The Apollo
Color Television Camera

Reprinted from the November 1969 Issue of
Westinghouse ENGINEER

Produced by Westinghouse Technical Information
Reprint 6603

**Aerospace Division
Defense & Space Center
Westinghouse Electric Corporation
P. O. Box 746
Baltimore, Maryland 21203**

The Apollo Color Television Camera

L. L. Niemyer, Jr.

A proven low-light-level monochrome camera design using the sensitive and versatile SEC camera tube was converted to a field-sequential color camera to provide earth-bound viewers their first color TV spectacular from space.

During the Apollo 10 and 11 flights, a compact color television camera provided real-time color scenes of the earth, the moon, spacecraft maneuvers, and the interior of the command module. The excellent performance of the camera under these abnormal and adverse conditions was witnessed by millions of viewers.

The camera was designed and developed for the NASA Manned Spacecraft Center by the Westinghouse Aerospace Division. The camera is unique in its concept, both for its role in NASA's total color TV system and for its configuration and performance as a television camera. The camera generates a field-sequential color signal using a single image tube and a rotating filter wheel. A ground station color converter changes the sequential color signal to the standard NTSC color signal for broadcasting. (See *Television Lines, Fields, and Frames*, page 176.) This approach permits a simple and reliable camera aboard the spacecraft and relegates the complexity of generating the compatible broadcast signal to the ground station where the complex signal processing required for color broadcasting is more readily handled. A conventional NTSC compatible color camera, with its three image tubes and associated signal-processing circuitry, could not have satisfied either the low weight and power requirements or the low-light-level performance requirements for the Apollo camera.

Developing the Camera

The field-sequential color camera is basically a black-and-white camera, synchronized with a three-color filter wheel in front of the camera tube. This filter wheel design made it possible to utilize the basic electronics and packaging from a Westinghouse monochrome camera that had already been developed. This existing family of compact cameras (WTC-13 and WTC-14) has been used for televising rocket shots, for underseas imaging tasks, and for other military applications where a low-power, lightweight camera with low-light-level capability is required. These cameras use the Westinghouse SEC (secondary electron conduction) camera tube, which provides the low-lag imaging sensitivity required for a color camera. Also, since the field rate of the WTC-13 camera conforms to the desired EIA standard (525-line scan, 60 fields per second, 2:1 interlace), the electronic package of the WTC-13 camera could be readily adapted for use in the field-sequential color camera.

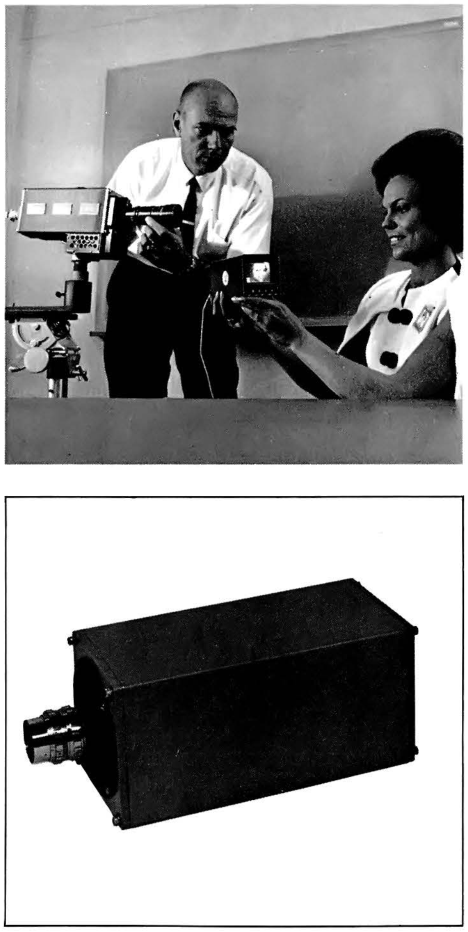
The Apollo color camera and its predecessor (WTC-13) are shown in Fig. 1. The color camera is 17 inches long, including the zoom lens, weighs only 13 pounds, and is completely self contained. (The WTC-13 camera weighs 8 pounds.) A small four-wire cable carrying a single dc input voltage and a composite video output suitable for modulating the transmitter is the only connection required.

A small viewfinder monitor occupying a volume of only 85 cubic inches and using 2.5 watts of power is used to assist the astronaut in aiming and focusing the camera. Thus, the astronaut does not have to depend on ground control for instructions.

The Total System

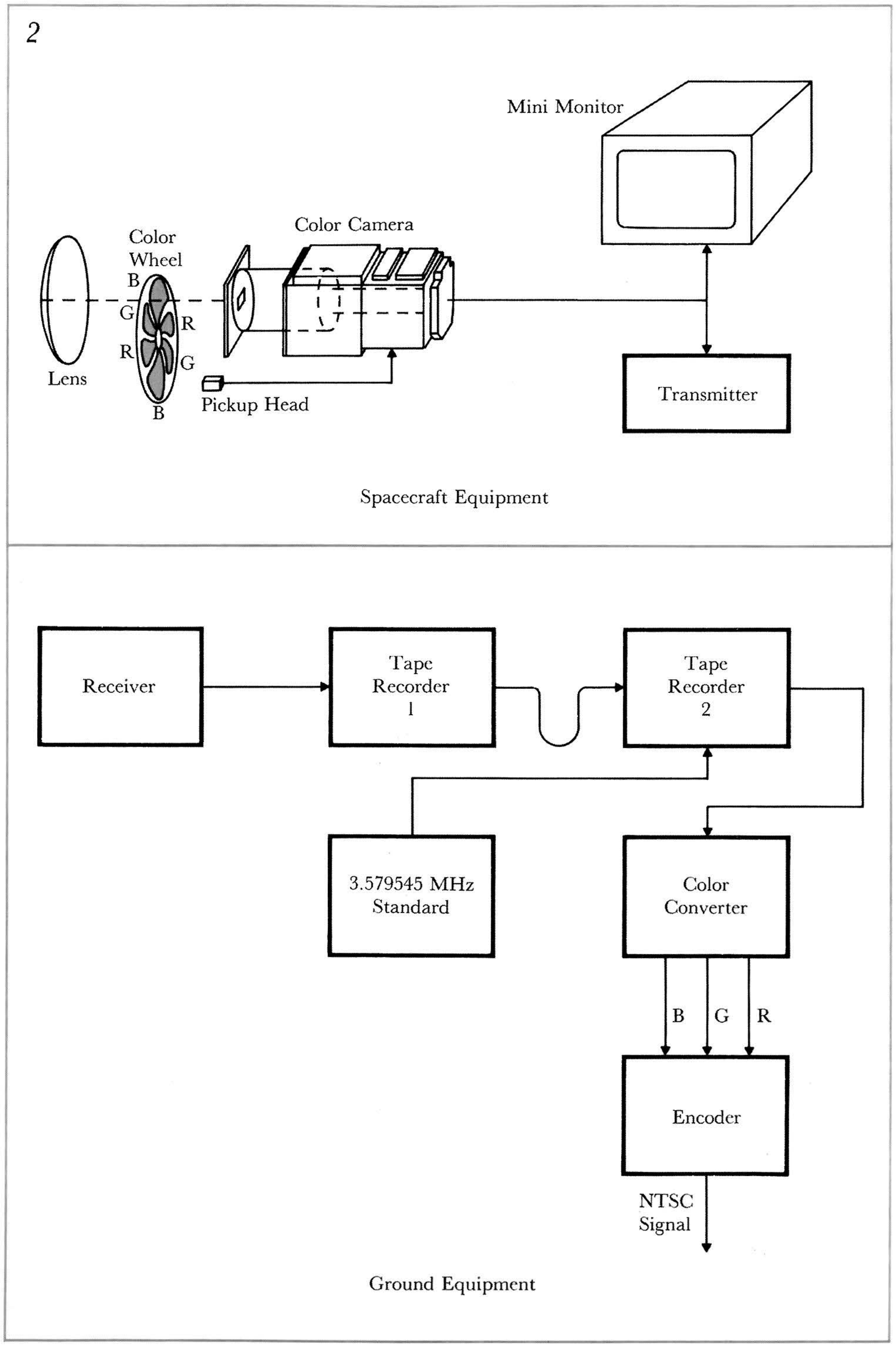
A general layout of NASA's Apollo color television system is shown in Fig. 2. The image is focused by the lens through the filter wheel onto the faceplate of the image tube. As the wheel positions a red filter in the field, the image tube stores the red information of the scene being viewed and then reads it out. This information is processed by the electronics of the camera and is fed to the "Mini Monitor" and to the 20-watt transmitter. The green and blue signals are generated in the same fashion and, since the color wheel is changing filters at a field rate of 60 fields per second, color information is generated at the standard field-sequential rate.

The field-sequential color signals, transmitted to the earth in the S-band region, are picked up by two receiving stations—one at Madrid and the other at Goldstone, California—and relayed to Houston. Here, the received signal is fed to two tape recorders in series to compensate the signal for doppler frequency shift. The



1—The Westinghouse-built components of NASA's Apollo color television system are the field-sequential color camera and a miniature monitor that aids the astronaut in aiming and focusing the camera. The camera (above) and its monochrome predecessor (below) use essentially the same electronic package. The color wheel assembly and synchronizing and driving circuitry were the primary adaptations required to convert the monochrome camera to a field-sequential color camera.

L. L. Niemyer, Jr. is a design engineer at the Aerospace Division, Westinghouse Defense and Space Center, Baltimore, Maryland.



2—The Apollo color television system uses a simple and reliable field sequential color camera to generate the signal transmitted to earth.

Ground processing equipment corrects the signal for doppler shift and converts the field-sequential signal to a standard NTSC video signal for broadcasting.

information is recorded as received by the first unit, and the second unit is driven with the subcarrier standard frequency, which adjusts tape speed to correct frequency errors introduced by doppler shift. A single tape recorder could have been used but the transmission would have had to be completely recorded before performing the second operation, thereby delaying the presentation at least that long. With two recorders in series, the delay is only about 10 seconds from input to output.

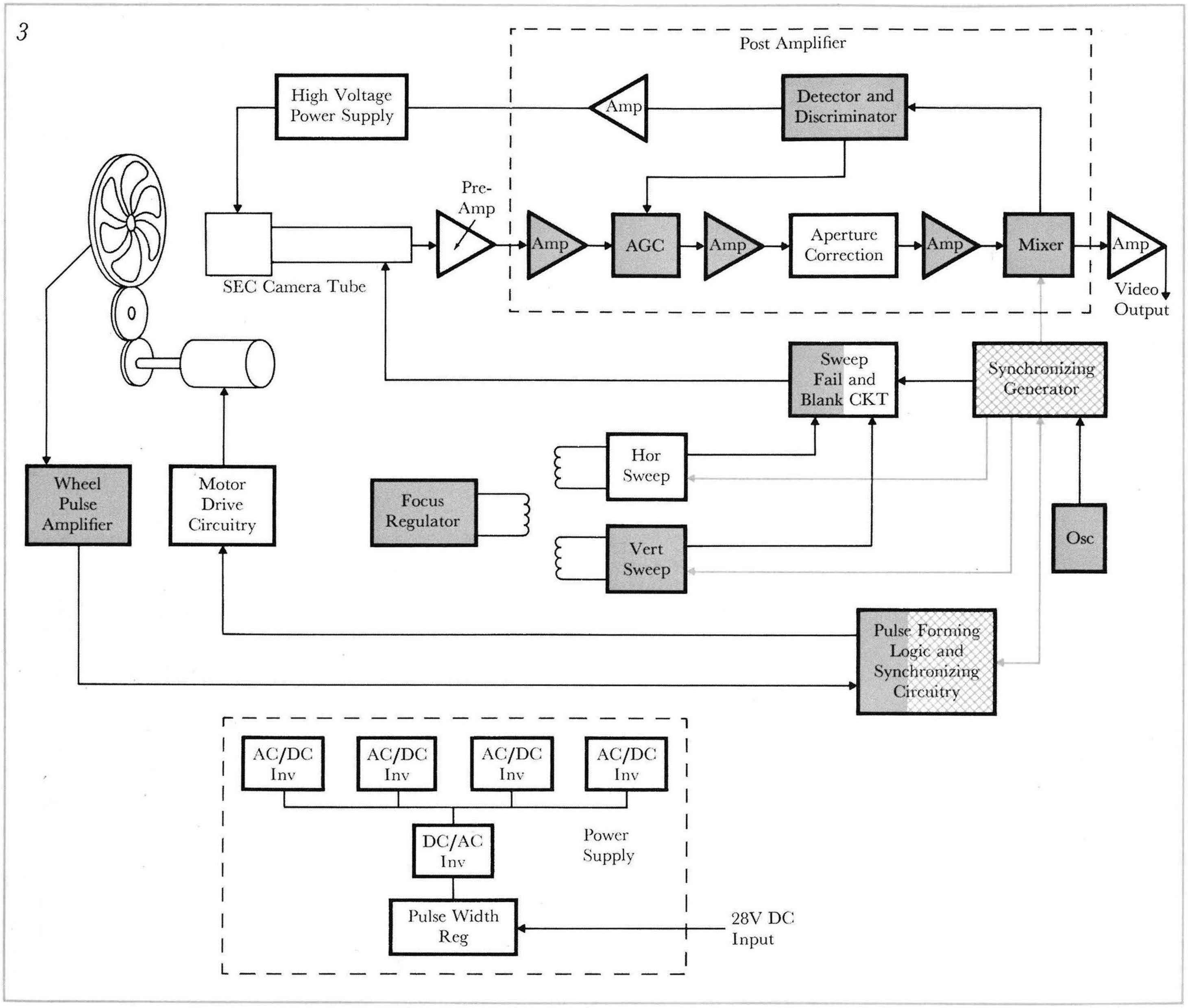
The sequential color information is fed from the second recorder to a color converter, a storage and read-out device that holds six fields in memory (red, blue, green, red, blue, green) and presents three fields in parallel at the output. (See *Television Lines, Fields, and Frames*, page 176.) As a new field is placed into memory, the oldest field is erased so that the information is updated at the field-sequential rate.

And finally, the color encoder transforms the color converter output to an NTSC signal for commercial broadcasting. The quality of the original color signal from the camera can be appreciated from the fact that the video signal, when viewed from the vicinity of the moon, may be degraded by as much as 105 dBm (1 milliwatt reference power) between the camera output and the input to home television receivers.

The Apollo Color Camera Design

A block diagram of the color camera is shown in Fig. 3. Almost 70 percent of the functional blocks are integrated circuits, not including the power supplies. The extent of medium scale integration employed is indicated by cross hatch.

The color camera with case removed is shown in Fig. 4a. It consists of three sections: the basic chassis is the monochrome camera with synchronization, pulse-forming, and drive circuitry added for the color adaptation; the second section is attached under the camera and forms the housing for the transformer and motor; and the third section, attached to the front of the camera chassis, contains the motor, gearing, and filter-wheel assembly and also serves as the lens mount.



3—The basic circuit components of the Apollo color television camera are shown in this block diagram. The colored portions represent integrated circuitry.

The video signal from the SEC camera tube is fed to the *preamplifier*. The preamplifier is made up of discrete components, primarily to provide low-noise performance. The input is a field-effect-transistor stage with a tube-load resistor of 300 kilohms. This is followed by a feed-back pair. The equivalent input noise current is approximately 1 nanoampere for 2 megahertz.

The *post amplifier* includes all the circuitry from the preamplifier to the high-voltage driver. Most of this circuitry is made up of hybrid integrated circuits. The output is a current source, which delivers a 3.5-volt swing into 100 ohms.

The *vertical deflection circuit* is of the Miller run-up variety, and it uses two integrated circuits and a dual transistor for the active components. The size of the scan is varied by adjusting the feedback resistor and the centering adjusted by offsetting the input operational amplifier.

The *horizontal deflection circuit* is a high efficiency reaction type with one percent linearity.

The *two power* supplies in the color camera are the high-voltage supply, driven by the ALC loop, and the low-voltage supply receiving 28-volt primary power from the spacecraft. The low-voltage power supply develops all the voltages for operating the camera circuitry and the image tube with the exception of high voltage for the camera tube photocathode. Its efficiency is approximately 60 percent at the nominal input voltage.

An internal view of the predecessor to the color camera, the WTC-13 monochrome camera, is shown in Fig. 4b. The open circuit board is the sync/sweep board, and it displays the three techniques of packaging: modules, medium scale integration, and conventional printed circuit wiring. The large flat package in the center of the board is the synchronizer, which delivers horizontal drive, vertical drive, mixed blank and mixed sync at its outputs. Fig. 4c shows the interior of this 1-inch square by ⅛-inch package, which contains 22 integrated circuit chips—14 dual bistable multivibrators and 8 gate circuits. The synchronizing generator is completely bistable, has no adjustments, and therefore is ideally suited for medium scale integration.

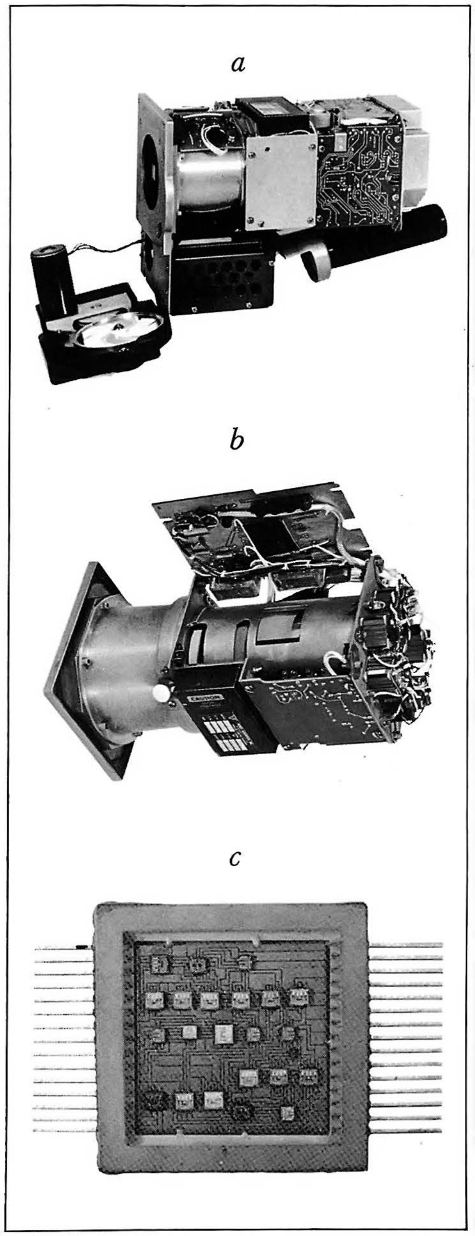
To conserve space, the printed-circuit boards are mounted with the printed circuit tracks outside and the modules and components projected inward around the cylindrical housing that contains the deflection assembly.

The input voltage to the camera is 28±4 volts dc, and power consumption is 20 watts nominally. Camera output is a standard EIA format at color standard frequencies with the exception that it does not carry the 3.58 MHz color reference burst, which is added at the ground station. It is a black negative signal from −0.75 to +2.75 volts (into 100 ohms), constrained within 20 percent to prevent over-deviation of the transmitter.

The bandpass of the camera is 4.5 megahertz with a 20 dB/octave roll off, which provides a theoretical limiting horizontal resolution of 360 TV lines/vertical dimension. Due to the fact that the signal-to-noise (S/N) ratio is high and that the roll off is finite, more extensive calculations and experience have shown the horizontal resolution to be in excess of 425 TV lines/vertical dimension.

The limiting vertical resolution fixed by the number of scan lines and their statistical positioning factor (Kell factor) is approximately 350 TV lines/vertical dimension.

The bandpass of the camera considerably exceeds the bandpass of the command module transmitter, which sets the limiting horizontal resolution of the system. (Limiting horizontal resolution is often referred to as resolution or limiting resolution.) The theoretical limit set by the transmitter bandpass is 160 TV lines, but because of high S/N and some camera processing, the resolution is actually in excess of 200 TV lines.



4—The Apollo color television camera (*a*) with case removed to show the components added to the low-light-level military camera package (*b*). Medium scale integration techniques were used where applicable (*c*) to minimize size, weight, and power requirements.

The Apollo color camera controls are limited to one switch associated with the electronics and the common lens adjustments of focus, iris and zoom. The switch is used to change the automatic light control detector circuitry from an averaging type for "inside" scenes to a peak detector type for "outside" scenes. (A typical scene for the outside mode would be the earth subtending one third of the vertical field of view.)

The lens is a standard commercial cine lens that has been extensively modified. The most significant modifications were to the format, adjusting its diagonal from 12.7 mm to 25 mm and to the mechanical mechanism (zoom, focus, iris). The lens was totally disassembled, baked in a vacuum, space lubricated and rebuilt. The lens characteristics are listed in Table I.

Testing for Space Environment

The original WTC-13 monochrome camera was designed to rigid military specifications, and the color camera has been designed to these same specifications. However the short delivery schedule did not permit sufficient time to evaluate those efforts, so testing was limited to the command module environment. Although testing in other areas was limited, the camera, lens, monitor and cables were thoroughly tested for complete operation in the command module oxygen environment. Another requirement was that the camera be subjected, nonoperating, to a vacuum and operate after exposure to vacuum. Therefore, the equipment was completely tested for vacuum transition.

Shock and vibration at liftoff and splashdown was accommodated by testing to determine a safe level that the camera could stand and one that could be acquired by packing. This level was set as a limit and was achieved by appropriate packaging.

The thermal situation in the command module while it is in space is unusual. The atmosphere is oxygen, kept at 5 psia, which presents a question of convection cooling because of the low density. In addition, the oxygen atmosphere is weightless and convection would have to depend on forced flow. Since the amount of forced flow generated by movement of the astronauts and several cooling fans is also an unknown, the camera has to be passively cooled by radiation.

Evaluation of the thermal design indicated that the camera could be used indefinitely in the command module. This evaluation was borne out by the long uninterrupted transmissions from the Apollo 10 and 11 flights. Moreover, the existing camera is thermally suitable for operation in the lunar module (LEM), since the environment is the same in the two modules. However, the LEM transmitter poses much more severe bandpass restrictions than does the command module transmitter, and interface equipment will be required.

Use of the camera on the lunar surface poses both vacuum and thermal problems. Assuming that the camera could be operated in a vacuum, there are periods when the lunar surface thermal environment would be suitable for the existing camera. If desired, the camera could be modified to extend its thermal range of operation. However, no decision has been reached as to whether the mission objectives should be extended to include more extensive use of the color camera.

The SEC Camera Tube

The key element of the camera is the SEC camera tube (Westinghouse WL-30691). This image tube is ideally suited for space applications because of its size, weight, power requirements, ruggedness, stability and simplicity of operation. It has in addition the features of wide dynamic range, tolerance to high saturation levels, and an electrical gain mechanism. The SEC tube has a linear dynamic range of more than 1000 to 1 for a high S/N and will accommodate saturating bright areas without blooming. The lens extends this range by 100 to 1. These features are essential for a portable unit such as the Apollo camera because it must work with almost no operational controls to handle changing or uncontrolled scene lighting.

For the Apollo color camera, the two most desirable characteristics of the SEC camera tube are its low-light-level capability and its lack of lag (Fig. 5). The low-light-level capability comes from the noiseless gain mechanisms and generally noiseless performance of the tube. The lack of lag is due to the signal generating mechanism of the SEC target and its relatively low capacitance.

Lag is a problem when viewing a moving scene because it results in a loss of resolution in a monochrome system and, in addition, an edge color breakup in a field-sequential color system. With most image tubes, such as a vidicon or an image orthicon, resolution becomes especially poor at low light levels. However, the lag characteristic of the SEC camera tube at low light levels is quite good and therefore its performance remains useful in that region.

The need for good low-light-level capability for the Apollo camera arises from two basic conditions—low lighting in the command module and light losses in the color wheel mechanism. The command module has a wide spread of light levels from spectral reflections of the sun to shadow areas of less than one footcandle. Since special lighting for the purpose of television is not practicable because of power, space, weight and layout problems, the entire light range extending to the low levels must be detected by the image tube.

The color-wheel losses are not unusual for a color television camera. Light losses are usually experienced through lens systems and the color filters in studio cameras. Thus, although the losses are kept to a minimum for the Apollo color camera, some are unavoidable. The lens in the wide-open position has a T number of 5.1, which is a 104 to 1 light loss. The ratio of the photocathode area to the product of filter and photocathode area is approximately 5 to 1 for all filters. The ratio of field time to transmission time is 2.5 to 1. Therefore, the total light loss is the product of these individual losses, or about 1290 to 1. In other words, for a 1.3 footcandle scene illumination with unity reflectivity, the image tube would receive approximately 0.001 footcandle faceplate illumination, a level well below the capability of a standard vidicon. However, the SEC camera tube, with the 2 MHz bandpass of the color camera, provides a S/N of approximately 35 dB at this light level, a signal that is more than adequate.

Automatic Light Control—The gain mechanism of the SEC camera tube is controlled by varying photocathode voltage from −2.5 to −8 kV. Automatic gain control is accomplished by sampling the video signal at the mixer and deriving a signal to control the photocathode potential. This control enables the SEC camera tube to handle a light range greater than 1000 to 1 and deliver a video signal with a minimum S/N of 32 dB.

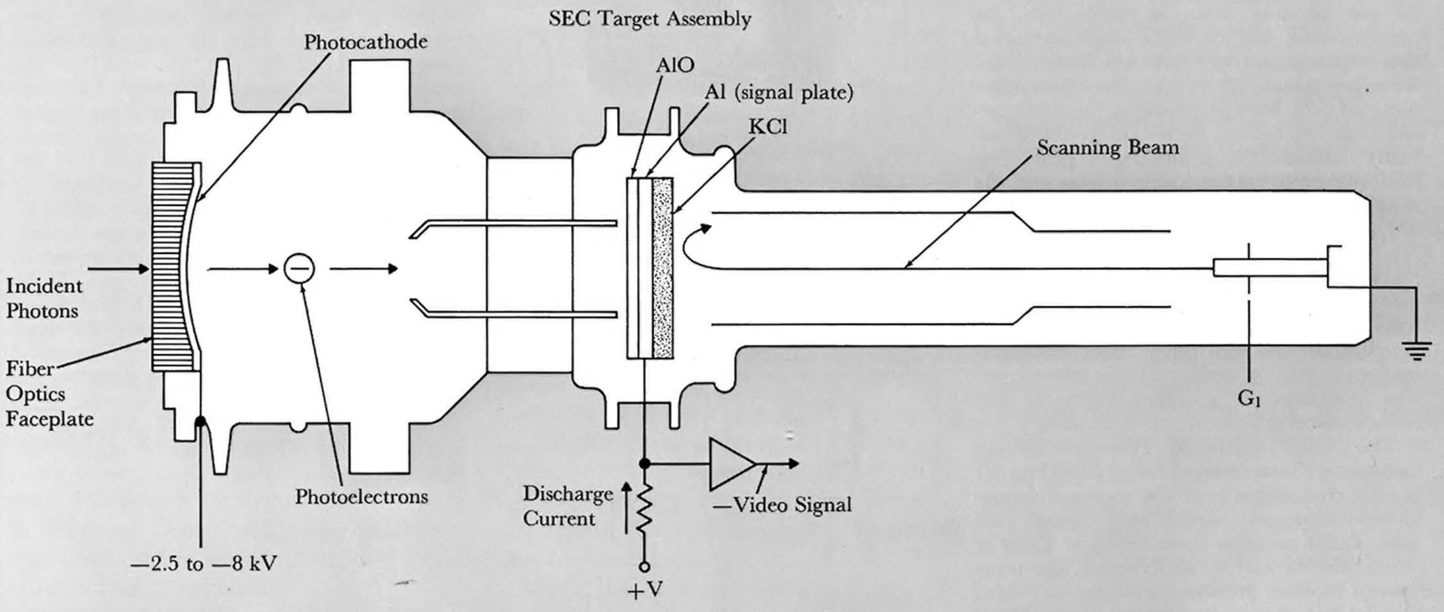
The gain curve of the SEC camera tube is nonlinear (Fig. 6), providing little additional gain for photocathode voltages greater than 5.5 kV. The color camera design takes advantage of this lack of gain above 5.5 kV to provide a safety factor for preventing the image tube from being damaged. (The damage level to an SEC camera tube is proportional to the exposure time for a given voltage.)

At very low light levels, photocathode voltage is allowed to rise to −8 kV to achieve maximum sensitivity. But when light level rises and the S/N output of the camera rises above 25 dB, photocathode potential is immediately limited to 5.5 kV. Although this results in a 20 percent decrease in S/N, this loss is hardly per-

Table I. Lens Characteristics

T Number		5.1 to 51
Zoom Ratio		6:1
Focal Length		25 to 150 mm
Field of View:	Wide angle—43° horizontal Narrow angle—7° horizontal	
	Near Focus	*f Number*
Wide Angle	20″	4.4
Wide Angle	1″	44
Narrow Angle	3″	4.4
Narrow Angle	2″	44

5



5—The light image is focused by the lens on the image faceplate. This light image causes the S-20 photocathode to emit photoelectrons, which are focused and accelerated by the geometry and an electrostatic field on the SEC target. Target gain is controlled by adjusting the photocathode accelerating potential (−2.5 kV to −8 kV).

The high-energy photoelectrons penetrate the aluminum oxide and aluminum layers to the KCl, where they strike a particle causing secondary electrons. The positive potential of the aluminum layer causes the secondary electrons to migrate to it, where they position with respect to the positive particle in the KCl layer. The electron charge is held in place on the signal plate until the target is swept by the electron beam. The electron beam deposits on the positively charged areas, returning the KCl surface to gun-cathode potential. This charging current, which constitutes the video signal, is capacitively coupled to the signal plate and causes current flow to the signal plate, developing the video voltage signal across the load resistor. Electron gain of the SEC target can be as high as 100. The combined gain of the image section and the SEC target is typically 10,000 μA/lumen.

The low-lag characteristic of the SEC target makes possible the excellent dynamic performance of the camera tube. The signal generating mechanism of the SEC target is essentially without lag because when secondary electrons are released into the vacuum interstices in the highly porous KCl film, secondary electron conduction takes place in a vacuum rather than in a conduction band. Therefore, the persistence effect caused by trapping and subsequent release of charge carriers in a conduction band is avoided. Thus, when the electron beam scans the KCl surface, electrons are deposited on the positively charged areas and no delayed positive charges appear after the beam sweep.

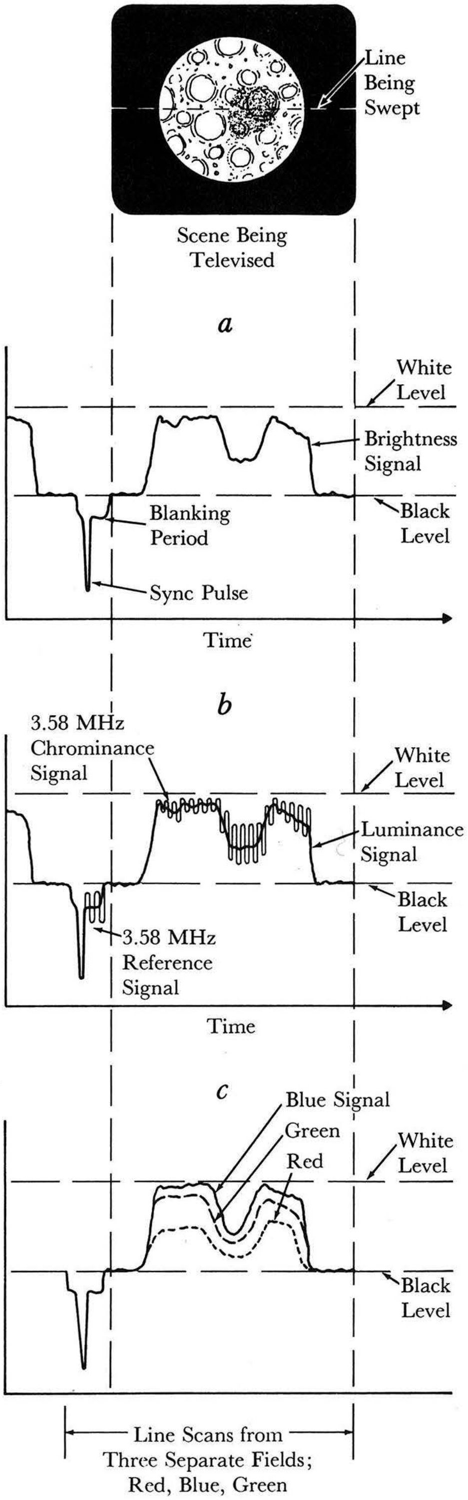
The relative freedom from lag in the SEC target makes possible a camera tube with a dynamic sensitivity that is only slightly less than its static sensitivity. For example, the SEC tube will develop resolution for a 20-second dynamic scene equal to that obtained with a static scene if the light level on the dynamic scene is increased by 2.5; under similar circumstances, an image orthicon requires an increase in light level of about 100.

Television Lines, Fields, and Frames

A black-and-white television broadcast signal for a single line scan (Fig. *a*) consists of a synchronizing pulse to lock the receiver's scanning beam to the broadcast scanning frequency, a blanking period that provides time for the scanning beam to return from the previous scan, and the video brightness signal that reproduces the brightness level of the scene being scanned. A complete frame (picture) of 525 lines is produced in 1/30 second, but, to reduce flicker, each frame actually consists of two interlaced fields, one field being the even numbered lines and the next field the odd lines. Thus, the standard TV vertical frequency is 60 fields per second. [To conserve bandwidth, the Westinghouse black-and-white TV camera[1] used for the moon-landing telecast transmits video information to earth at 10 frames per second (no interlacing) and 320 lines. From this information, signal processing at the ground station synthesizes a standard interlaced 60-field-per-second signal for broadcasting.]

The NTSC (National Television System Committee)[2] standard color signal (Fig. *b*) is fully compatible with the standard monochrome broadcast signal even though the color signal contains three different kinds of video information. A color camera uses three camera tubes to produce three separate video signals, one for each primary color. These color signals are electronically matrixed to provide two signals for broadcasting: the *luminance* signal is synthesized from the three primary color signals—59 percent green, 30 percent red, and 11 percent blue—but for all practical purposes is identical to a monochrome signal; the *chrominance* signal, also derived from the three primary color signals, is superimposed on the luminance signal and is both phase and amplitude modulated. The luminance and chrominance signals are reprocessed at the color television receiver to reproduce the three primary color signals. But to a black-and-white receiver, the chrominance signal frequency (3.58 MHz) is such that signals from consecutive fields are 180 degrees out of phase and the chrominance signal is blanked out.*

The mechanical field-sequential scheme used for the Apollo color camera uses a color wheel to insert color filters before a single camera tube so that red, blue, and green fields are transmitted sequentially at the standard color field rate (59.94 fields/second). Thus, a full-color field must be synthesized from three separate single-color fields (Fig. *c*). This is accomplished at the ground station with a magnetic disk recorder of the type used for instant replay. The color fields, transmitted from the camera in serial form, are switched and recorded on six separate tracks on a magnetic disk (red, blue, green, red, blue, green). Six tracks are used rather than three to provide time for erasure between recordings. Switching logic and delay circuits are used to develop synchronized red, blue, and green output fields in parallel. Since red, blue, and green fields are coming into the recorder at 59.94 fields per second in serial form, and are commutated out at 59.94 fields per second in parallel, each field transmitted from the camera must be used three times, yielding an effective color field rate of 20 fields per second. The three parallel output signals from the recorder are fed to a color encoder where they are converted to the standard NTSC signal (Fig. *b*) for broadcasting.



---

*Actually, this cancellation is due to the choice of the subcarrier frequency of 3.579545 MHz, which is an odd multiple of one half the line frequency. The line frequency chosen is 15734.264 Hz, and $(15734.264/2) \times 455 = 3.579545$ MHz. Since there are 252.5 lines per field, $15734.264 \div 252.5 = 59.94$ fields per second, the standard vertical frequency for color.

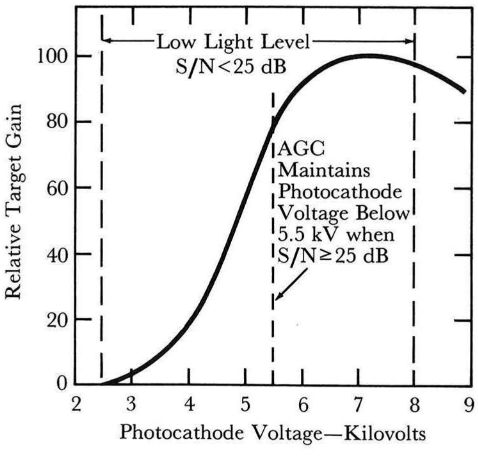
ceptible to the observer. The amplifier automatic gain control circuitry (AGC) limits photocathode voltage to 5.5 kV maximum over a light range, but permits the voltage to drop for higher light levels. The photocathode voltage reduction from this point is linear because the gain curve is reasonably linear below 5.5 kV.

The Color Wheel and Motor

The color wheel is a compromise in size, transmission efficiency, and uniformity. If it could have been large and rotated stably, its transmission could have approached 100 percent with no deviation in uniformity. However, size was a primary consideration for the Apollo camera and compromises were necessary, with some innovations to minimize losses.

The color wheel has six sections comprising two sets of red, green and blue filters (Fig. 2). This configuration is dictated by the speed of the motor (1798.2 r/min) and the gear ratio of 3 to 1. Thus, the color wheel rotates at 599.4 r/min (or 99.9 r/s) and yields six fields per revolution at the standard vertical color frequency of 59.94 hertz.

Between the filters are opaque regions, a compromise required by the small (three-inch) diameter of the color wheel. As the red filter rotates past the image tube faceplate, the red component of light information is integrated by the target. To prevent color mixing, this information must be read off the target by the scanning beam before the green filter arrives. Thus, the electron beam scan must follow the red filter and precede the green filter. With a large-diameter wheel and the filters positioned on the outer rim of the wheel, the dividing line between filters travels almost parallel with the scanning beam so that there is no problem in keeping the scanning beam operating within the confines of the desired filter. However, because of the small diameter of the wheel used in the color camera, it is necessary to use an opaque region between each filter, the size and shape of which is determined by wheel size and by the stability of the scanning beam and wheel rotation. Frictional load shifts and hunting in the motor cause some erratic motion in the filter wheel so the size of the opaque region allows for these irregularities.



6—Gain of the SEC camera tube is controlled by adjusting photocathode voltage between −2.5 kV and −8 kV. For very low light level scenes, the image uses the full voltage; for scenes with S/N at 25 dB, the automatic light control reduces photocathode voltage to 5.5 kV to protect the camera tube with an imperceptible loss in S/N.

Once the opaque region is sized, the scanning electron beam must be synchronized with the wheel to keep the beam within the confines of the opaque region. This is accomplished by sensing wheel position with a pickup device (Fig. 3). The wheel pulse signal is amplified and used to set the synchronizing generator that controls the sweep circuits, thus keeping the beam correctly positioned relative to color wheel position.

The ability of this system to keep the scanning beam in the opaque region depends to a large extent upon the stability of the synchronous motor, which is only as good as its input frequency. For that reason, the motor input is referenced to the camera's basic clock frequency, which has excellent stability. To minimize power consumption, the motor is driven with a pulse input, which results in a total power consumption of approximately 12 watts at nominal input voltage. (If a class A driver had been used to drive the motor, total power would have exceeded 30 watts.)

The filters are dichroic depositions selected for maximum transmission and spectral response. When modified by the spectral response of the S20 photocathode and a daylight source, their response closely matches that of the P22 phosphor. These filters are deposited on one piece of glass and sealed by another.

The Role of Color Television

The feasibility of using color television aboard a spacecraft has been proven and the public interest confirmed. The question now arises as to its practical application. The astronauts demonstrated some of these applications during the Apollo 10 and 11 flights when they televised the crew indicating their condition, the instrumentation, and the unusual condensation in the tunnel for ground support evaluation. In future missions, the color camera might also be used as a navigation aid by viewing the moon's surface with long focal length lenses and having ground support personnel determine spacecraft position by comparing the telecast picture with lunar maps.

There are many other potential applications, most of which can be classified as remote viewing; this classification includes viewing at points that are inaccessible because of position, or because of a hostile environment. For the present these are the most likely conditions for television applications in the space program because spacecraft by necessity have limited viewing positions and outer space is certainly an extremely hostile environment for man.

In addition to providing real-time communications useful to NASA ground personnel and the public, the Apollo color system has another scientific feature that should not be overlooked. The use of a calibrated color filter wheel permits true color information to be derived by data reduction from the recorded video transmission. This technique would provide a form of spectral analysis that might have useful applications in future space missions.

REFERENCES:

[1] E. L. Svensson, "The Lunar Television Camera," *Westinghouse ENGINEER*, March 1968, p 46-51.

[2] C. A. Scarlott, "Color Television," *Westinghouse ENGINEER*, May 1954, p 98-105.

PRINTED IN U.S.A.