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Film and Television in Space Technology

During this Society's 101st Technical Conference held in New York City, April 16–21, 1967, two complete sessions were devoted to Space Technology. The papers included discussions of means for obtaining images from both earth and lunar orbiting and also by soft-landed lunar cameras. Means of simulation of space missions as well as methods of reconstructing images on the ground were described.

Neither the wealth of slides and films nor the hardware (such as that for Surveyor I) which were shown at the Conference can be fully described in the group of papers included in this issue. Of particular interest at the Conference was the proection of the Hasselblad slides of the Space Rendezvous.

The seven papers in this issue of the Journal *include five which completely describe all segments of the Lunar Orbiter photographic system, including both the spaceborne and the groundborne equipment and their interrelation. The sixth paper discusses the special characteristics which are being built into vidicons to make them specifically suitable for space application. The final paper describes the Surveyor I TV camera design, operation and facilities for selecting pictures for transmittal. We look forward to other technical papers about motion-picture and television arts and sciences in the space programs.*—F. J. Bingley, *101st Conference Topic Chairman*

The Lunar Orbiter Photographic System

By B. L. ELLE, C. S. HEINMILLER,
P. J. FROMME and A. E. NEUMER

The photographic system which produced the photographs of the lunar surface is a complex one. Inherent in its design is provision for dual lens photography, film processing, conversion of the film images into video signals for relay through the spacecraft transmitter and reconstitution of the photographic image on earth after receipt of signals by the orbital tracking stations. The prime objective of the Lunar Orbiter Mission is to secure topographic data of the lunar surface to enable selection and confirmation of suitable Apollo landing sites. In addition to the stringent performance objectives, the equipment design was strongly influenced by a number of constraints: e.g., size, weight, power consumption, pressure environment, the ambient thermal environment and the limitation on system control and instrumentation. Fundamental to the photographic system design was the selection of a suitable film processing chemistry and lenses. These are all reviewed in detail. The performance photographic requirements for the ground equipment are also briefly discussed.

A MAJOR GOAL OF the United States space program is to land men on the moon within the next few years. To accomplish this goal, knowledge of the lunar surface is essential, and a series of programs to acquire this knowledge have been and are being conducted under the sponsorship of the National Aeronautics & Space Administration (NASA) to support the Apollo manned landing flights.

Ranger provided important preliminary information which helped establish criteria for succeeding programs. Surveyor I landed and provided a close-up look at the lunar surface. The Lunar Orbiter, under the overall direction of NASA-Langley Research Center, provided the first high-quality photographs of large areas of the lunar surface.

A previous paper* on the Lunar Orbiter was written before it was an accomplished fact. The present series of papers is intended to cover in more depth the details of the photo systems and some of the critical design decisions necessary for its successful completion.

As specified by NASA, the primary task of the Orbiter was to examine photographically on each mission at least 2000 km^2 of the lunar surface with high resolution so as to be able to detect protuberances or cones as small as $\frac{1}{2}$-m high with a base of 2-m diameter as well as flat slopes 7-m square with a slope angle not less than 7°. In addition, a moderate resolution system was to be included capable of detecting targets 8 times larger over an area of 40,000 km^2.

The initially established target area encompassed the lunar surface between ±60° lunar longitude, and ±10° lunar latitude. The photographic target area, therefore, is the center portion of the front side of the moon facing the earth and was so established because of the trajectory constraints of the Apollo mission landing vehicle. To permit overlapping and contiguous coverage capability of the entire target area, an orbit plane inclined at a low angle relative to the lunar equator was selected for the spacecraft.

Selection of a film system rather than the previously used video space systems was a significant departure from previous programs and a recognition of the vast storage capability of photographic emulsions.

Lunar Orbiter would be of maximum value as support to the Apollo program if photographs of the lunar surface were available to identify sites or verify adequacy of landing equipment considerably ahead of the planned Apollo flights. Since the Orbiter program was not officially initiated until early 1964, the total

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Presented on April 18, 1967, at the Society's Technical Conference in New York by Bruce L. Elle (who read the paper), C. S. Heinmiller, P. J. Fromme and A. E. Neumer, Apparatus & Optical Div., Eastman Kodak Co., 400 Plymouth Ave. North, Rochester, N.Y. 14650.
This paper was received on February 28, 1967.)

* Leon J. Kosofsky and G. Calvin Broome, "Lunar Orbiter: a photographic satellite," *Jour. SMPTE, 74:* 773–778, Sept. 1965.

time available from hardware concept to first flight was about 2½ years. Off-the-shelf hardware was specified to be used whenever possible. The truth of the matter in respect to the photo system was, however, that even though many past proven concepts were used, virtually no flight hardware existed which satisfied the severe weight, power and qualification requirements of the Lunar Orbiter Program.

Mission Parameters as Applied to the Photo System

Although many of the NASA requirements had been anticipated, The Boeing Co., the prime contractor, and the two Lunar Orbiter major subcontractors, Kodak and RCA, participated in a series of trade studies resulting in the definition of many mission parameters which served to establish design effort boundaries.

To assure entry into a suitable lunar orbit without impacting the moon, an elliptical approach orbit and final elliptical photo orbit, having a perilune of 46 km, were selected. Although initially quite controversial, an attitude-stabilized system providing three-axis spacecraft control was selected rather than a spin-stabilized vehicle. This configuration provides excellent maneuverability and pointing control as well as a stable platform so that high-resolution film, requiring relatively long exposure times, can be employed.

Communication with the spacecraft must provide high-quality video transmission characteristics or the capabilities of the photographic system would be wasted. The selection of the communication system resulted only after careful study of power available, antenna gains and signal-to-noise ratios. A double-balanced modulator, a 10-W traveling wave tube, a 24-in. parabolic high-gain antenna and a 230-kHz bandwidth were settled upon as being the optimum solution within imposed constraints.

The power budget allocated to the photo system was 100 W.

The Atlas Agena launch vehicle which was specified will place slightly more than 850 lb into a translunar trajectory. Decision to use this highly reliable booster resulted in weight budget assignment to the photo system of only 133 lb.

Basic Design Decisions

Several basic design decisions were made early in conceptual stages of the Lunar Orbiter Program which established the sophistication of function and the configuration of the photo system.

A dual-lens 70mm frame camera was chosen as a trade-off between weight and optical performance requirements. The two lenses selected were 610mm and 80mm focal length which were compatible with the scale factor and resolution requirements of the system. The lens format-cycling arrangement also yields stereo to assist in lunar surface analysis. For processing, the KODAK BIMAT Transfer Film processing system was chosen because of its several unique characteristics. And finally, there was selected a readout system whose prototype utilizing a linescan tube had a previous history of successful space operation. All of these system components are described in detail in this and the succeeding papers.

Use of a high-resolution film was required because of the scale factors and lunar resolution requirements. Such film is inherently of low speed which mandated long exposure times. Additionally, as the planned spacecraft orbit was elliptical, velocity of the spacecraft as well as the velocity to height ratio (V/H) of the spacecraft would continually change during the photo portion of the mission. Photo-performance smear analysis based upon possible variables resulted in the decision to incorporate an active optical V/H Sensor in the camera system. Again, to conserve weight and power and to avoid inaccuracies from converting sensor output to motor control, the V/H Sensor output shaft is used to directly drive the image motion compensation (IMC) for both the high- and moderate-resolution camera platens.

Careful mission planning permits the selection of photographic targets under predictable solar illumination conditions. Based on available data from visual observations made from earth, a nominal programed exposure time of 1/50 s was chosen. Additional settings of 1/25 and 1/100 s were provided and were selectable by ground command. An active automatic exposure control system in the spacecraft, as opposed to programed control, was considered. An early study examined the relative merits of both methods and considering such factors as shutter accuracy, scene latitude, readout latitude and variation of exposure across the camera frame, it was demonstrated that an automatic system provided no significant advantage and its use in a camera designed for minimum weight and maximum simplicity and reliability was not recommended.

The photo system's thermal control had to be simple, effective and compatible with the spacecraft which served as the photo system thermal sink. A radiation fin arrangement was established for basic thermal coupling to the spacecraft. Areas within the photo system were zoned and maintained within necessary temperature limits as required. All cooling takes place as a result of shell-surround environment or through the bottom fins of the photo system to the spacecraft equipment mounting deck. Strip heaters and electronic sensors and controllers were designed and are used within the photo system when it is necessary to elevate and control temperatures.

To provide the capability of photographic processing, it was necessary to enclose the photo system within a hermetically sealed and pressurized container. A shell-pressure relief valve was selected and used to maintain the system at a pressure of between 1.0 and 2.0 psia. Potassium thiocyanate salt pads maintain the photo system internal environment at a relative humidity of approximately 50%, absorbing or releasing moisture as required.

A ground reconstruction system similar to a previously proven successful concept was decided upon. Circuit updating and necessary modifications to make the system compatible with the Lunar Orbiter constraints of scan frequencies and signal levels were performed.

Design Analysis and Verification

Understanding and applying the relations which govern the unique photometric properties of the lunar surface are a prerequisite to design analysis discussion of Lunar Orbiter photography. Light (B) reflected from the lunar surface is the product of the lunar reflectance or albedo (ρ), the incident light or Solar constant (R) and the photometric function (ϕ).

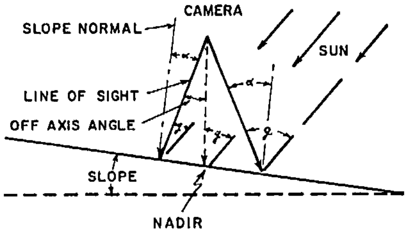

Fig. 1. Schematic diagram showing angles affecting photometric functions.

$$B = R\rho\phi, \text{ where } R = 12{,}500 \text{ fc}$$

ϕ can be defined in terms of two angles (Fig. 1), a solar phase angle (g) and a surface angle (α). It should be noted that g and α vary throughout the field of view of the cameras as α is the angle between the slope normal and the line of sight and g is the angle between the line of sight and the incident light.

It is apparent from studying the plot of the photometric function for various values of g and α (Fig. 2), that if a photograph were to be taken along the sunline with the sun at zenith the result would be of extremely low contrast, since the slope has little effect upon the amount of light reflected and there would be no shadows. Analysis of this type of data resulted in the decision to take all lunar mission photos at a phase angle of between 50° and 80°.

NASA initially specified a signal-to-noise ratio (SNR) technique for judging the overall system performance. It was envisioned that the final photographs would be scanned with a microdensitometer and the resulting signal (density) would be compared to the rms background noise.

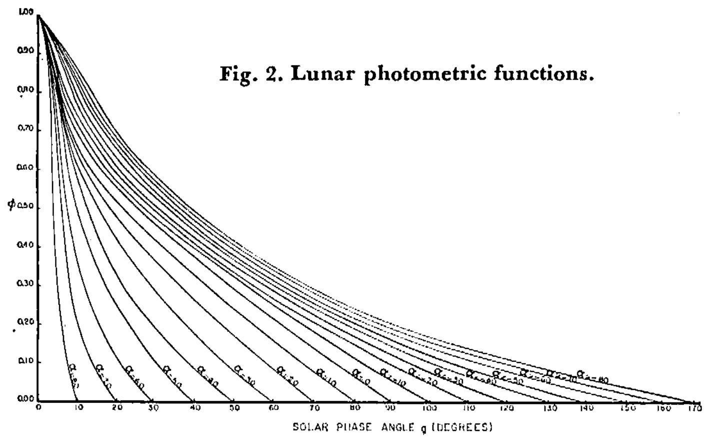

Fig. 2. Lunar photometric functions.

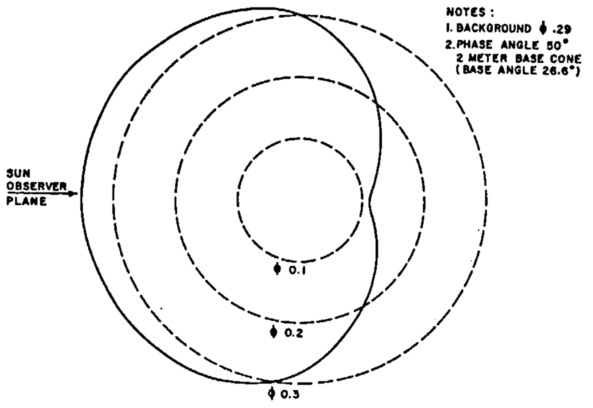

Fig. 3. Photometric functions for 2-m cone.

For test purposes, it was specified that a flat test target be used having adjacent bars of alternating brightness such that they simulate the maximum highlight and the darkest portions of the previously mentioned 2-m base cones under the mission lighting conditions. The width of these bars should simulate ½ m (1-m period) on the lunar surface. The target was to be photographed and transmitted through all of the data links and ground reconstruction equipment as though in an actual mission. The final reconstructed picture would be scanned by a densitometer having a scanning aperture of effective ½ m diameter. The resulting signal should have a peak-to-peak signal strength at least equal to the rms noise.

There is very little history in the use of SNR in a system of this sort and a working specification in conventional tri-bar terms was therefore desirable. First, it was necessary to establish some limits for both spatial frequency and target contrast. The ½-m bars specified by the NASA at a nominal orbit altitude of 46 km are equivalent to a spatial frequency of 76 cycles/mm in the focal plane of the 610mm lens. To determine contrast, the 2-m cones previously referred to were examined in terms of their photometric characteristics under the mission lighting conditions. Figure 3 is a plot in polar coordinates of the photometric function when the cone is viewed from directly above and for a phase angle of 50°. As will be seen, some portions of the cone have a brightness equal to the background and the maximum contrast ratio is approximately 3:1. At larger phase angles, this contrast ratio increases rapidly and approaches infinity at an angle equal to the complement of the cone base angle. Since 3:1 contrast represents a worst case, this was agreed on along with a spatial frequency of 76 lines/mm as the working specification for the photo systems.

Although very early studies had indicated that a 3:1 tri-bar resolution of 76 lines/mm would be adequate for detection of the specified lunar cones and slopes and would provide a SNR in excess of unity, an experimental program to verify this was initiated.

A target was made which contained tri-bar targets both at 3:1 and high contrast, simulated cones and lunar slopes, sine wave targets, and bar targets for SNR measurements. This target was photographed at mission scale, read out through the entire system and reconstructed. The final photographs were examined visually and, in addition, the ½-m wide bar targets (1 meter period) were scanned with a microdensitometer having an equivalent aperture of ½ m. The results indicated that in terms of visual detection of the NASA slopes and cones, a system tri-bar resolution specification of 76 lines/mm at 3:1 contrast was considerably more demanding. In terms of SNR, as determined from the microdensitometer traces, it was found that the results varied considerably as a function of the technique used for analysis and it was concluded that the method is very cumbersome as a measurement tool. Although a reliable correlation between tri-bar resolution and SNR could not be determined within the scope of the test, SNR's considerably in excess of the target goal of one were nevertheless obtained at a spatial frequency of 76 lines/mm.

As an analytical tool for predicting system performance, however, the SNR has proved to be very convenient and was used throughout the course of the design to help establish limits for various parts of the system. The signal through the system was determined from the modulation transfer functions (MTF) of the various components.

The MTF of each system element was either derived or measured directly. One major element is the MTF which results from residual image smear. A computer program was written to predict the smear due to mechanical alignment, vibration, and attitude control tolerances. This was combined with smear resulting from IMC tolerances to provide an overall smear budget for the camera.

All MTF's were combined to yield an overall system response. The enhancement of the signal due to the contrast of the vehicle film and the electronic peaking which was incorporated in the video electronics, was taken into account in the analysis. Figure 4 shows the calculated overall system response.

The various noise contributors of the photo system were derived: random granularity of the film, the line scan tube phosphor, the photomultiplier tube in the readout system, the video electronics and the communications system. Both signal information and noise were fed into a computer program. Figure 5 shows the calculated SNR as a function of both spatial frequency and film density.

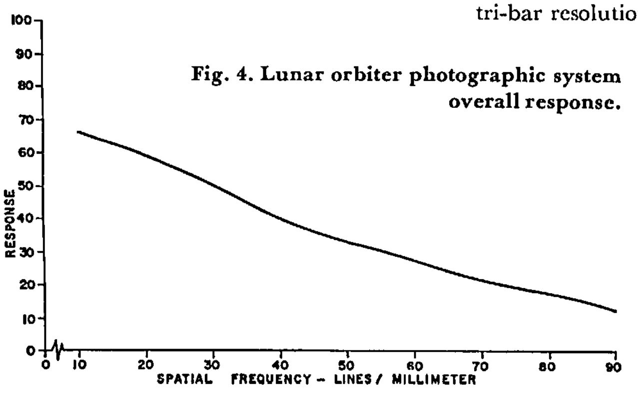

Fig. 4. Lunar orbiter photographic system overall response.

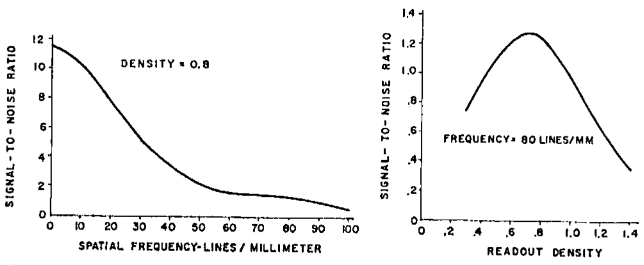

Fig. 5. Typical SNR profiles for Lunar Orbiter photographic subsystem.

Additional design analysis was performed on the film-handling system using an analog computer, and finally both the structural and thermal designs were analyzed with a digital program. These are discussed in more detail in companion papers. It is of interest to note that flight instrumentation data almost exactly duplicated the thermal computer program.

Photographic Parameters

As previously mentioned, film has tremendous information-acquisition and storage capability. Each film in the Lunar Orbiter was carefully selected for its contribution to overall performance. Kodak High Definition Aerial Film (Gray Base), Type SO-243 in 70mm width was used in the Orbiter photographic system cameras. This fine-grain, low-speed film (Aerial Index of approximately 3.0) is compatible with the selected *f*/5.6 lens speed and 1/25, 1/50, 1/100 second exposure range under the 50° to 80° solar illumination decided upon for mission photography.

Providing more than 450 lines/mm recording capability, KODAK SO-243 Film has low enough speed to make it relatively insensitive to space environment ionizing radiation. Design calculations showed that a supply enclosure shielding of only 2 grams/cm^2 was adequate to protect the unexposed film from fogging under worst case trajectory conditions through the Van Allen radiation belt. Incidentally, because the weight would be prohibitive, the photo system is not protected for major radiation problems such as solar flares as these phenomena, although intense, are infrequent and can be predicted with some degree of accuracy. Photo mission launches will not be planned during periods of predicted high flare activity.

KODAK SO-243 Film was selected for its aforementioned characteristics as well as for its compatibility with Bimat processing. The emulsion yields a high-quality, controllable image when laminated with KODAK Dry BIMAT Transfer Film (ESTAR Base), Type SO-111, which has been imbibed to a predetermined amount of Kodak PS 485K Bimat Imbibant. The SO-243 Film is coated on a gray-base triacetate support and neither requires nor carries any other antihalation dye or backing that would have to be removed during processing. The gray base is also compatible with the readout system.

Figure 6 depicts a typical sensitometric curve for photo system film processed for $3\frac{1}{4}$ min at 85 F. The plot represents the effective density of the processed film and is plotted in terms of readout density. The plot is lower in minimum density and higher in contrast than a standard ASA visual-match diffuse-density plot because of the spectral effect of the P-16 Line-Scan Tube light source and of the specular optics of the readout system.

Before use, the flight film is pre-exposed along one edge as shown in Fig. 7. These exposures include calibration data which are used to monitor photo system operation during an actual mission and also to evaluate mission output. The pre-exposed information includes a 0.3 background density to provide a reference level for setting readout gain, diagonal focus lines to indicate optimum readout scanning spot focus, resolution charts to evaluate readout quality independent of camera image quality, a gray scale for sensitometric calibration, and a frame identification number.

The next film to be established was that employed in ground equipment for production of the 35mm reconstructed record. Here the video signal produced by the readout is reconverted to a photographic image. Again P-16 phosphor is involved, this time as the exposing source, as the 35mm film is driven continously through the recording camera and exposed to an intensity-modulated line on the face of the cathode-ray tube. The available exposure level did not present unusual difficulties since scanning rate of 800 Hz is quite slow relative to conventional TV systems. The film selected is Eastman Television Recording Film, Type SO-349. It is identical to Type 5374 film except that it has negative type (PH22.139-1964) rather than positive type (PH22.36-1964) perforations. The processing chosen produces a sensitometric curve as shown in Fig. 8. At this stage the relayed lunar surface image is a positive, enlarged 7.2 times from the original 70mm film, but with alternate scan segments having the mirror-image geometry produced by the readout. The recording equipment is adjusted so the maximum readout signal produces a visual density of 2.0 on the film. At the same time, the minimum readout video signal is reproduced as a reconstructed record density of 0.5. This 1.5 density range is satisfactory both for viewing and for reproduction.

The 35mm reconstructed records are next optically combined onto $9\frac{1}{2}$-in. film, providing negative images which are then constructed as though they were direct enlargements from portions of the original camera film. The reassembly printer which compensates for the readout geometry inherent in the 35mm records will be described in one of the following papers. These reassembled negatives have a magnification of 0.89× from the 35mm positive (6.4× from the camera film) and are reproduced from the 35mm film at essentially unit contrast including allowance for the printer Q factor. KODAK Aerographic Duplicating Film, (ESTAR Base), Type 2427, is the film used since it is a relatively fast duplicating film as required by the printer illumination, has satisfactory quality and can readily be processed to the required contrast.

After reconstruction and reassembly, it is normal practice to produce at least two additional print generations of both the 35mm and $9\frac{1}{2}$-in. records. In both cases prints are made on high-resolution

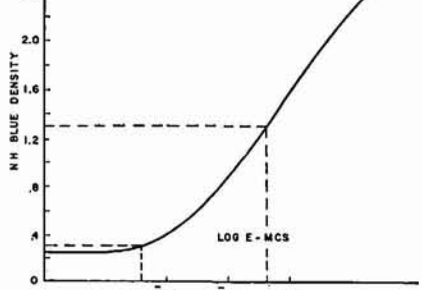

Fig. 6. Sensitometric curve of Bimat processed SO-243 Film NH blue densities.

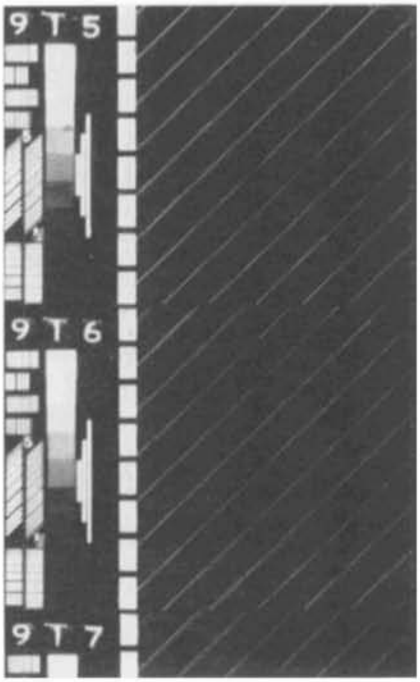

Fig. 7. Pre-exposed format.

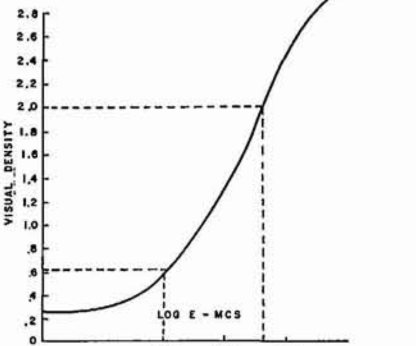

Fig. 8. Sensitometric curve of SO-349 Film visual density.

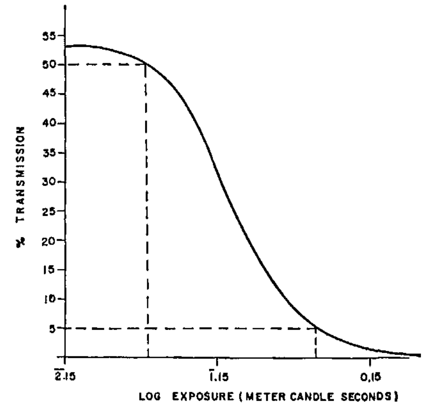

Fig. 9. Sensitometric curve of Bimat processed SO-243 Film transmission V_s Log E.

sprocketless contact printers and processed for an effective contrast of 1.0. For prints of the 9$\frac{1}{2}$-in. reassembled negatives, additional generations are produced on Type 2427 as is the direct reassembly. 35mm prints are made on EASTMAN Fine Grain Duplicating Panchromatic Negative Film, Type 5234, and processed with a positive developer in a 90 F spray processor. The requirement here for unit contrast is quite different from that of most 35mm print materials, but 5234 has been satisfactory both for processing characteristics and general quality.

All of the photographic parameters of the system have been combined to yield an overall tone reproduction curve. The essential elements included are:

(1) camera lens,

(2) camera film,

(3) readout system (including the flying-spot scanner, the photo multiplier and the video amplifier) which produces a video signal proportional to the processed film transmission,

(4) the RCA data link to the ground station,

(5) the ground reconstruction electronics,

(6) the kinescope tube which displays the modulated flying spot for photographic recording,

(7) the recording lens, and

(8) the reconstructed record film.

There are several distinctly nonlinear elements included. The camera film characteristics shown in Fig. 6 are basically nonlinear even if plotted in terms of density and log exposure. Since the readout produces a signal proportional to transmission, the relationship between density and transmission is also required. Figure 9 shows the curve of Fig. 6 in terms of transmission and log exposure. Further nonlinearities are present in the ground-equipment kinescope tube and the SO-349 Film used to produce the 35mm reconstructed record. Figure 10 shows the relationship of grid voltage and relative log kinescope brightness which, as can be seen, tends to compensate for the SO-349 Film characteristics of Fig. 8. These factors combined with the others listed which are all near linear have been combined to produce the full tone reproduction curve shown in Fig. 11.

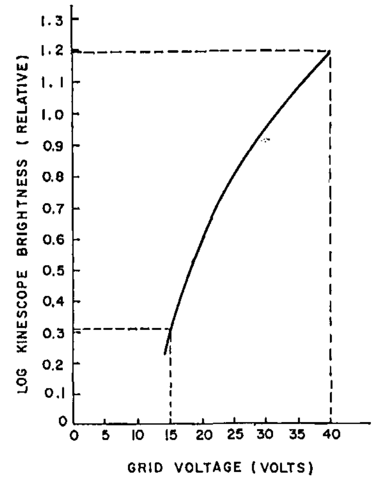

Fig. 10. Log kinescope brightness V_s grid voltage.

The reproduction curve of Fig. 11 is based on a standard readout adjustment whereby the maximum signal corresponds to a camera film density of 0.3. Thus any densities in the picture area below 0.3 will not be distinguished. This decision recognizes that densities below 0.3 will have very low contrast and necessarily carry little information. Another density level often used as reference is the camera density of 1.3, where the transmission and therefore the readout signal are 10% of its level from 0.3. This 10:1 range is considered the practical dynamic range of the Photo System and is identified on the tone reproduction curves as well as in many system performance calculations.

Optics

For the high-resolution camera lens, an existing Pacific Optical Co. 610mm (24-in.) focal length $f/5.6$ design was chosen. This lens was ideally suited because of its compact size and relatively simple construction. It has six airspaced elements. In its original form, the lens was designed to cover a larger field than needed in the Lunar Orbiter. Therefore, in order to reduce weight, a redesign was initiated to reduce both the lens diameter and the thickness of the elements. The first attempt at redesign was not satisfactory because of a shift in the color correction toward the blue end of the spectrum. In this connection, it is to be noted that most long focal-length aerial lenses are designed to be used with a yellow filter in order to reduce scattering by the earth's atmosphere. This is not a problem in lunar photography since there is no atmosphere and it was desired to use the lens unfiltered in order to take advantage of all the illumination available. Continued efforts at Kodak and Pacific Optical eventually provided a better achromatization for use with SO-243 Film. A follow-on program at Kodak added an aspheric correction which was tailor-made for each lens assembly. This reduced the residual monochromatic aberrations to less than $\frac{1}{6}$ wavelength and resulted in on-axis tri-bar resolution on SO-243 Film in the range of 120 to 140 lines/mm for a 3:1 contrast target. These readings were obtained with a tungsten source and with no filter over the lens. The measured MTF is shown in Fig. 12.

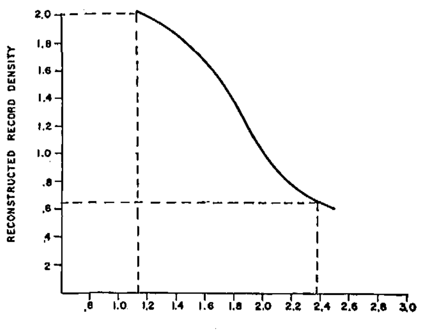

Fig. 11. Photographic system tone reproduction (1/25-s exposure).

Several 80mm lenses were considered. The Schneider Xenotar was selected because of its excellent performance, compact size, simplicity of construction (5 elements) and ready availability mounted in a between-the-lens shutter. A typical measured-response curve is shown in Fig. 12. Although the shutters were extensively modified to attain reliability necessary for flight use, standard off-the-shelf commercial lenses were purchased, the best ones were selected and used without change for flight at a fixed aperture of $f/5.6$. Incidentally, the lenses were cali-

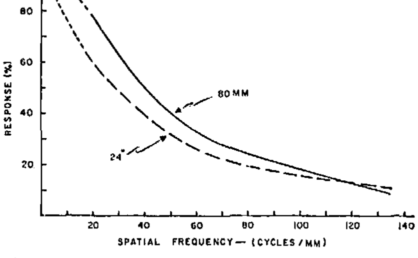

Fig. 12. Measured MTF of typical 24-in. and 80mm camera lenses for a heterochromatic source.

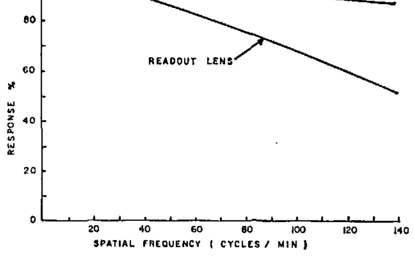

Fig. 13. Measured MTF of readout lens and GRE lens (at vehicle film scale) for a P-16 phosphor equivalent source.

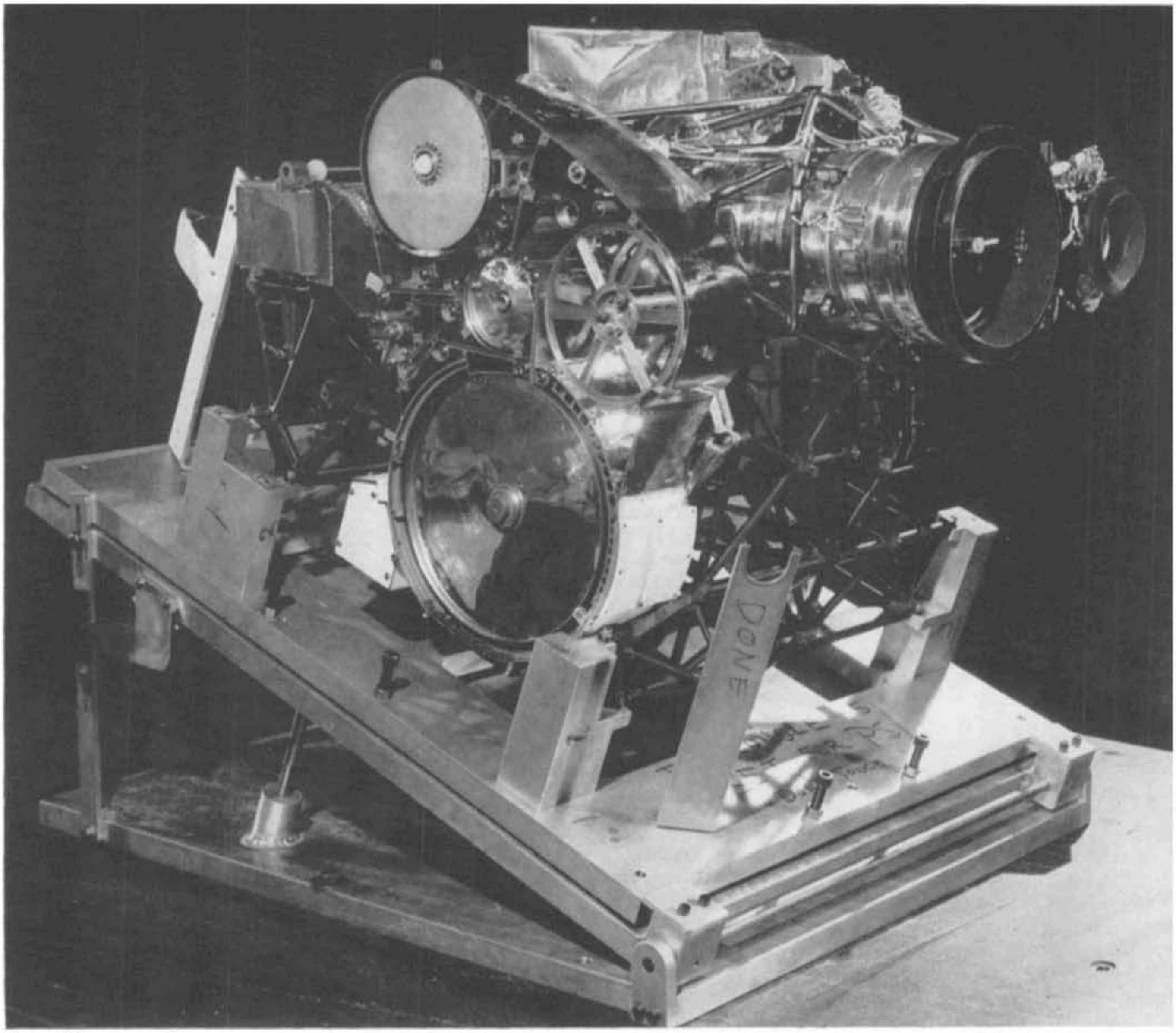

Fig. 14. Photographic system prior to installation into pressure shell.

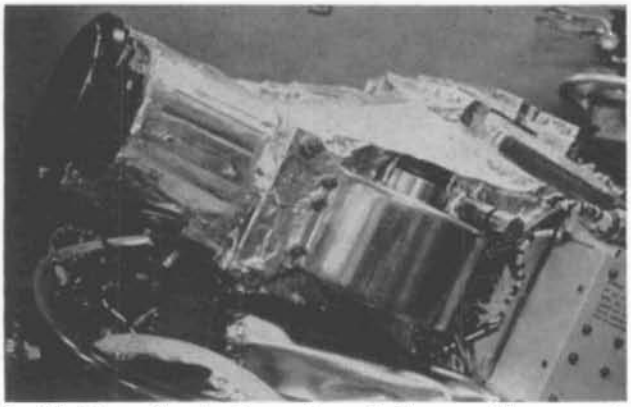

Fig. 15. Three-fourths front view of photographic system in lower half of pressure shell.

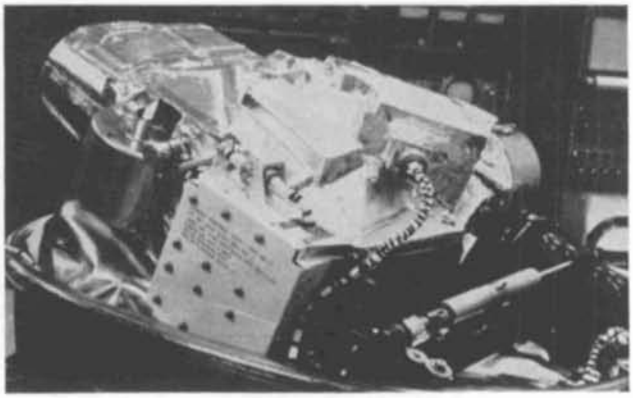

Fig. 16. Three-fourths rear view of photographic system in lower half of pressure shell.

brated for radial distortion in the 80mm camera assembly prior to use.

For readout, the high-intensity single-line scan from the LST is imaged at 22.5× reduction on the 70mm flight film by a special Kodak lens designed for an achromatization to match the P-16 phosphor used (370–410 mμ region). This $f/1.5$ seven-element lens is used in the system at an aperture of $f/2.4$. Figure 13 shows the measured MTF of this lens at this aperture.

The ground reconstruction system uses an adjustable aperture, $f/2.0$ eight-element Eastman Kodak designed objec-

Table I. Photo System Major Elements.

- *A. Photo System:* Overall size — 26-in. y axis, 22-in. x axis, 32-in. z axis; overall weight 147 lb.
- *B. Camera:* Dual-frame type; 610mm and 80mm lenses; 70mm film; focal plane shutter 610mm lens, between-the-lens shutter 80mm lens; exposure times 1/25, 1/50, 1/100 s; IMC controlled by V/H Sensor.
- *C. Processor-Dryer:* Kodak Bimat film processing system; transport speed 2.4 in./min; processing temperature 85 F, drying temperature 95 F; drying time 11.7 min.
- *D. Readout:* Special flying-spot scanner; line-scan tube source; 22.02 s/framelet readout rate; framelet size 0.105 in. × 2.269-in.; 230 kc bandwidth.
- *E. Film Handling:* Continuous thread-up through entire system; film motion forward in photographic mode and reverse in readout mode; tension control by means of storage loopers; film plane change by twisters; total thread-up length (launch condition — loopers empty) 247 in.
- *F. Structures:* Main frame aluminum; 610 mm camera frame titanium, 80mm camera frame aluminum, outershell aluminum approximately 0.020 in. thick.
- *G. Instrumentation:* Total 37 telemetry points, 20 ground tests points to monitor PS status; signal output analog (0 to 5 V) and digital (0 V $^{+1.0}_{-0.3}$ for negation-logic "zero" and 6 V $^{+1.0}_{-0.6}$ for affirmation-logic "one").
- *H. Environment:* Thermal control by radiation fins and heaters; humidity control potassium thiocyanate pads; internal gas (nitrogen) pressure 1.0 to 2.0 psia; gas make-up system internal to PS.

tive, also compatible with the P-16 ground CRT spectral range. Measured response for this objective is seen in Fig. 13.

Hardware Configuration

The photo system is an extremely compact package of intricate function. The major elements and their characteristics are shown in Table I. Figures 14, 15 and 16 show some of the basic functioning elements and their spatial relationships. Note that every effort has been made to conserve space and weight. Structural mounting feet are attached through the lower pressure shell and act as the mechanical mounting interface for the photo system to the spacecraft. The flat bottom portion of the lower shell is also equipped with thermal radiation fins for radiating heat loads generated within the payload to a set of opposed radiation fins attached to the spacecraft equipment mounting deck. Several high heat dissipation subassemblies such as the Command Control Programmer, the main logic control and command processing electronics, the dc/dc converter which generates necessary operational and instrumentation voltages for the various photo system black boxes, and the sync and sweep electronics which control the focus and deflection coils for the LST readout source are mounted by means of special heat transfer strips to the bottom of the shell. The lower shell also contains thermistor instrumentation points and heaters and controllers to maintain the lower portion of the system within established thermal limits.

The internal structure mounts into the lower shell and supports the line-scan tube, optical-mechanical scanner, the film take-up and Readout Looper in a lower functional plane.

The processor-dryer and its two integrally mounted 90° twisters provide a film path between the upper and lower functional planes. The camera storage looper, the camera, its associated drive and control mechanisms, and the film supply are mounted in the upper plane. The camera structure, fabricated from titanium, is attached to the aluminum internal structure at three mounting points. The two functional planes are separated thermally from each other by a low-emissivity thermal blanket. Temperatures are rigidly controlled in the camera or upper shell section to 70 F ± 5 in order to optimize optical performance. The lower portion of the photo system is subjected to a larger thermal variation because of the greater amount of heat generated by power consumption during readout modes.

Items such as the nitrogen make-up bottle, the V/H electronics assembly and the reference frequency generator whose functions are relatively insensitive to position are tucked into the shell where space is available.

Potassium thiocyanate salt pads are distributed throughout the photo system at positions which provide optimum humidity control capability.

Two hermetically sealed optical windows provide ports for the two camera lenses to view the lunar surface.

The photo system is bolted together with flanges and an O-ring seal, and a pressure relief valve is incorporated which maintains internal pressure at 1.1 to 2 psia.

Summary and Conclusions

Much of the technical background and many of the requirements and decisions necessary to create the Lunar Orbiter Photo System have been reviewed. A pertinent question might now be "How successful was the effort?"

The photo system provided approximately three times the area coverage required. The system's weight of 147 lb was within a few pounds of early prediction of 141 lb, but heavier than the 133 lb assigned by our customer. Our original proposal guaranteed 155 frames of useful photography which was upgraded by design consideration to 194 frames. By careful sequencing and planning, our actual mission acquisition has been in excess of 210 frames. Unofficial analysis of image quality has indicated that objects less than 3 ft and probably as small as 2 ft have been detected from an altitude of 25 miles with the 24-in. lens. Again, unofficial analysis indicates 80mm photography as permitting the recognition of objects as small as 6 m compared to an 8-m requirement.

The thermal design, when monitored by the plotting of actual flight data, follows predicted trends within a few per cent. Mechanical scan linearity was somewhat poorer than anticipated. This particular situation was alleviated by preprinting fiducial marks at known spacings across the film.

Additionally, a shutter trip anomaly occurred on Lunar Orbiter Mission I. Although extensive interference tests had been performed, the anomaly had never been duplicated in ground tests prior to the mission. The problem was determined to be sensitivity in the electronics of the shutter trip circuit. Circuit design was modified to cure the problem and a series of tests devised to give assurance that the anomaly would no longer be possible during mission performance.

The photo system has proven its ability to produce high-quality photographs on successful Lunar Orbiting Missions. The Ground Reconstruction Equipment (GRE) has also yielded excellent quality reconstruction prints.

Acknowledgments

The mission could not have been successful without the tremendous planning effort by The Boeing Co. Not only did they build the spacecraft but they also established the requirements for the Deep Space Instrumentation Facilities (DSIF) monitoring and data acquisition sites. The overall program was managed by NASA whose dedicated personnel spent many hours in coordinating and planning various events. Also a contributor to mission success was RCA, Astro-electronics Div., who designed and fabricated the communication system and the solar panels for the Orbiter.

Not to be overlooked in the Lunar Orbiter effort are the subcontractors who worked with Kodak under extreme pressures of schedules. These include CBS Laboratories for the Line-Scan Tube and the Sync and Sweep Electronics which were in turn subcontracted by CBS to Barnes Engineering, Bolsey Assoc. for the V/H Sensor and the 24-in. focal plane shutter, Lear-Siegler for the High Voltage and Photomultiplier Power Supplies, Gulton Industries for the DC/DC Converter, Pacific Optical for the 24-in. Paxoramic Lens, American Time Products for the Reference Frequency Generator, Kidde for the Nitrogen System, Arizona Gear for the Pressure Relief Valve, the Budd Company for the pressure shells, and RF Communications for the Ground Reconstruction Electronics system.