (Telescope Staff 1971) and The Telescope Experiment (Davis 1968).

The principal objective of the Telescope experiment is to measure the ultraviolet magnitudes of very many stars in a statistically significant fraction of the sky (see, e.g. Whipple and Davis (1960); Davis (1968)). During its operational life in the Orbiting Astronomical Observatory (OAO-2), the four ultraviolet-sensitive television cameras carried by the experiment indeed achieved the desired statistical sky survey by recording some 8500 television pictures of stellar fields, each $2^\circ \times 2^\circ$, covering a total of 10% of the sky (see, e.g. Davis (1970)). The stellar data will soon be cataloged in other documents. Recorded here are descriptions of the design and performance of the Telescope experiment and the techniques used for analyzing its data, in the hope that this information will be helpful to later experimenters and to users of the scientific results.

The design, fabrication and operation of the Telescope experiment manifest its astronomical objectives. Because the objective is observation of a significant fraction of the sky, image tubes that view an adequate area at each exposure were the natural choice for detectors on the telescopes. But there were no ultraviolet-sensitive television camera tubes in existence when Telescope was initiated in 1959, and there was no design of a system to use them in a laboratory photometer, let alone a stellar photometer for space-flight. Nor was there an Orbiting Astronomical Observatory with well-defined characteristics into which the photometer must fit. Thus, the engineering experience of Project Telescope started from scratch, evolved through most of the first decade of the space age, and culminated in OAO-2.

Within the sky area observed, magnitude measurement of some several thousand stars is a reasonable statistical sample. Be-

cause stars become increasingly more numerous with decreasing apparent brightness, the television cameras must record stars 10^4 times dimmer than the brightest ultraviolet stars. This requirement sets the sensitivity threshold and the dynamic range required and satisfied by the Telescope hardware.

The sensitivity is achieved by specially produced ultraviolet-sensitive television tubes that employ the secondary electron conduction (SEC) principle in an electron-image storage target. The development of these Westinghouse Uvicon tubes from a starting point where the SEC principle was a new laboratory discovery, to final successful flight operation, is a technological triumph of Telescope.

As a stellar photometer, the Uvicon with its electronics derives its remarkable dynamic range from the property that the brightness of a star is registered on the target as an electron image that increases in both charge density and spatial extent as a function of the brightness of the star. Thus, in its digitized format, the image of a star is a matrix of charge-density values. The brighter the star, the more elements the matrix contains.

The digitization of the television picture requires special circuitry because the OAO spacecraft systems cannot accommodate rapid transmission of a television picture. This design consideration is satisfactorily met by a technique labeled super-scan by the EMR Telemetry Division of Weston Instruments, Inc., in which the readout electron beam is off the remaining image most of the time. When the system is ready for data input, the beam is swiftly deflected to the next image point to be sampled, the charge is measured for a small region around the point, and the beam swings back off the image to wait for the next cycle.

The arithmetic sum (Σ) of the values above background for the matrix elements of a star image is taken as the primary Telescope measure of the ultraviolet magnitude of the star. The processing of the Telescope observations then requires that the correspondence between Σ and stellar magnitude be accurately known as a function of image position on the camera photocathode and target, of time, and of temperature and other system parameters.

The correspondence between Σ and ultraviolet magnitude is far from linear. An initial mathematical model for it was generated from extensive laboratory measurements made before the OAO launch. When the experiment was in orbital operation, most parameters in the model were redetermined, and their temporal evolution derived from the stellar observations themselves. For this purpose, the telescopes were periodically directed toward standard star areas. Procedures for improvement of model parameters were implemented with the condition that multiple observations of the same star at different epochs, at different exposure times, and at different positions on the

television picture should yield the same magnitude within expected system accuracies.

These mathematical procedures not only generate the parameters needed for data processing but also yield retrospective engineering information on the time dependence of system sensitivity. The photometric sensitivity decreases with time, as was generally anticipated before launch.

The most useful indication of the accuracy of the processed stellar data comes from the scatter in the magnitude values for multiple observations for each of some 1500 stars. For the different cameras and spectral bands, the standard deviation of this scatter ranges between 0.1 and 0.2 mag. This is in substantial agreement with the 0.1 mag accuracy goal established early in the Telescope design.

Image focus might have profoundly degraded this accuracy but did not. A change in the optical or electronic focus affects the image size in a way that can generate inconsistent Sigma values and magnitudes. That this does not happen appreciably is a validation of the mechanical and thermal design of the telescope systems.

The Telescope experiment incorporates many engineering concepts to enhance reliability. Much of the electronic circuitry is quad-redundant at the component and module level; these systems were still operating normally when they were turned on again and rechecked 26 months after launch. The high-voltage power supplies in the flight package give no indication of arcing problems; the adopted design and potting procedures can be recommended for future uses. Although there are four telescopes in the experiment and four ultraviolet spectral bands to be covered, these are not related in a one-to-one fashion. Instead, a filter configuration bisects the camera field so that each half responds to a different spectral band; thus, for redundancy each spectral band is observed by two camera tubes. However, this concept is not an unqualified success, because star images overlapping the dividing line cannot be used.

The most troublesome problem involving reliability concerns protection of the Uvicon target from accumulating a charge of such size that electrostatic forces puncture or rupture the target material. (Fortunately, recent SEC tube designs avoid this phenomenon.) The Telescope project had to use tubes susceptible to this limitation and therefore had to compensate for it by circuitry design and operational procedures. Even so, one tube suffered target damage early in orbital operations. Although this caused a decrease in operational efficiency, no qualitative loss resulted. Because of the redundant filter configuration, data continued to be taken in all four spectral bands until observations were discontinued.

After 16 months of operation (40% longer than the nominal objective), Telescope sensitivity reached a level below which

further routine observations were unjustified. On April 26, 1970, Telescope was turned off, while still in operable condition. It was turned on again briefly on February 2, 1971, and found to be in the same condition as 9 months earlier. At the time of this writing, Telescope can still be operated and take further data if objectives arise for which its sensitivity is adequate.

The subsequent sections of this paper relate further details about those aspects of Telescope design, engineering and performance that seem most significant to the authors. § II includes a short description of the Telescope instrument. It also addresses some engineering problems and their solutions. § III describes briefly the data-processing procedures implemented for Telescope operations.

If still further detail is needed, the reader is referred to two comprehensive documents from which this paper has drawn much of its material: The Telescope Experiment (Davis 1968) and Performance Evaluation of the Telescope Experiment (Telescope Staff 1971).

The latter document tabulates conclusions from experience with the Telescope experiment, as follows.

1. Optical, mechanical and thermal design of the telescopes proved fully satisfactory in terms of image quality and stability.

2. Contamination-control procedures during ground operations were fully successful.

3. Positional stability of star images in the final television pictures was not completely satisfactory, and careful attention to factors affecting it, such as magnetic fields, is necessary.

4. The lack of an opaque shutter as opposed to the electronic shutter we employed prevented us from using a significant number of dark experimentation periods.

5. High-voltage power supplies, ion traps and associated circuitry (anti-arcing) performed perfectly.

6. Quad-redundancy design in Telescope produced a reliable operation of the electronic package, but at the cost of some increase in power and weight.

7. Superscan readout performed well.

8. The calibrator lamps proved to be valuable for providing a record of Telescope performance from the time the flight telescopes were first assembled, through all phases of subsystem and system testing, to well after launch.

9. The calibrator lamps carried initial calibration data into orbit, but did not provide thereafter sufficient data for accurately establishing the time dependence of the photometer response.

10. Protection against target-material breakdown (crossover) is a critical requirement. The Telescope techniques proved to

be satisfactory for three of our four cameras.

11. For some methods of preventing target-material breakdown and, in particular, the method used in Telescope, the output signal becomes critically dependent on the focus of a stellar image on the target. (This did not become a problem in Telescope but does represent a potential problem for future similar experiments.)

12. Uvicon sensitivity during orbital operations decreased with time. Nevertheless, the useful life of the Telescope experiment significantly exceeded the pre-launch goal of one year in orbit for gathering scientific data.

13. Scattered sunlight severely limited Telescope's opportunities for daylight observations. The most important scattering sources were the sunlit earth and the spacecraft itself.

14. Geocorona seriously interfered with Telescope measurements in the spectral band that includes 1216 Å.

15. Calibration of the Uvicons in orbit was possible and necessary.

16. Photometric accuracy, after orbital calibration, is better than 0.2 mag.

17. The use of two filters on each camera, one for each half of the field of view, provided useful redundancy but posed significant data-reduction problems. It also required rejection of many stars that were observed near the dividing line.

18. Excessive manual intervention in the data-reduction system was necessary because the housekeeping data were on a different data channel from the video data and the camera number was not included with the video data.

Our overall conclusion is that the Telescope experiment system successfully demonstrated the capability of a versatile and precise, space-borne astronomical television photometer.

II. CHARACTERISTICS OF THE CELESCOPE TELEVISION PHOTOMETER

The SAO experiment (Telescope) consists of two major integrated packages: The Telescope Optical Package and the Bay E-4 electronic module assembly.

The Telescope Optical Package contains four Schwarzschild telescopes, each of which images a star field onto the ultraviolet-sensitive photocathode of a special-purpose image tube (Uvicon) (Doughty 1966). In turn, the photoelectrons emitted by the photocathode are imaged on a target where the image is integrated and stored as an electrical-charge pattern for readout at the desired time. The video signal developed by the readout of the image tubes is amplified and supplied to an electronic data-processing system (Bay E-4 module assembly) for data processing in the manner prescribed by a preselected operating mode. Figure 1 illustrates how the Telescope was

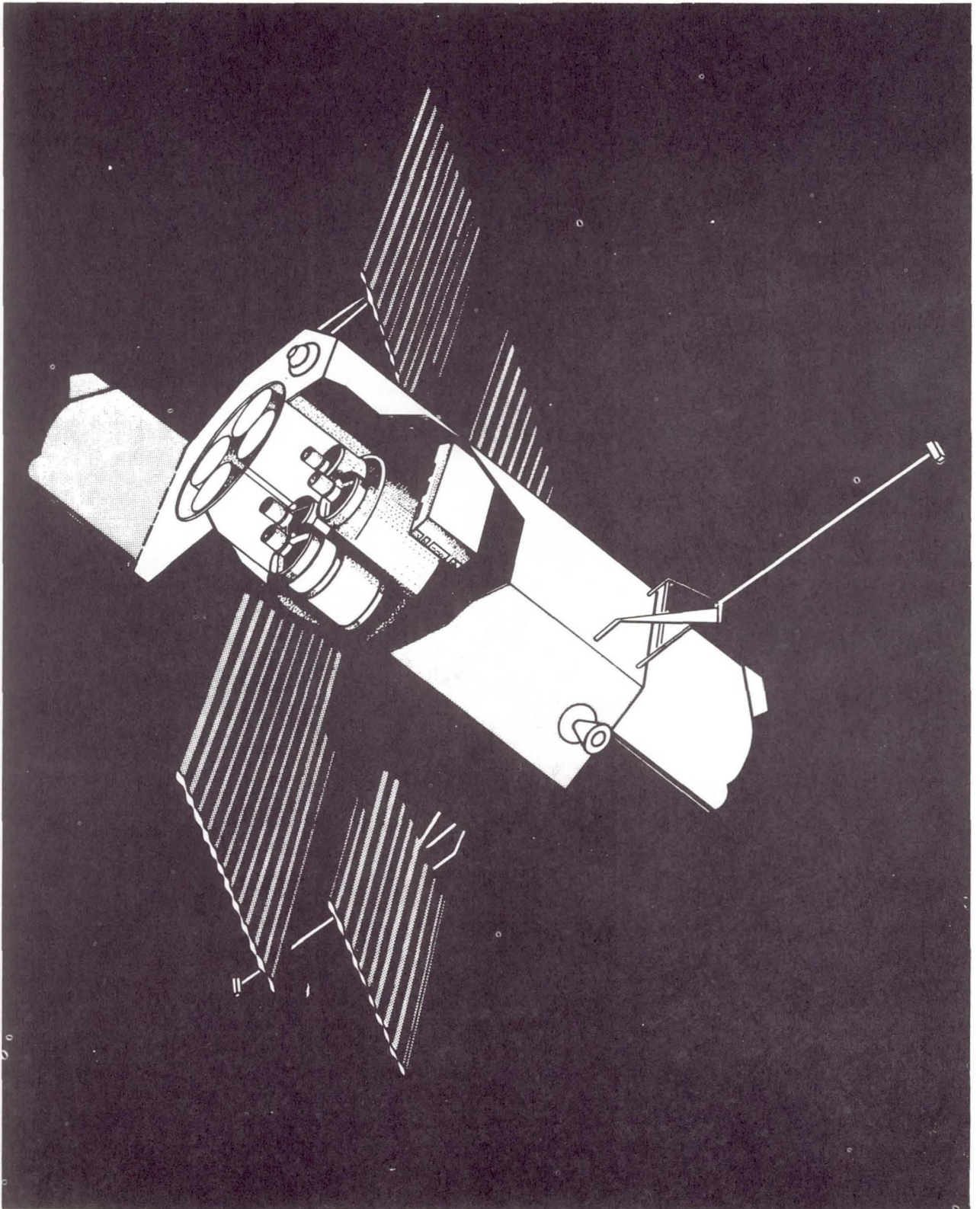


Figure 1.—OSO spacecraft with cutaway showing the Telescope experiment.

mounted in the OAO.

Each Schwarzschild-configured telescope has a diameter of 12.5 in. A telescope assembly is illustrated in Figure 2. The secondary mirror obscures an area of 6.5-in diameter of each aperture. The light is reflected by the primary mirror (hyperboloidal) and brought to focus at a point beyond the plane of the intercepting secondary mirror. The secondary mirror (oblate ellipsoidal), in conjunction with the Uvicon faceplate lens, focuses the light at a surface coincident with the photocathode surface of the faceplate of the Uvicon camera tube.

The field of view of each telescope is determined by the active area of the image-tube photocathodes and is nominally square with an equivalent angular area of $2^\circ \times 2^\circ$. Each telescope tube is designed to compensate passively for optical defocusing caused by thermal expansion and contraction. The use of titanium as tube material, in conjunction with an aluminum

TELESCOPE ASSEMBLY

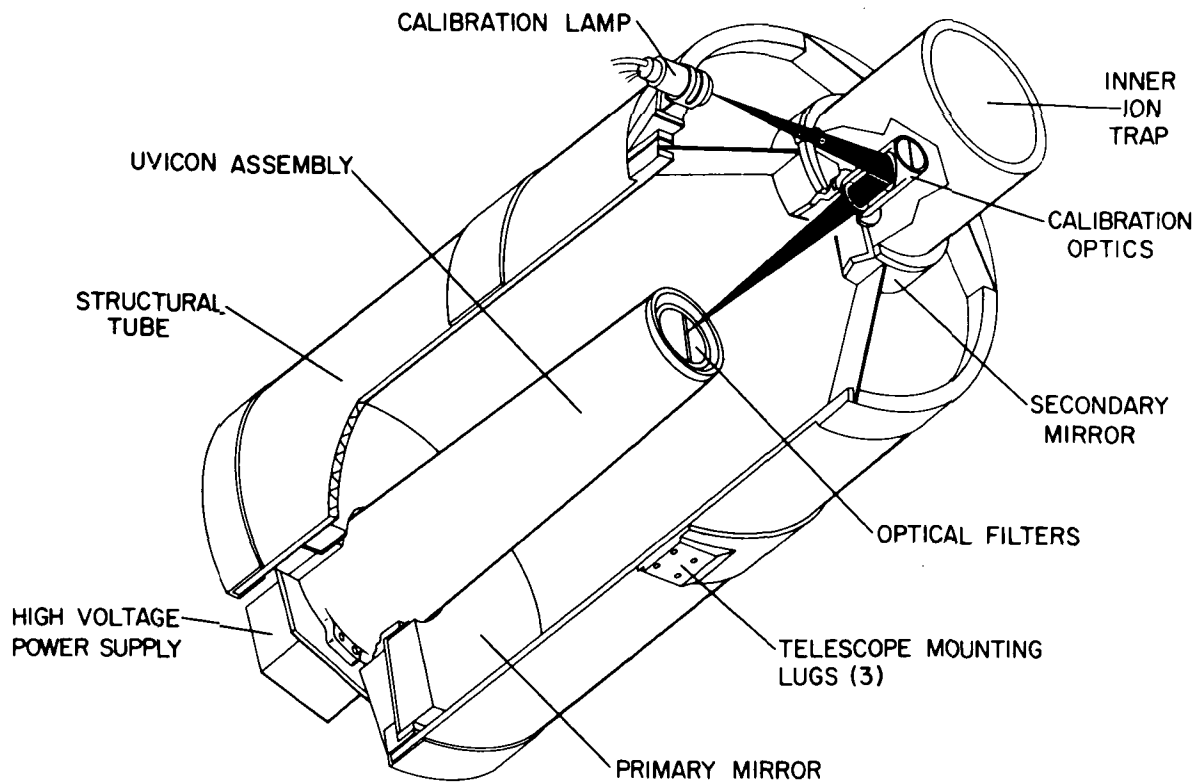


Figure 2.—Cutaway of the telescope assembly.

alloy for the camera-tube housing, compensates for defocusing effects over a 100°C temperature change. To reduce the loss of spacecraft heat to outer space, each telescope was heavily insulated on the outside of the titanium tube and the mounting lugs were designed for minimum contact area.

The field of view of each Uvicon is optically split into two areas of different sensitivity by mounting two different semicircular filters in the focal plane of the photocathode. Further spectral selectivity is achieved by the use of two types of Uvicon: A and D. They differ only in their photo-emissive surfaces. The type-A is sensitive between 1050 and 3200 Å, and the type-D between 1050 and 2000 Å. The resulting spectral responses can be seen in Figure 3.

The calibration optics of the optical subsystem consist of a calibration lamp (with controlled and calibrated emission characteristics), apertures (to simulated star point sources of ultraviolet intensity), and a mirror and lens located in the aperture of the secondary mirror of each telescope. The point source of light from the calibration lamp and aperture

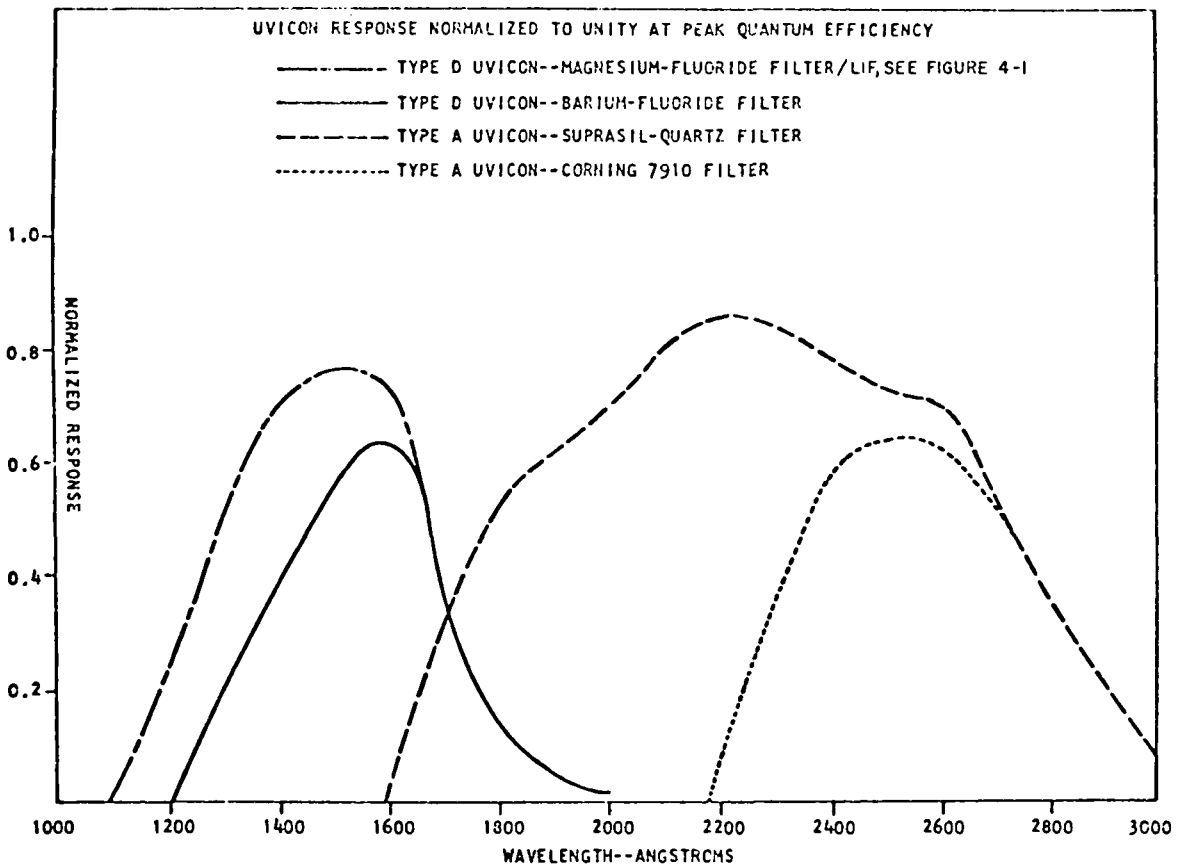


Figure 3.—Typical spectral response characteristics of Uvicons.

is reflected by a mirror, 45° off the plane normal to the optical axis of the telescope, through a lens that brings the light from the simulated stars to focus at the plane of the face-plate lens.

The electronic subsystem of the SAO experiment incorporates command and control functions for the operation of the SAO experiment. No command functions are incorporated into the system for mechanical adjustment or operation, as the design of the SAO experiment is such that the telescopes remain in satisfactory focus under the anticipated environmental conditions. The television camera tubes are effectively exposed to ultraviolet energy only when high voltage is applied to the imaging section of the tube; thus, no mechanical shutter is required.

In this system, exposure to ultraviolet light and scanning of the target are never performed simultaneously. As exposure is controlled by high-voltage on-off commands, the sensitivity of the system can be adjusted by varying the exposure time (the time during which high voltage is applied to each camera). The high-voltage commands energize three high-voltage potentials from 7 to 8 kV. These voltages are tailored for each Uvicon to produce optimum image-section focus. Each camera module is provided with its own high-voltage power supply.

As a result of an exposure interval, an electrical-charge (star-image) pattern is built up on the target of the Uvicon camera. To convert the star image on the target into a video signal, the target must be scanned (read out) by an electron beam. The readout mechanism involves replacement of electrons on the charged areas of the target.

The target can be damaged and effectively destroyed if the potential on the target exit surface (scanned surface) is allowed to increase indiscriminately. Certain conditions of operation can cause the emission from a target element of more electrons than are deposited by the readout beam. This condition, known as crossover, if allowed to continue, will further increase the surface potential at discrete points on the target to the level where electrical breakdown will occur between the exit surface and the backplate of the target, and holes will be punctured into the target.

During orbital operations, we encountered target-material breakdown (also called destructive crossover) four times. Three of these instances occurred in camera 2 and could be traced directly to differences in manufacturing techniques between it and the other three tubes. Camera 2 ceased operation in March 1969, apparently as a result of poor vacuum induced by overexposure to light in December 1968. Two types of overexposure were encountered: overexposure to ultraviolet light (Lyman alpha radiation in the daytime) and overexposure to visible light from the illuminated earth during the waiting per-

iod between exposure and readout. These modes of operation did not damage the other three tubes, primarily because they had higher crossover potentials. Neither daytime operation nor long waiting periods between exposure and readout were necessary, and such operations were not performed after December 1968, except for engineering evaluation.

The fourth instance of target-material breakdown induced two pinholes in the target of camera 4. That instance was brought about by a temporary interruption of ground communication with the satellite, caused by a computer hardware error on the ground; it did not degrade the scientific usefulness of camera 4.

Camera 3 began to show signs of incomplete priming in August 1969 but remained operable. Camera 4 also showed some signs of incomplete priming in December 1969, but modifications in the operating procedures eliminated the symptoms. In both cases, the symptoms consisted of a broad high-background ring in the outer region of the picture.

The most significant change in camera operations was a secular decrease in sensitivity (see Figure 8, § III below). This decrease was satisfactorily represented in our data-reduction program as a gain change dependent only on time and camera number, and not on signal level nor position. The signal from the calibrator lamps decreased faster than would be indicated by the gain change derived from stellar observations, indicating that the primary mechanism for inducing the gain change may be long-term exposure of the target to light. Secondary contributing factors may have been decreasing beam current from the thermionic cathodes and darkening of the lithium fluoride faceplates from exposure to the radiation belts.

The Uvicon is very sensitive to optical focus and to magnetic fields. Defocusing by 0.002 in would have resulted in photometric gain changes considerably larger than the upper limit we were able to place on this effect. The only spacecraft system that interfered with our data-gathering ability was the magnetic unloading system, which blurred the images and changed the gain characteristics. That system was routinely turned off during Telescope data-gathering operations. The earth's magnetic field shifted the television images but did not distort the pictures. The maximum excursion of the center of the raster relative to the optic axis was about 15 arcmin and did not interfere with our operations.

The video signal from the electron-beam readout is in the microampere range, and a video preamplifier is used to condition this signal for transmission outside the camera package. The video preamplifier provides low-noise high-gain amplification of direct Uvicon output signals. Further amplification of the video signal to a level necessary for digital encoding or sync mixing is accomplished in the video amplifier.

The scanning beam can be deflected in either an analog or a digital mode. The analog scan is a 300-line raster with a 1.6 msec sweep duration and a total 0.48-sec scan time. The digitally swept beam is functionally more complex than the analog; however, the readout process at the target is the same. The digital deflection initiates a digitally indexed scanning beam equivalent to an element-by-element scan, 256 elements per line and 256 lines, and a total scan time of 10.5 sec. A unique unblanking technique known as superscan was employed in this experiment. The beam is positioned well into the previously readout area for all but the short period of time (less than 10 μ sec) during which the video is being sampled.

The resultant video signal (in either mode) is then transferred to the Bay E-4 module assembly for processing in either ANALOG, PCM or STORE mode before transmission (or storage) by the OAO spacecraft data-handling system.

In the ANALOG mode, the signal from the Uvicon is amplified and mixed with synchronization signals (resulting in a composite video output) for transmission. In both PCM and digital STORE modes, readout is accomplished in digital sweep mode in the Uvicons. In the PCM mode, the video output of the camera is sampled and encoded to 7-bit accuracy. The entire data train is transmitted in real time as PCM telemetry data. In the STORE mode, only data that exceed a preselected threshold are encoded.

Only PCM signals were analyzed for scientific purposes. The other modes were tested and found to work according to specifications; however, no failure occurred that required modifying our plans for using PCM as the primary mode for acquisition of scientific data.

During 16 months of active operation, and an additional 9 months in orbit not operating, Telescope experienced no change in operating characteristics other than the secular decrease in Uvicon sensitivity and the failure of the Uvicon in camera 2. There were no effects that could be directly attributable to space radiation; pictures taken in the South Atlantic Anomaly had the same characteristics as those taken elsewhere.

III. REVIEW OF CELESCOPE DATA-PROCESSING PROGRAMS AND CALIBRATION PROCEDURES

Before discussing the main topics of this section, we should like to show some typical examples of our television pictures. One must remember that we are interested in photometry, not positional astronomy. The shape and size of the images are more than adequate for our purposes.

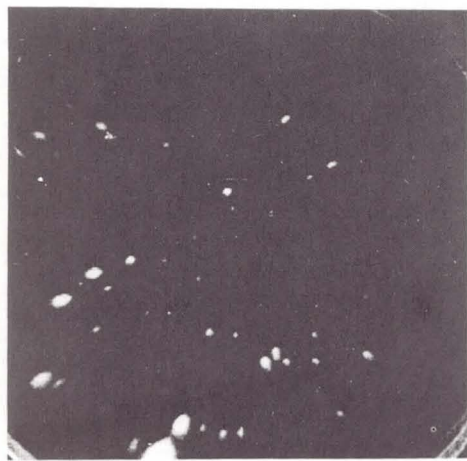
Figure 4 shows one of these pictures. Note the target ring in each corner of the picture. Each frame consists of 256 scan lines designated by the number k , with each line contain-



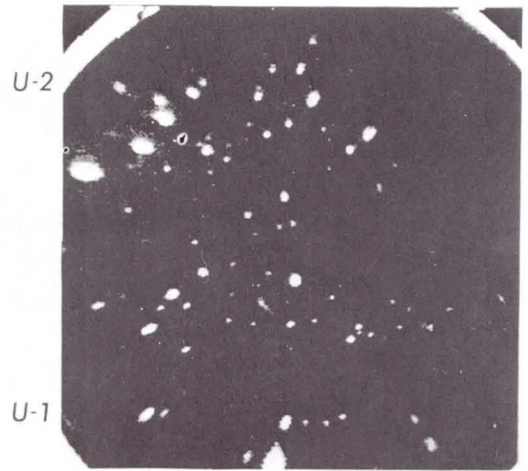
Figure 4.—Stars in Orion.

ing 251 pixels designated by the number ℓ , making a total of 64,256 intensity points $I(k, \ell)$. Lines 1 to approximately 115 have one spectral range; lines 115 to 141 have a composite response from both filters; lines 142 to 256 have a second spectral range. Most spacecraft pointings had exposures from three cameras. Figure 5 shows a montage of pictures from three cameras and a ground-based photograph. The stars in the television pictures range from 6 to 12 mag. The diffuse radiation in the U4 filter of camera 4 is the Lyman alpha radiation from the geocorona.

CELESCOPE PHOTOGRAPHS



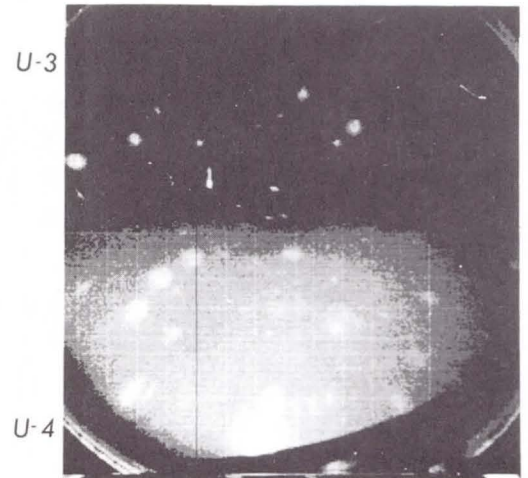
CAMERA 1



CAMERA 3



GROUND-BASED CAMERA



CAMERA 4

410-M

R.A. = 128.9 Dec. = -45.1

w.a.d. 3/69

Figure 5.—A composite picture in the Vela region.

The information in a television picture can be expressed and analyzed mathematically as a matrix in which the coefficient represents the signal amplitude for the k th television scanning line and the l th television-picture element. As the input signal increases in strength, the matrix image increases in both width and amplitude.

Figure 6 is a block diagram showing the basic design of the Telescope equipment and the various steps by which this equipment transforms the input information into the appropriate output video signal. At the top of Figure 6 are summarized the steps by which the Telescope instrument transforms starlight of intensity I and position α, δ into the matrix A ; at the bottom are given the equations by which the data-reduction system inverts that transformation to recover the intensity and position.

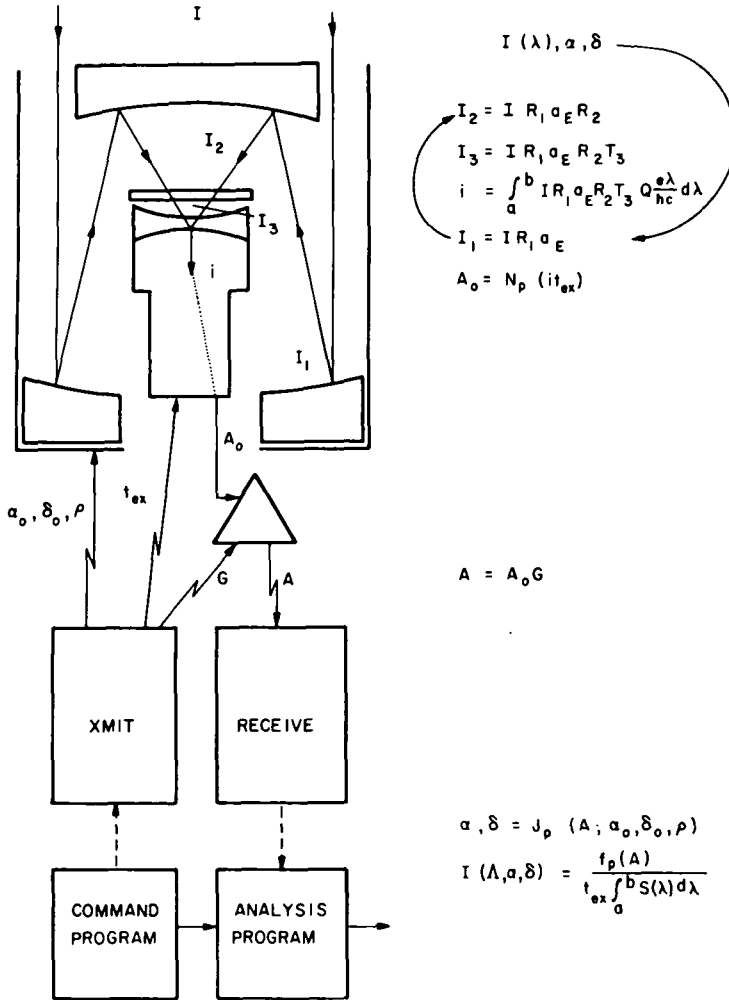


Figure 6.—Block diagram and information flow in the Telescope system.

The data-processing system that evolved during the project deserves some philosophical comment. In spite of extensive pre-launch preparations for data reduction, we were not well prepared for noisy data (streaks, parity errors and partial frames), nor were we ready to handle the Lyman alpha geocorona radiation in cameras 2 and 4.

We received a large number of television pictures from the experiment. Some of them were troublesome because of parity errors originating in the transmission link or in the data-handling equipment. We found that a quick and accurate quality check of the data was mandatory. They were hand carried from the data-processing section to our operations team at the OAO Control Center and immediately evaluated.

The final data-reduction system has a feature that we consider worthy of special attention: a composite observation file, which consists of composite observation records. Each record contains space for all the information that we ever expect to know about an object.

Each object in a picture starts as an empty record with locations for all the information that the data system generates. Subsequent programs read the information from and add information to the record. Each piece of data has an existence bit that tells if the information is in the record; therefore, the availability of information in the record can be determined without unpacking all the data. Sufficient blank spaces are reserved for information that may be added later. The advantages of common input and output routines are self-evident. In addition, the data can easily be used and sorted.

The data system shown in Figure 7 consists of four main programs: Phases 0, 1, 3 and 5. (Phases 2, 4, 6 and 7 existed but either have been absorbed by the existing phases or were dropped.) The temperatures and pointing information are checked at the Phase 0 level. Some data were missing or incorrect on a significant number of the pictures because the necessary data were on four separate data channels and were merged after they were received at GSFC.

The frames then proceed to Phase 1, the heart of the data system. It is the program that finds all the stars in each frame and all the intensities $I(k, \ell)$ associated with each star. We assume that the stars are relatively sharp spikes on a smooth background and that we can fit a general cubic equation, $A + Bk^3 + Ck^2 + Dk + Ek^2 + Fk + Gk^2 + H + I^2 + J^3$, to the background. Any intensity points that are 2.5 standard deviations above the fitted background are regarded as parts of stars.

The program has three distinct parts: the first section fits the background; the second decides which points are signal and to which star they belong; and the third prints the output of the stars for any necessary manual review and creates an output tape for the remaining stages of processing.

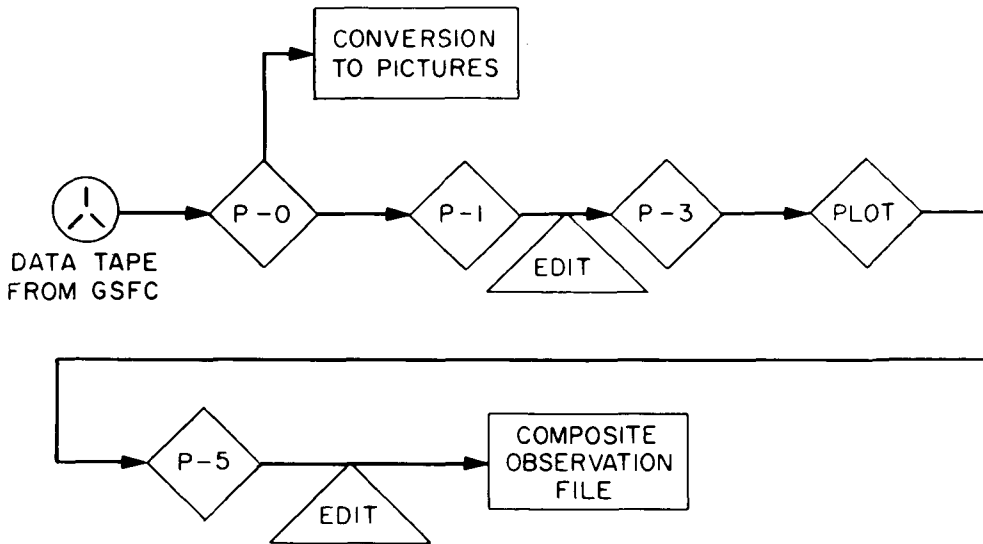


Figure 7.—Schematic diagram of the data-processing system.

Phase 3, the intensity reduction program, uses the raw input intensity calculated by Phase 1, the instrument temperatures, and the calibration data to calculate the intensity of the star. It also eliminates the known positional distortion in the frame and calculates the angular position of each object relative to the center of the frame. To do this it needs to calculate the target gain at any position on the target.

Phase 5 matches the stars in each frame with the Telescope catalog of stars, using a configuration match between the stars in the frame and those in the catalog. The program will correctly match the frame with the catalog even if the input center for the frame is 30 arc min from the actual center. The automatic identification program worked satisfactorily for most of our data. The frame must be manually matched if there are fewer than four stars common to both the frame and the catalog. A review of all frames for correct star identification follows.

Before we launched the experiment, we realized the need for in-orbit calibration and planned to take data for it. The least we could expect was a decay in sensitivity with time, but because of the two years between component calibration and the launch, we also planned to check the calibration in orbit. In addition, we felt strong pressure to acquire quickly a statistically significant amount of scientific data. The apparent conflict between the two goals of gathering calibration data and gathering scientific data in the initial orbits was

not easy to resolve. We pushed on to gather early scientific data at the expense of early calibration data. After the first month of operation, we began systematically to gather data for this task. They are listed below and are discussed in order:

1. A regular grid of stars or star fields; observations with a separation of 10 to 30 arc min between pointings.
2. Repeated observations of the same stars at regular time intervals.
3. Multiple exposures at the same pointing with different exposure times.
4. Repeated observations at the beginning and at the end of every standard slew sequence.
5. Multiple exposures at the same pointing and exposure time.

In order to map the camera sensitivities, each camera observed a number of stars of different intensity with two or more exposure times at each of 40 positions. Whenever possible, we used areas containing many stars so that the frames contained many calibration stars at the same time.

We observed the first regular grid, which was a compromise between calibration and data collection, from orbits 400 to 490. During this period, many stars were observed six times to obtain calibration data as well as scientific data. Later orbital periods were devoted entirely to this type of operation, and they provided data for the calibration-improvement program. Data from these grids were essential for the calibration of the experiment.

The time decay of the system is most easily determined if the same stars are observed at the same positions on the target at regular intervals. Because of sun, power and thermal constraints, this was impossible with our experiment, but we did observe a number of standard star fields as often as practical. Three star fields were used as primary calibration areas. We observed one as long as possible and then observed one of the other two fields as a standard until it was no longer available. Thus, we continually observed one of the three primary standard fields at least once during every operating period. These three areas, along with any chance repeat observations more than 20 orbits apart, provided the data that were used to determine the time decay for each camera-filter combination.

Identical exposures test the repeatability of the instrument. Each of our standard 36-exposure patterns started and ended at the same point for a quick check on the stability of the instrument's sensitivity. Twice, we took approximately ten consecutive exposures of several different stars to determine the repeatability of the observations. Magnitudes determined from these sets of observations varied by less than 0.2

mag.

The calibration data were used to determine

1. An exposure time correction.
2. The decay characteristics of the cameras.
3. The change in the area sensitivity of the target gain from initial calibration until launch.

All the data require an exposure-time correction, but it is only important for short exposure times. We deduced the correction by determining the additional increment of time that gave the best agreement in magnitudes between consecutive exposures of 1, 5, 15, 30 and 60 sec of the same stars.

The time-decay history of each camera-filter combination was determined by fitting a power series to the star data with a least squares technique. Each star must have a unique magnitude at time zero. Its magnitude calculated from measurements at any other time will increase if the system decays. Magnitudes are defined as $-2.5 \log(\text{power})$; hence, lower power signals have larger magnitudes. We therefore assumed that

$$M(t=0) = M(t_1) - \sum_1^n A_n t_1^n .$$

If a star was observed twice,

$$M(t=0) = M(t_1) - \sum_1^n A_n t_1^n = M(t_2) - \sum_1^n A_n t_2^n ,$$

and hence the equation

$$M(t_1) - M(t_2) = \sum_1^n A_n (t_1^n - t_2^n)$$

when solved for all pairs of stars defines the coefficients A_n in the decay equation for the system. Note that this is a linear correction; that is, every magnitude receives the same additive correction.

The standard calibration-area data and all chance repeats greater than 20 orbits apart were used in these fits. Other data were not used, because they reflect area sensitivity changes and isolated frame shifts rather than time decays. The curves determined with this program are shown in Figure 8. Each curve stops at the last reliable data point.

We used a Fletcher-Powell optimization technique to refine the target-gain curves. The input data were selected from the regular calibration grids and any other data that were appropriate. All marginal data and data that were contaminated by the filter discontinuity were eliminated from these runs.

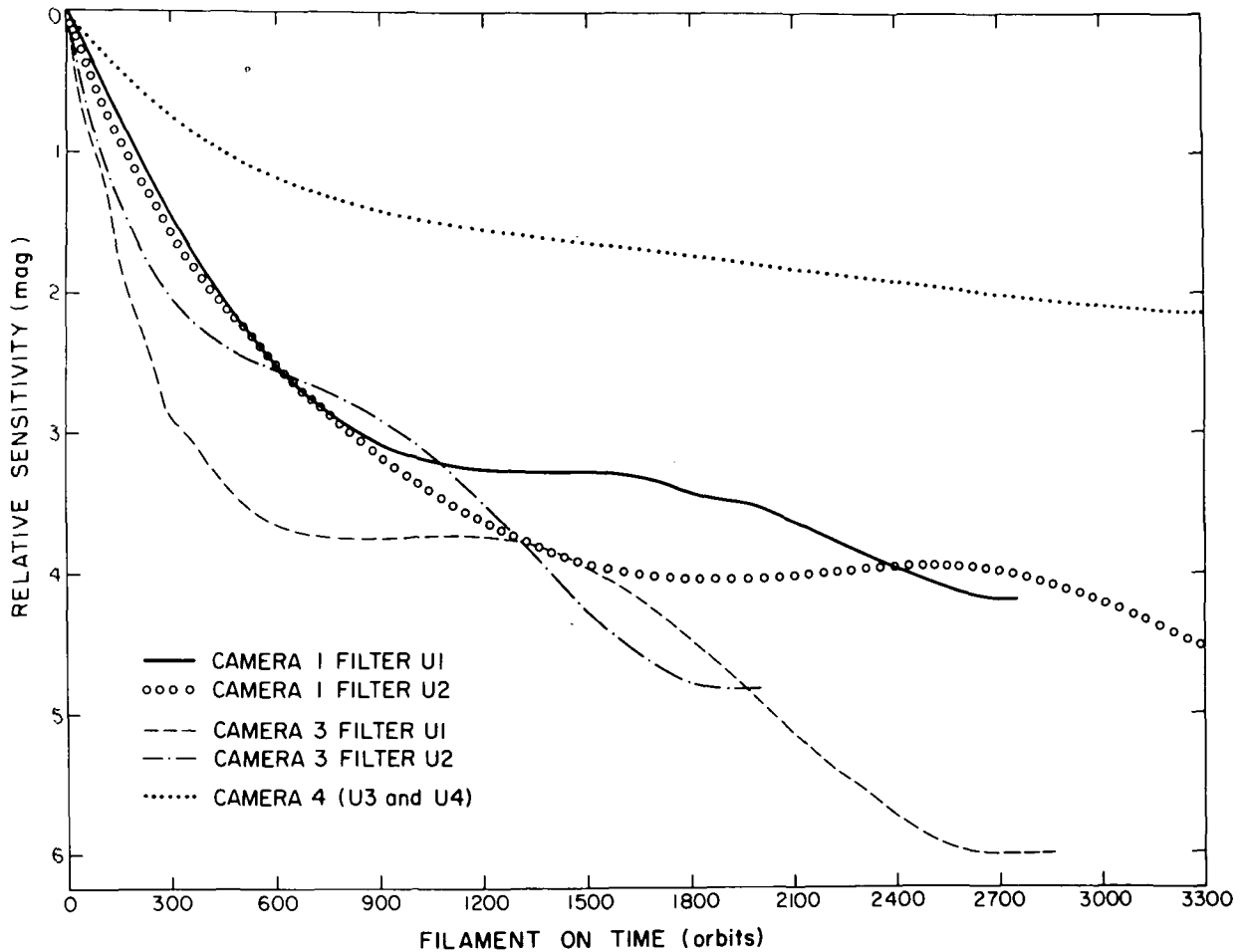


Figure 8.—Telescope sensitivity curves.

The program uses pairs of stars observed at different positions on the target. It computes the required gain change for each grid point that will minimize the RMS magnitude deviation of all pairs of stars. Since we assume that reciprocity holds for our tubes, we also use data at different exposure times. A series of laboratory tests on similar tubes showed no reciprocity failure.

The procedure for calibration improvement went as follows. Each camera was treated separately, and the stars in one filter were not compared with the stars in the other. First, the decay program calculated a decay curve for each filter. These curves provided a first-order correction to the magnitude calibration, and then the optimization program improved the gain curves. These curves were then used to calculate new magni-

tudes. Next, we calculated a new set of decay curves. The iteration between these two techniques continued until the results converged. The resulting gain curves showed only slight variations from the curves determined from the pre-flight data.

A short comment about the amount of data is included here because insufficient data may produce misleading results. All the programs had sufficient data for a meaningful solution. The decay equation contained six coefficients for camera 1 and five for cameras 3 and 4. At least 320 data points were used for the least squares fit. The gain-curve optimization program has 500 parameters and a minimum of 1500 data points.

Table 1 lists the final result of the magnitude-improvement procedure.

Table 1. Final RMS magnitude discrepancies

Camera	RMS discrepancy (mag)
1	0.17
3	0.20
4	0.19

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