

mountains. The rim of the crater is 11,000 ft above the crater floor. The horizontal distance across the part of the crater shown in this photograph is about 17 mi.

Figure 12 shows a portion of the backside of the moon taken with the 80mm camera from an altitude of about 910 mi. The area shown is approximately 580,000 mi².

Figure 13 is a vertical view recorded by the 80mm camera from 28 mi. The location is 4°15' north latitude and 4°30'

east longitude. The prominent feature is the Friesnecker Fault. The spacecraft was in its 23rd orbit when this photo was made.

Acknowledgments

The GRE circuit design was done by R. F. Communications who also fabricated and tested the GRE hardware. The recording cameras were furnished by Winston Research. The authors gratefully acknowledge the assistance of these subcontractors as well as many associates

at Eastman Kodak for the development of the overall GRS.

Discussion

Anon: You mentioned that in some of your built-in test equipment you used a multi-burst generator and also a ten-step staircase generator. Did you do any experimental work using coherent sine waves on the steps of the staircase to check resolution as a function of density?

Mr. Grammer: We did not do that this time, but we have used it in the past. We have fixed frequency output from the generator which we use at various levels independent of the staircase.

Unit and System Design of a Lunar Operating TV Camera

By DONALD T. HECKEL

When Surveyor I soft landed on the moon it began within an hour to transmit the first of over 11,000 TV pictures of the moon. The camera's design requirements were set by a wide range of temperatures, the need to maneuver the camera to view any area, the spacecraft's power supply and the need for verification from the spacecraft to confirm to the operator that the camera had received and executed each command. The camera has a complex variable focal length lens complete with focus adjustments and a commandable iris. The camera is positioned vertically on the spacecraft and the lens looks directly into the rotating-mirror assembly. A focal plane shutter exposes a 1-in. hybrid vidicon tube for 150 ms prior to the frame readout. Problems encountered are described and illustrations show the variety of conditions under which the camera performed.

ON WEDNESDAY, JUNE 1, 1966, Surveyor I soft landed on the moon and, within the hour, began transmitting the first of over 11,000 television pictures from the moon. This mission culminated nearly four years of design, development, fabrication and testing. Like any other complex system design, the Surveyor TV subsystem was designed to operate within the expected lunar operational constraints and those imposed by the overall spacecraft system design. The camera is shown in Fig. 1 as it appears on the spacecraft.

Operation Design Constraints

Temperature

The expected temperature range of the 66-h flight to the moon and on the lunar surface made it necessary to design a camera and associated equipment to survive a nonoperating exposure to the temperature range of -250 F to +250 F;

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also, the camera must then be able to operate over a temperature range of -20 F to +165 F.

Heaters were imbedded in each chassis and around the vidicon tube faceplate to heat the camera until it was warm

enough to become operational. A thermal analysis showed that the only critical area in the camera at high temperatures was the vidicon photoconductor which is baked on the faceplate at +140 F. A passive thermal radiator was designed on the outside of the camera to dissipate the heat away from the faceplate. The faceplate itself was surrounded by a boron nitride collar which has high thermal conductivity while being a good electrical insulator (Fig. 2). This collar provides a path for heat away from the vidicon faceplate and out to the thermal radiator as well as a means of supplying heat to the faceplate.

Preliminary thermal analysis indicated that operating the TV camera at lunar noon would be almost impossible for

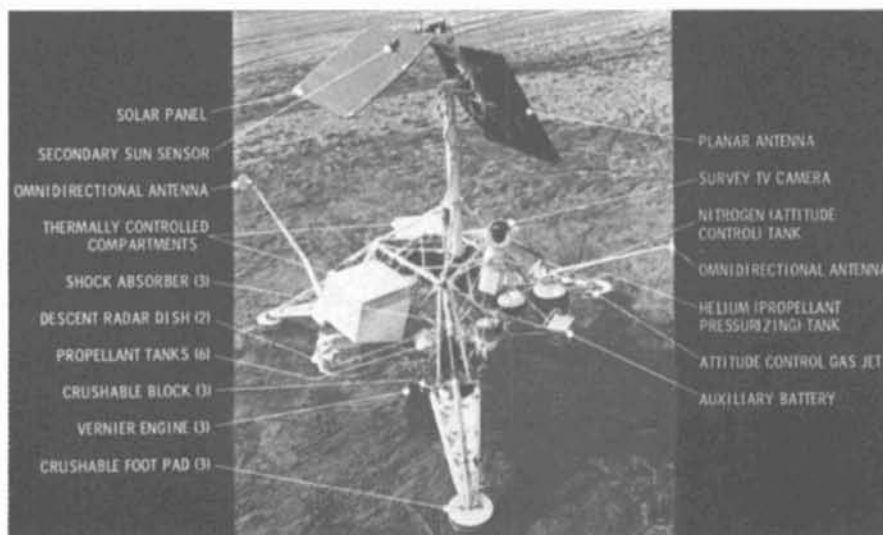


Fig. 1. Surveyor I configuration.

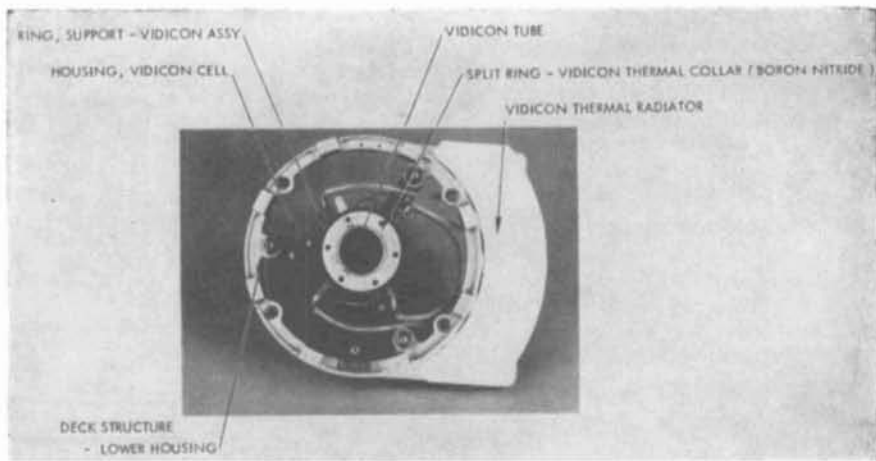


Fig. 2. Vidicon and boron nitride collar.

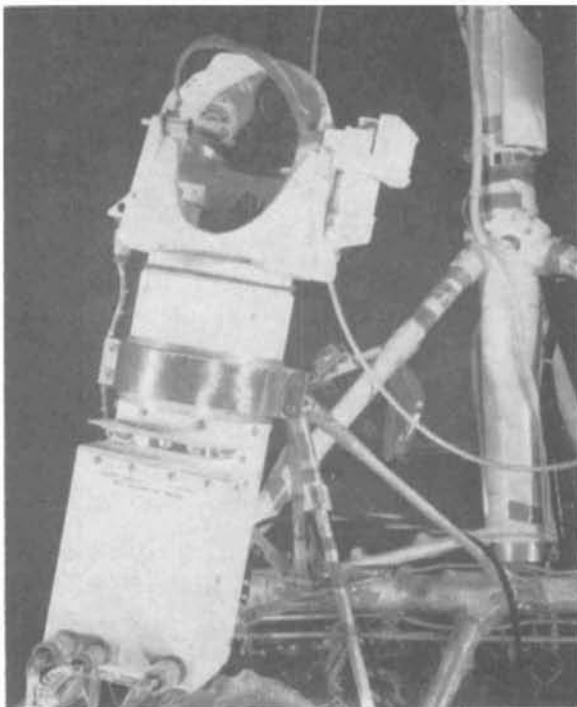


Fig. 3. TV survey camera and mirror assembly.

more than a few minutes at a time followed by a long period for cooling through radiation, otherwise the maximum operating temperature would be exceeded. Fortunately, it was found that the solar panel and planar array antenna (Fig. 1) could act as an umbrella or sun shade for the TV camera to prevent direct sunlight from striking it and permit almost continuous operation. A moon shield was considered to prevent heat radiated from the lunar surface from striking the camera since the surface is the greatest source of external heat. However, it was not found necessary to implement this shield.

Viewability

It was necessary to position the camera as high as possible on the spacecraft to maximize the camera view of the surrounding lunar surface and the space-

craft itself (Fig. 1). This prevented the camera from being nestled securely in one of the thermal controlled compartments which are positioned low on the spacecraft, and then peeping out through a lens port like the Mariner and Ranger cameras.

A mandatory requirement was the ability to maneuver the camera by earth command so that it could view any area that the earth-based operator wished to see. Power and thermal limitations precluded movement of the entire camera, so the camera was designed to look into a mirror that could rotate in both azimuth and elevation (Fig. 3).

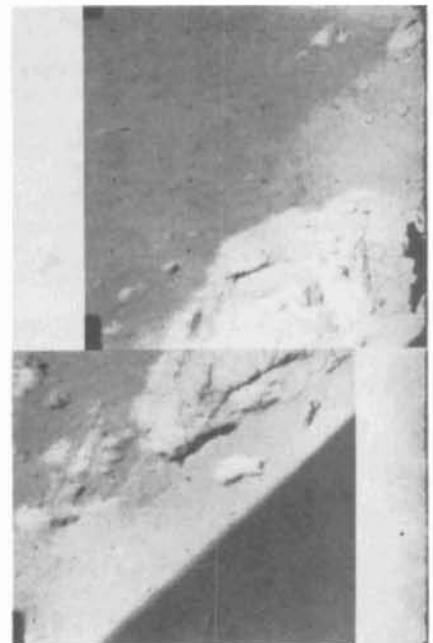


Fig. 4. Mosaic of two pictures (taken at 100 mm focal length)

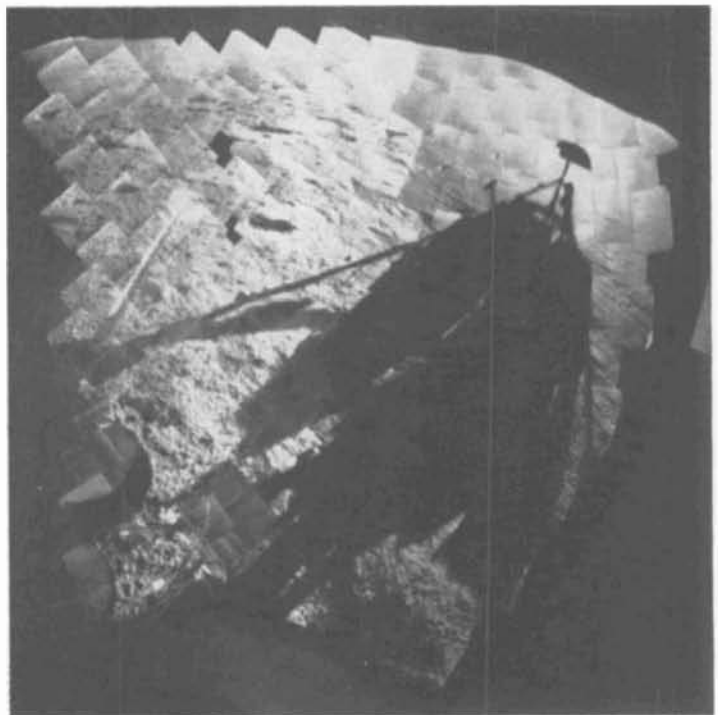


Fig. 5. A reconstructed full panorama.

The mirror assembly is designed to rotate the optical line of sight in steps of 3° in azimuth and 5° in elevation each time it is so commanded. The lens has a $6.4^\circ \times 6.4^\circ$ narrow angle field of view which allows overlap on each picture. This allows several pictures to be put together in case a particular mirror step could only view half of a desired picture (Fig. 4). It also allows scientists to mosaic a set of pictures together and reconstruct an entire lunar panorama just as the camera sees it (Fig. 5).

Power

The TV subsystem had to be designed

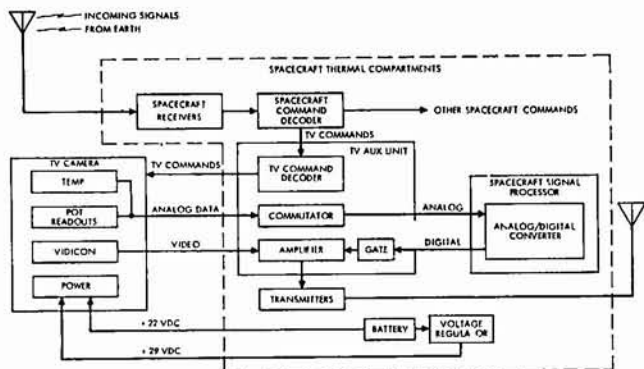


Fig. 6. TV camera-spacecraft block diagram.

to operate off of the spacecraft power subsystem which provides only two sources of power. They are +22-V dc-unregulated which varies from 17 to 27.3-V, and +29-V dc-regulated to $\pm 1\%$. The TV subsystem power supply was designed to convert the +29-V dc to chopped dc by means of two switching transistors. This permitted the required voltage levels to be obtained by means of a transformer with subsequent filtering and regulation to the operating voltages required by the camera circuitry and vidicon tube.

Commands

Numerous commands were required to have a fully automatic, robot-type camera that could operate under all expected illumination and thermal conditions. It was required to have a subsystem command decoder capable of receiving, decoding and disseminating 27 individual commands to the camera. Although this may seem high for just taking TV pictures, they were required to perform the design goals.

- 2 commands to turn the camera on and off,
- 1 command to turn on the vidicon temperature control circuitry,
- 1 command to turn on the chassis heaters,
- 1 command to turn off all thermal controls,
- 1 command to take a picture,
- 1 command to revert from 600-line scan mode to 200-line scan mode,
- 6 commands to turn the mirror in azimuth, elevation and in double steps (viewability of 360° in azimuth and 120° in elevation),
- 2 commands to open and close the iris in discrete steps over the range of $f/4$ to $f/22$,
- 1 command to activate an automatic iris control ($f/4$ to $f/22$),
- 2 commands to change focal length (zoom) in the lens (25- and 100-mm focal length),
- 4 commands to change focus in single steps and in multiple steps (focuses from 4 ft to infinity by means of 50 lens focus steps),
- 2 commands to rotate the filter wheel cw and ccw (4 filters: red, green, blue and clear),
- 2 commands to permit taking time exposure pictures (additional logic permitting a special command sequence to activate "star mode"), and

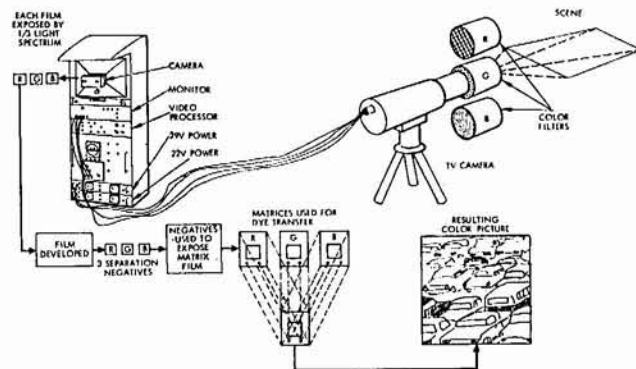


Fig. 7. Color reconstruction process.

1 command to override a shutter inhibit safety signal.

TV Data Via S/C Telemetry and Command Verification

It was essential that the earth operator be able to know that a transmitted command had been received at the spacecraft and executed. Wirewound potentiometers were geared to each lens filter wheel, and mirror drive motor on the camera to provide analog position readouts. As the motor turned the drive mechanism and the pot, the calibrated readout allowed the exact functional position to be derived by the earth operator. Functional positions, i.e. optical settings, iris opening, etc., had been calibrated to voltage ratios on the pots prior to launch.

Fifteen different data points within the camera were selected for transmission to earth immediately after each picture was transmitted, including temperature, mirror and lens position information. Some of the temperature sensors' outputs were selected for continuous transmission to earth.

Since all outputs from the camera are analog, it was necessary to process all of them, with the exception of the video, through a commutator and route them to an analog-to-digital converter in the spacecraft signal processing system. The digitized data are then returned to the TV subsystem for transmission after each video sequence (Fig. 6).

Color Capability

A rotating filter wheel was added to the TV camera to add a color capability without complex circuitry. A red, green and blue filter were selected to separate the white light spectrum approximately into thirds. This allows a colored picture to be obtained in the following way:

The earth operator rotates the filter wheel until the red filter is over the lens, and then takes a picture. He repeats this sequence with the blue and green filters. After the three photos are received and processed, it is possible to superimpose them into a single color photo as shown in Fig. 7.

Surveyor I took several hundred color photos of the moon—see the cover of

Life Magazine for the week of July 1, 1966. Unfortunately, the uniform grayish color of the moon does not show the true camera color capability.

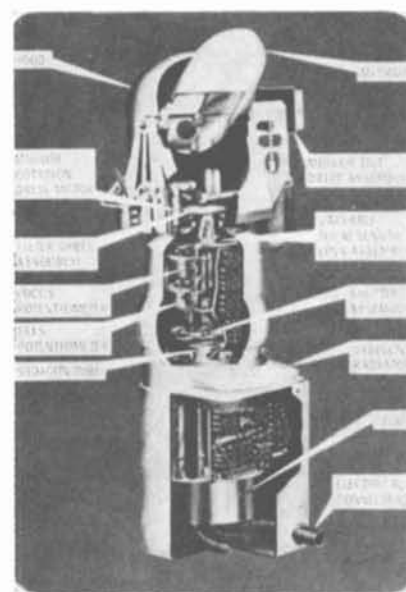


Fig. 8. Cutaway view of TV camera. (See p. 776 for Figs. 8A and 8B.)

Camera Configuration

A cutaway view of the camera is shown in Fig. 8. As already explained, a rotating and elevating mirror assembly is used to observe up, down and around. An incoming light ray is reflected from the mirror into the camera. It first passes through the colored filter element and into a complex zoom lens system composed of 13 glass elements (Fig. 8A). A beam splitter attached to the end of the lens deflects 10% of the incoming light ray to a photosensitive diode which inhibits the shutter and prevents the vidicon from being exposed if the camera accidentally looks into anything bright enough to damage the photosensitive surface, such as the sun. A focal plane shutter (Fig. 8B) follows the beam splitter and is positioned directly over a 1-in. diameter hybrid vidicon tube using electrostatic focus and electromagnetic deflection.

The variable focal-length lens has the ability to focus from 4 ft to infinity at two

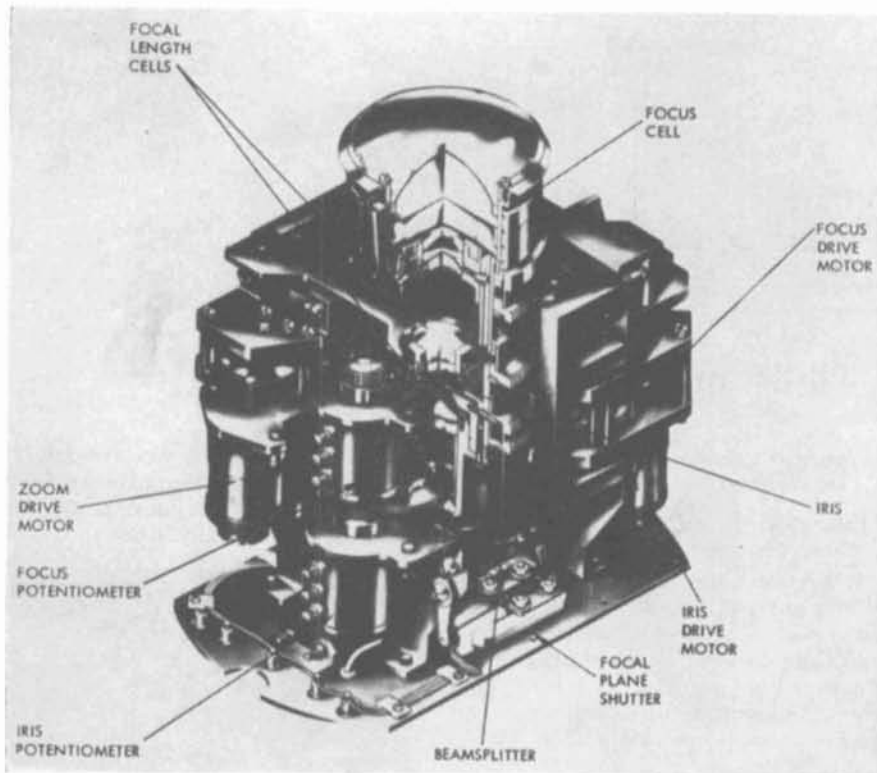


Fig. 8A. Variable focal-length lens assembly.

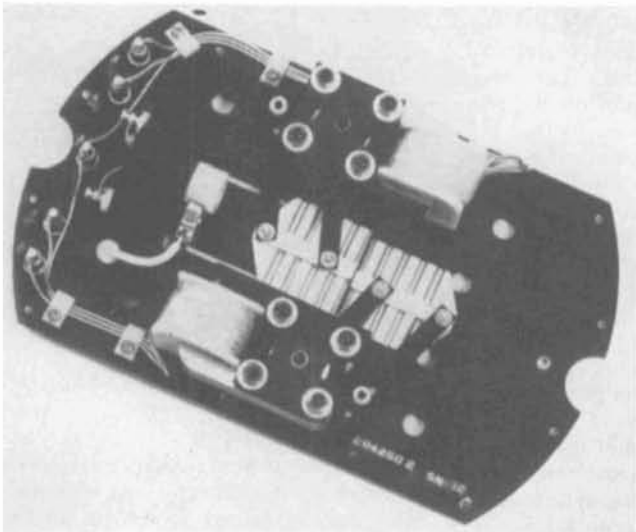


Fig. 8B. Shutter mechanism.

focal length positions of 25mm and 100mm. This zoom ratio of 4 to 1 allows scientists to obtain magnified views of the lunar surface as well as wide angle observation of $25.3^\circ \times 25.3^\circ$ (Fig. 9).

The zoom mechanism is not normally used at focal lengths other than at the minimum and maximum positions of 25 and 100mm. Zooming was intended as a safety device so that an in-focus picture could be obtained even if the rotating zoom mechanism should jam between the two focal-length positions.

An iris cell with an $f/4$ to $f/22$ range was selected after considering the expected lunar illumination levels. The iris cell has six earth f /stops at $f/4$, $f/5.6$, $f/8$, $f/11$, $f/16$, and $f/22$. A reversible motor drives the iris cell to the adjacent f /stop after receipt of an earth command.

The same photocell which samples light by means of the lens beam splitter to act as a vidicon safety device is used to control the automatic iris servo.

The photocell output is sensed by a differential amplifier. An iris drive motor adjusts the iris aperture to regulate light until the differential amplifier is balanced, thus providing ideal vidicon illumination.

The vidicon is exposed by a focal plane shutter which has a nominal 150-ms exposure time. It also has the ability to take 1.2-s time exposure bulb pictures. A third method of exposing the vidicon inhibits the vidicon cathode (erasing) current, while the shutter remains open, allowing the vidicon to integrate light over extended periods to obtain true "time exposure" pictures of

low magnitude stars and lunar night photos. Photos may be obtained with as little as 0.008 fL of reflected earth shine (Fig. 10).

The vidicon tube has 25 small 0.004-in. circular black reseau marks that are evenly spaced over the vidicon format in 5 rows of 5 dots each. These marks are accurately placed on the inside of the vidicon tube faceplate and their locations are accurately mapped prior to camera assembly. They are used to determine and correct the linearity and distortion in a received picture.

Video Sequence

A command is transmitted to turn on the camera power. The camera remains in this quiescent state until a "take picture" command is received. At this point, the camera automatically activates the entire sequence depicted in Fig. 11. The first vertical blanking pulse after receipt of the "take picture" command initiates camera-generated commands to turn the transmitter on in high power and open the camera shutter to expose the vidicon. Horizontal sync pulses are then transmitted to earth for 200 ms to allow ground monitors to be synchronized to the lunar based camera. The picture is then read out from the vidicon and transmitted to earth for one second, followed by 200 ms of digital information giving the positions of the lens, and mirror functions as well as thermal data for that particular picture. At the end of this sequence, the transmitter high power is turned off, and the vidicon is erased continuously until the next picture is requested. It is possible to obtain one complete 600-line scan mode picture every 3.6 s and a picture of lesser quality every 2.4 s. The quality is lower because the vidicon has one fewer erase scans.

The 600-line scan mode has a bandpass of 220 kHz and uses the single spacecraft planar array antenna with a transmitter power of 10 W. A second mode of 200 lines with a bandpass of 1.2 kHz was designed in order to allow TV pictures to be obtained in case the planar array antenna was either damaged on landing, or impossible to reposition to face the earth. This low resolution mode requires 21.2 s to obtain one TV picture and 40.6 s of erasure time for a total time of 61.8 s. This reduced bandwidth allows 200-line scan mode TV pictures to be transmitted using either of the two spacecrafts' omnidirectional antennas emitting 10.0 W of power in high power mode, or using the planar array in a low power mode of 0.1 W.

Major Design Problem Areas

Wirewound Potentiometers

The variable wirewound potentiometers used for analog position information had a high failure rate. The wiper arm and pot wires exhibited galling and cold

welding when operated while being subjected to an ultra high vacuum (10^{-10} to 10^{-12} torrs). Since these pots are geared to functions like the lens iris, they would sometimes create enough friction to cause sluggish operation or a failure of the actual drive mechanism (Fig. 12).

Many potentiometer-lubricant designs were considered. One unique method that proved workable was to use a pot with a wiper arm fabricated from a highly conductive dry lubricant. However, schedule limitations precluded the incorporation of this design in the spacecraft. A solution was empirically found to be merely that of lubricating the existing pot wires and wiper arm.

Vidicon Photoconductor Flaking

The vidicon tube photoconductor would peel or flake from some faceplates after exposure to cryogenic (approximately -250 F) temperatures. This is depicted in Fig. 13. A failure analysis showed that if a tube once passed this low temperature test, it would always pass. This made a selective process for tubes mandatory where they are required to pass a cryogenic soak before being selected for use in a camera. The SC-1 vidicon survived 3 days of temperatures in the range of -140 F during the earth-lunar transit, and 14 equivalent earth days or one lunar night at less than -250 F.

Lubrication

All of the lens (Fig. 8A), mirror, and shutter (Fig. 8B) moving parts required a lubricant that could withstand an extreme thermal and lunar dust environment while in an ultra high vacuum in the order of 10^{-12} to 10^{-15} torrs. Further, it must be compatible with and operable during a lengthy test program conducted in earth ambient.

Greases and oils could not be used as they outgas in a vacuum, condense on the colder optical surfaces and then impair the camera optic, as well as losing their lubricative qualities. Special niobium diselenide dry lubricants solved the problem.

Component Cracking at Cryogenic Temperatures

Another major problem was component cracking on freeze-coated chassis boards. This was solved by spraying hot epamid on the board to limit the thickness, and then cryogenically testing the board to locate any thick spots that may have developed in the spray operation. These thick spots were responsible for causing the components to crack at -250 F.

Scientific Evaluation

Two small 3.5-in. diameter calibration charts, of which one can be observed in Figs. 14 and 15, are mounted on the spacecraft leg and omnidirectional an-

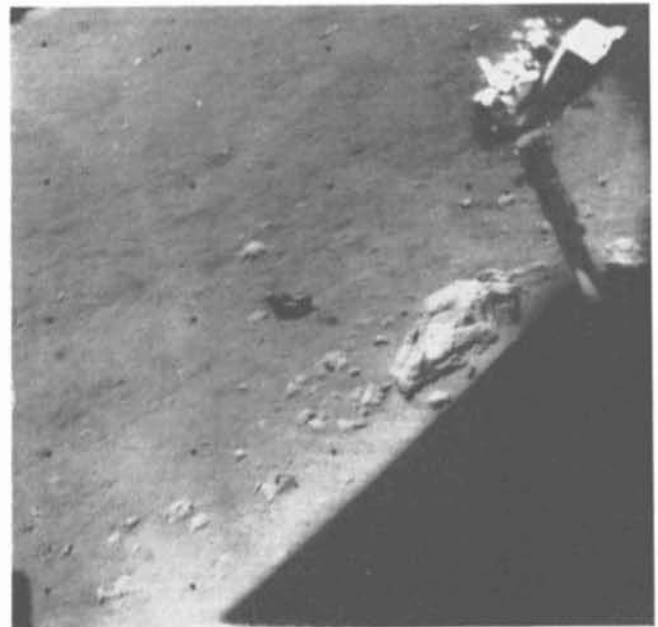


Fig. 9. TV picture taken with variable focal-length lens at 25mm focal length, compare with two photographs taken at 100 mm (Fig. 4).



Fig. 10. Photograph of the Surveyor I shadow taken using reflected earth light.

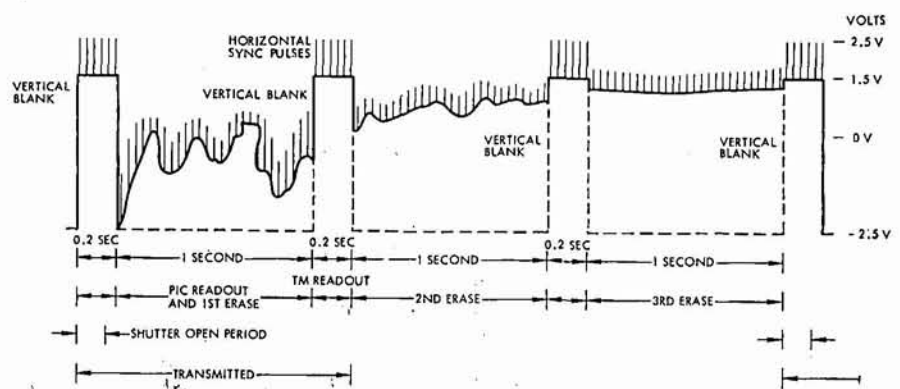


Fig. 11. Video sequence.

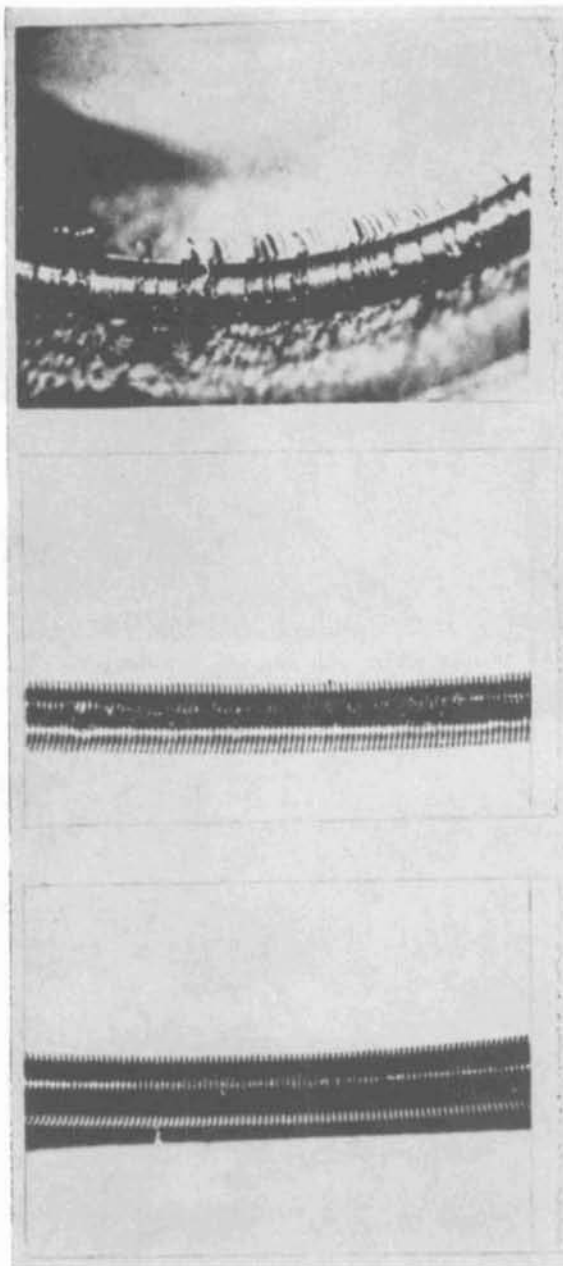


Fig. 12. Potentiometer galling and cold welding in thermal vacuum. *Top*, portion of resistive element exposed directly to the following test conditions: 10^{-9} to 10^{-7} mm of mercury, 25 C ambient temperature, electrical loading, and 1500 rotational cycles; *center*, portion of resistive element within an enclosed resistor housing exposed to the following test conditions: 10^{-9} to 10^{-7} mm of mercury, 25 to 135 C ambient temperature range, electrical loading, and 7500 rotational cycles; *bottom*, portion of resistive element within an enclosed resistor housing exposed to the following test conditions: 10^{-9} to 10^{-7} mm of mercury, 25 to 135 C ambient temperature range, electrical loading, no cycling.

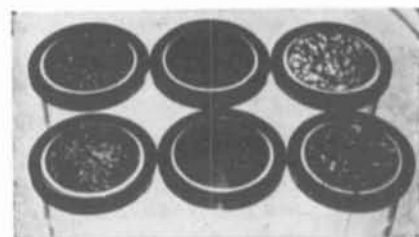


Fig. 13. Vidicon tube photoconductor flaking at low temperatures.



Fig. 14. Surveyor I lunar photo before computer enhancement.

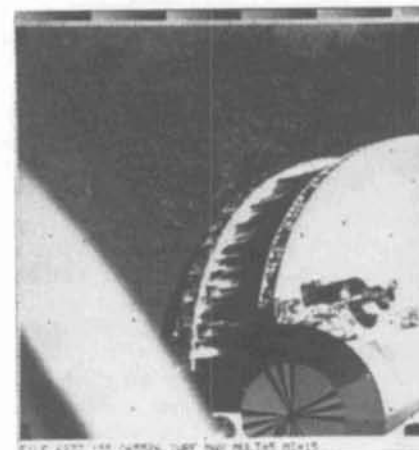


Fig. 15. Surveyor I lunar photo after computer enhancement.

tenna in clear view of the TV camera. These charts were designed to aid in evaluating post-landing video data including photometric and colorimetric parameters. A small wedge-shaped pattern of selected shades of gray are positioned around an outside circle while three color wedges with known CIE chromaticity coordinates comprise the inner circle. Small groups of wedge-shaped black lines are positioned between each color segment to provide a means of approximating camera resolution. A small post is positioned in the center of the chart to allow a sundial-type means of obtaining sun to spacecraft angle information.

The camera has the capability of resolving an object 0.5 mm in size at an object distance of 4 ft. It can obtain TV frames with illumination levels of 0.008 to 2600 fL. The picture can be processed using computer processing techniques

to remove inherent noise and improve the picture. Figures 14 and 15 depict a photo before and after this processing. Geologists use this type of information to evaluate the lunar surface structure and its composition.

Black reference marks are an integral part of each vidicon and are used to determine absolute black. These marks are used as a reference for photometric calibrations of received pictures.

Scientists were able to evaluate the size and frequency distribution of lunar debris and the characteristics of the matrix of unresolved material between the grains. Cohesion and thickness of surficial fragmental layers were studied as well as the material ejected by the impact of the spacecraft footpads.

Actual surface temperatures could be compared for the first time with those predicted by earth-based means. Lunar surface electrical properties may be de-

termined in the future by data from the two Surveyor radar systems. The depth of the surface depressions (Fig. 16) made by one of the crushable blocks is being analyzed to provide lunar dynamic resistance and static bearing capacity information.

On June 14, 1966, approximately 43 TV pictures were taken of the solar corona. Scientists were able to determine a measurable radiance out to an estimated 3 to 4 solar radii from the center of the disc as well as observe a very prominent coronal streamer.* On June 11, 1966, and again on July 12, 1966, TV pictures were taken to observe movement of dust particles on the vycor glass mirrors positioned on top of the thermal compartment radiators. New particles were ob-

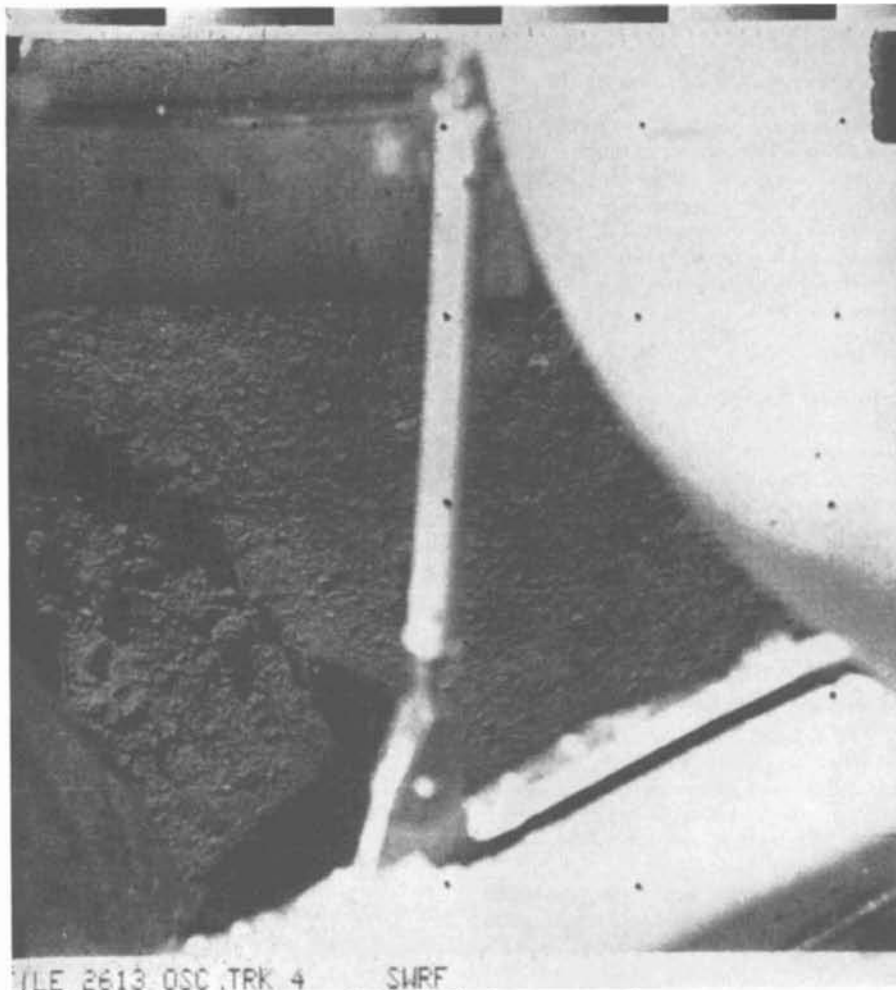
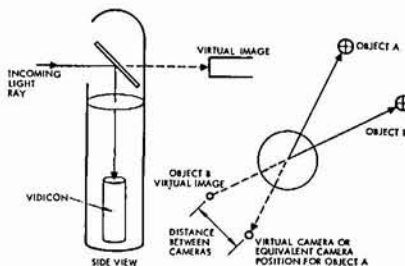


Fig. 16. Spacecraft crushable block depression. This photo has been computer enhanced.

Fig. 17. Diagram of the surveyor folded optical system.



using the one Surveyor camera with its folded optical system as shown in Fig. 17. (The point of convergence for the optical axes from different apparent camera positions is the intersection of the camera's

real optical axis with the elevation axis of the mirror.) When the mirror rotates about itself in azimuth and/or elevation, it moves the apparent location of the camera's entrant nodal point in a circle (sphere) about the real camera's optical axis where it contacts the mirror elevation axis. This provides a stereo effect useful in evaluating objects at close range.

The successful Surveyor I mission provided man with his first accurate close-up look at the lunar surface. It gave us our only photometric and colorimetric information from the moon. Additional time is required to fully evaluate the data to derive its full scientific meaning, but Surveyor will always be remembered as the world's first true soft landing spacecraft.

Acknowledgments: The author wishes to acknowledge the significant contributions to the Surveyor TV system made by R. L. Quandt, W. K. Lang, W. H. Bockwoldt, H. W. McNeela and L. H. Allen. The Surveyor spacecraft was designed and built by the Hughes Aircraft Co. for the National Aeronautics and Space Administration and the Jet Propulsion Laboratory.

Discussion

Anon: What is the highest temperature that a vidicon used in Surveyor was subjected to?

Mr. Heckel: On the vidicon faceplate, the highest temperature we recorded during the Surveyor I lunar mission was 130.7 F. However, we have subjected vidicons to a temperature test as high as 170 F.

Anon: Did you get a picture?

Mr. Heckel: Yes, we did. However, the tests mentioned above conducted in thermal vacuum showed that white spots appear on the readout of the raster as if small circular areas in the photoconductor are saturated with light. These tests confirmed that the spots became larger and more abundant as the temperature increased. We have a maximum operating temperature as a result of this, in an attempt to prevent or limit these spots.

Anon: What is the lowest temperature at which you could receive pictures?

Mr. Heckel: We have tested the camera in thermal vacuum chambers at temperatures as low as -50 F. The vidicon faceplate temperature was about +28 F. We keep the vidicon faceplate as close to +70 F as possible, even though the camera electronics will operate properly at -20 F.

* Technical Report No. 32-1023, Surveyor I Mission Report, Part II. Scientific Data and Results, Jet Propulsion Laboratory, Pasadena Calif., Sept. 10, 1966.