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Technical Memorandum No. 33-76

Planetary Photography:

Television Camera for a Geological Survey of the Planet Mars

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ABSTRACT

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High-resolution pictures of the planets may be obtained with an electronic camera mounted on a spacecraft. Special techniques must be used to process the pictures to allow transmission back to Earth at planetary distances. An electrostatic Vidicon is shown to be a particularly useful transducer for planetary photography. An experimental flight camera system is described with some of the results obtained in the laboratory.

I. INTRODUCTION

Our knowledge of the planets is limited by the resolving power of our Earth-based telescopes. An electronic camera mounted on an exploratory spacecraft has the capability of improving the resolution by several orders of magnitude. The extent to which this capability may be achieved is related to the camera sensitivity, the quality of the communication channel at planetary–earth ranges, and the spacecraft potential, i.e., stability, payload-weight and primary power capacity.

Deep space communication facilities may be presently expected to have a useful channel capacity in terms of picture transmission at ranges of the order of 100 million miles.* Two of the closest planets, Mars and Venus, come within this range at yearly intervals. Because Venus is obscured by its atmosphere, attention is naturally directed at Mars for the first photogeomorphological planetary explorations.

The finest photographs of Mars have not exceeded a resolution of 100 km. A thousandfold improvement in resolution to 100 meters would provide highly significant pictures of Martian topology.

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*Pioneer V, 23 × 10^6 miles (5-watt transmitter). Venus Radar Experiment, 35 × 10^6 miles (10 watt effective, omnidirectional).

II. LOGISTICS

The spacecraft must be launched several months ahead of the experiment to insure a close approach at Mars opposition. Picture-taking may then commence at a spacecraft range of 100,000 km from Mars and continue for several hours or until the Mars terminator is passed.

As real-time transmission is not possible, pictures must be stored in the spacecraft for transmission to Earth after the pictures are taken. At this time information is sent to the Earth stations at the maximum rate permitted by the capacity of the communication channel. Even so, several days may be required to transmit the pictures.

III. MARS ILLUMINATION

Two views of Mars as observed from a spacecraft for a trajectory approaching to 13,000 km are shown in Fig. 1. These present views are of most interest for geomorphological picture studies. Depicted are a sub-solar view at -3.34 hr and a Mars terminator view at $+0.66$ hr from closest approach as determined by planetary studies. The use of two cameras permits overlapping fields of view for identification purposes and improved information content. Thus high-resolution pictures may be taken with a long focal-length telescope, while overlapping larger areas might be covered with a short focal-length objective. The corresponding scanned fields-of-view for two cameras with objective fields of 0.62 and 3.15 deg respectively are shown on the Mars surface. The more valuable information will be secured in the region of the Mars terminator where the contrast will be higher.

The relative intensity of Mars luminance as observed from Earth is shown in Fig. 2 (Ref. 1). The data is for a phase angle of 39 deg corresponding to the picture of Fig. 1. Relative intensity is determined by photometric microdensitometry of a photographic negative of the planet. The maximum variation of intensity over the sub-solar portion of the planet is seen to be of the order of 15 percent. Small areas of the surface that would be covered by a narrow-angle camera apparently have greatly reduced light gradations, approaching 1 percent of the maximum high-light illumination. Pictures that will be imaged onto the photo-sensitive surface of the television camera tubes may thus be categorized into two classes: bright pictures of low to medium contrast and dark pictures of medium to high contrast with an over-all dynamic range of illumination of the order of 100:1.

The high-light luminance of the Mars surface may be approximated:

$$I_s = \alpha E \left(\frac{r_e}{r_m}\right)^2 \theta \text{ lumens/ft}^2$$

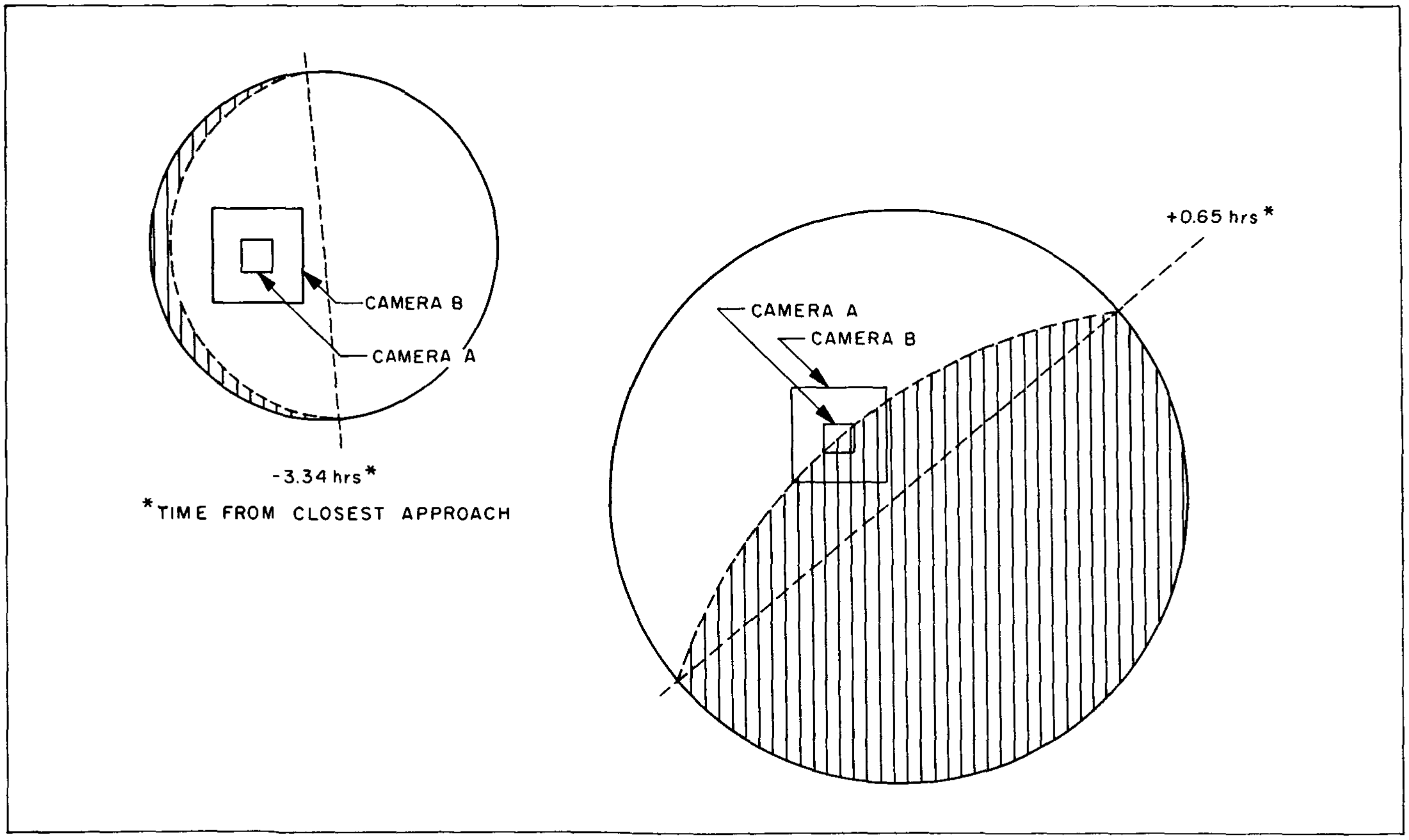

Fig. 1. Mars as observed from spacecraft

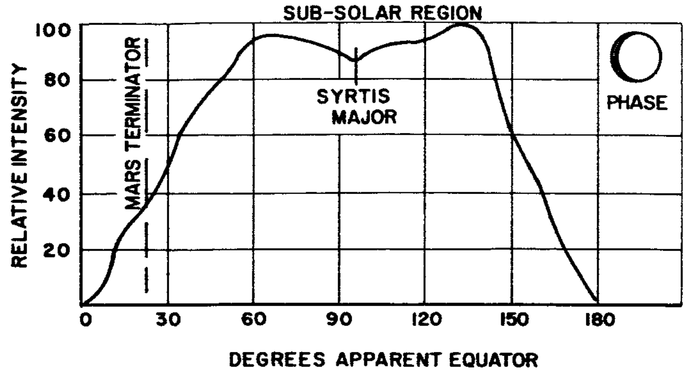

Fig. 2. Relative intensity of Mars 1939 luminosity

where α is the albedo, E the solar constant, r_e and r_m the distances of Earth and Mars from the Sun, and θ the angle of incidence. Thus assuming a high-light albedo of 0.1 with θ at the normal to the surface and a solar constant of 12.5×10^3 lumens/ft²

$$I_s = 0.1 \times 12.5 \times 10^3 \times \left(\frac{92}{140}\right)^2$$

$$= 535 \text{ ft-lamberts}$$

IV. TELEVISION CAMERA

A. Resolution

The resolution of the television camera

$$R = \frac{r\theta}{NK}$$

where r is the range, θ the field of view, N the numbers of television lines, and K the Kell factor. At a range of 15,000 km and with 400 scanning lines and a Kell factor of 0.7 the resolution when using the telescopic objective,

$$R = \frac{15 \times 106 \times 0.011}{400 \times 0.7} = 60 \text{ meters}$$

As the spacecraft is not a completely stable platform some smearing of the image is to be expected. In terms of resolution, smear $= \phi t r$ where ϕ is the angular movement of the platform rad/sec and t is the camera exposure time. At 15,000 km for $t = 20$ msec and $\phi = 1$ min of arc/sec the smear $= 3 \times 10^{-4} \times 10^{-2} \times 15 \times 10^6 =$ 90 meters.

B. Photo-Cathode Illumination

The photo-cathode illumination of a television camera (Ref. 2) is given in terms of exposure time by

$$I_{pc} = \frac{I_s T R t}{4f^2} \text{ ft-c/sec}$$

where I_s is the scene illumination, T the transmission efficiency, R the scene reflectance, and f the f-no. (focal length/effective objective diameter). Thus for a 20-ms f4 exposure,

$$I_{pc} = 0.15 \text{ ft-c/sec}$$

For an expected 100-to-1 light gradation the camera high-light illumination would thus vary from 0.0015 to 0.15 ft-c/sec.

Sensitivity comparisons between television cameras are shown in Fig. 3. Orthicon cameras have sensitivities of the order of 10^{-6} ft-c/sec. However, the sensitivity of the

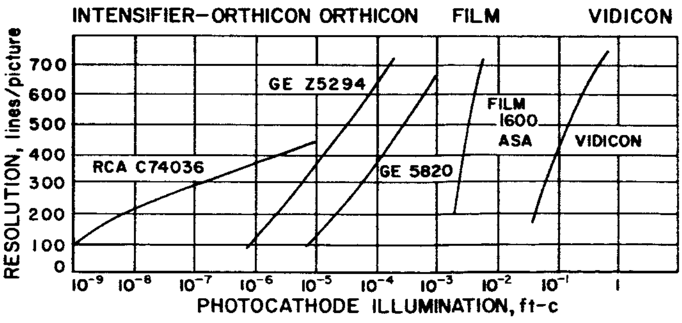

Fig. 3. Relative sensitivity of television camera tubes, 30 frames per sec

Vidicon is seen to approach the photo-cathode illumination requirement indicated above, assuming a 33-ms exposure time to transpose the data into ft-c/sec.

C. *Picture Quality*

Picture quality is determined ultimately by the optical-electrical transfer characteristics of the transducer. The transducer may be evaluated in terms of the ratio of the output signal to the background noise (Ref. 3). Corresponding resolution and sensitivity are then expressed in terms of signal-to-noise ratios as shown for a Vidicon in Fig. 4. Related are the photo-target illumination in ft-c/sec and the video signal output SN ratio. For this tube and amplifier combination the gamma over the linear range is unity. This form of comparison is particularly applicable to space television systems as contamination by noise is a particularly pertinent problem. Within this frame of reference a high quality picture is defined as that produced by a peak-to-peak video signal at least 30 db above an rms noise background. An acceptable picture has a 20-db SN ratio.

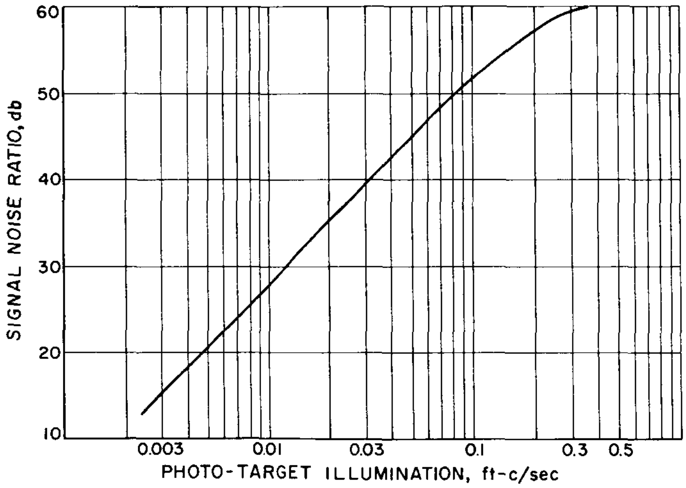

Fig. 4. Vidicon transducer characteristics

D. *Encoding*

The camera signal must be encoded to permit storage in the spacecraft and subsequent PCM, i.e., coded modulation of the transmitter (Ref. 4). The x, y, z axes of the prism illustrated in Fig. 5 represent the digital process for an intensity-modulated signal generated by a scanning process. Encoding requires that the video analog signal be sampled and quantized. In accordance with the Nyquist sampling rate the sampling time T may be $1/2f_c$ where f_c is the highest video frequency generated by the scanning. Thus a low f_c not only permits a low sampling rate with consequent circuit simplicity but also improves the camera SN ratio or sensitivity which is a function of B, the video bandwidth. The highest video frequency is dependent on the vertical scanning rate which in turn is determined by the storage time of the Vidicon photoconductor. Storage times of approximately 10 sec are currently being achieved.

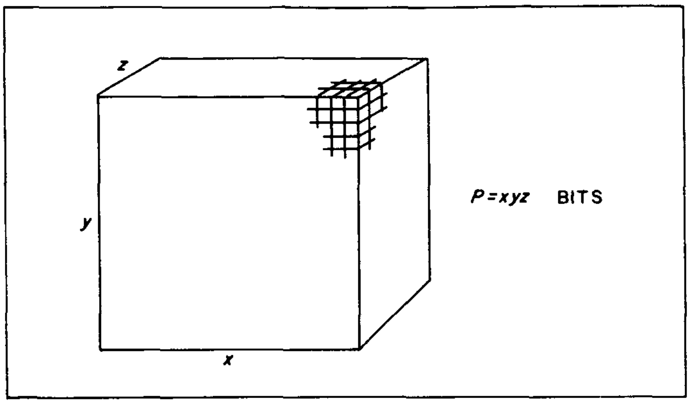

Fig. 5. Digital process as related to scanning

The highest video frequency

$$f_c = \frac{N}{2t\eta}$$

where N is the number of picture elements, t the vertical scan in seconds and η the line time utility factor.

$$f_c = \frac{400 \times 400}{2 \times 10 \times 0.8} = 10\,\text{kc}$$

for 400 lines scanned at a 10-sec rate with $\eta = 0.8$.

The total number of bits generated by the encoding process of the picture signal $P = N \log_2 I$ bits where I is the number of intensity levels to be quantized. For the 400-line scan and 32 levels, $P = 400 \times 400 \times 5 = 800{,}000$ bits. The time to transmit Q pictures,

$$T = \frac{QP}{C}$$

where C is the system capacity in bits/sec. Assuming a C of 20 bits/sec, and ten pictures,

$$T = \frac{10 \times 8 \times 10^5}{20} \approx 100\,\text{hr}$$

V. PROPOSED SYSTEM FOR PLANETARY PHOTOGRAPHS

A. Description

A block diagram of a proposed television camera system is given in Fig. 6. To conserve weight and insure power economy, electrostatically operated Vidicon camera tubes are used. Ruggedized electrostatic tubes are available that will withstand stabilization temperatures of over 125°C. In particular, electrostatic operation insures freedom from interference with magnetometer experiments. A picture of an electrostatic Vidicon is presented in Fig. 7. Scanning and control functions for the two cameras are logically controlled from a master 1-mc clock signal. To simplify control operations, both cameras take pictures continuously and alternately following planetary acquisition. With a stored picture read-out time of 10 seconds and with interleaved camera operation, several pictures may be taken per minute.

B. Beam Modulation

Vidicon sensitivity at low levels of target illumination is almost completely determined by the preamplifier performance. Hence if a Vidicon is to be used for a Mars experiment considerable care must be exercised in the design of the amplifier. Thermal noise at the preamplifier input terminals may be defined by the Nyquist equation, $\overline{e_n^2} = 4KTRB$ volts rms, where K is Boltzman's constant, R the Vidicon signal-output resistance, T its temperature, and B the noise-bandwidth of the video amplifier. To simplify the design of the preamplifier, beam-modulation of the Vidicon target may be employed. In this system the scanning beam is chopped at a high-frequency and the photoconductive target amplitude modulates the beam in accordance with the incident illumination. (This technique was originally proposed by R. C. Heyser of

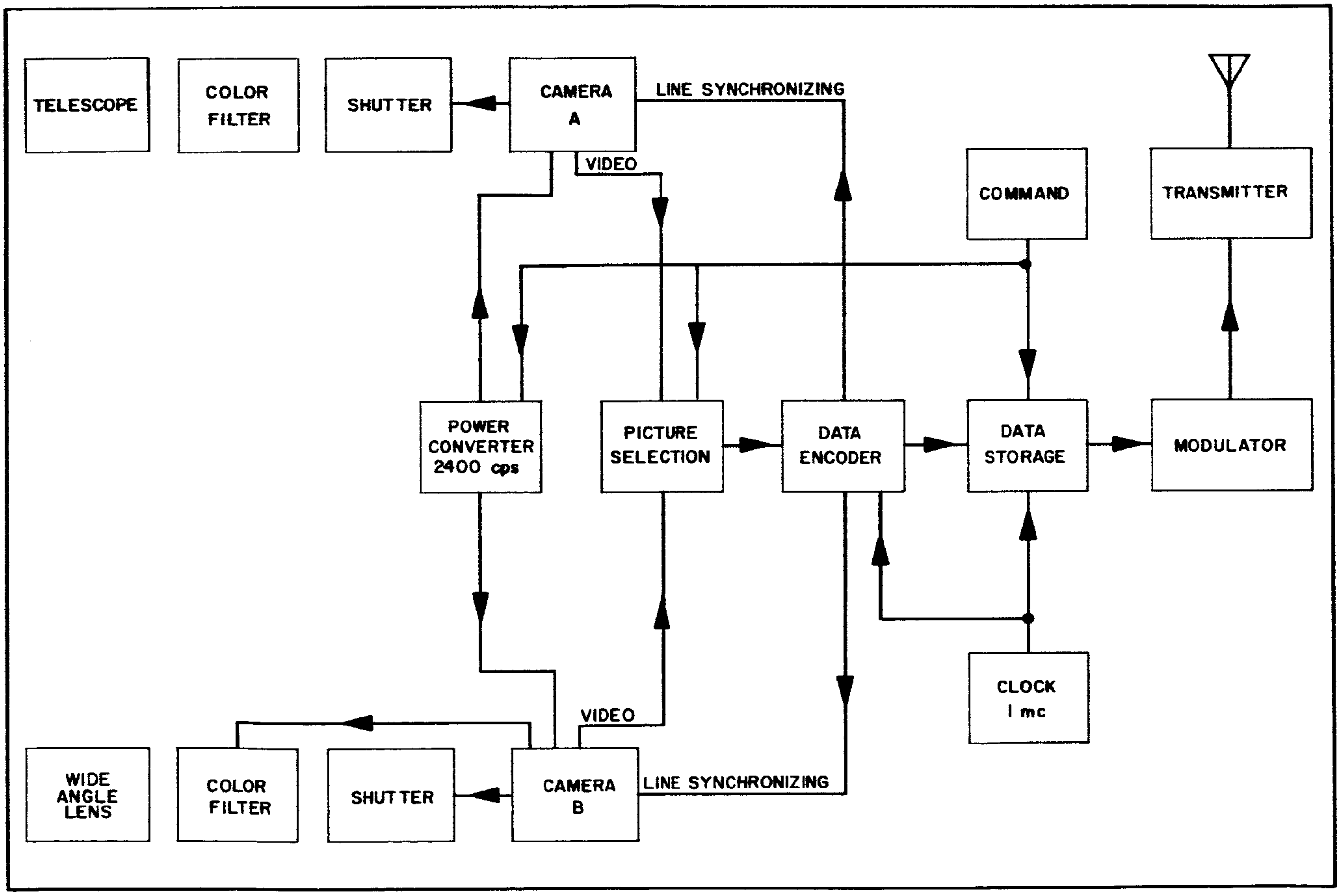

Fig. 6. Block diagram of space television camera system

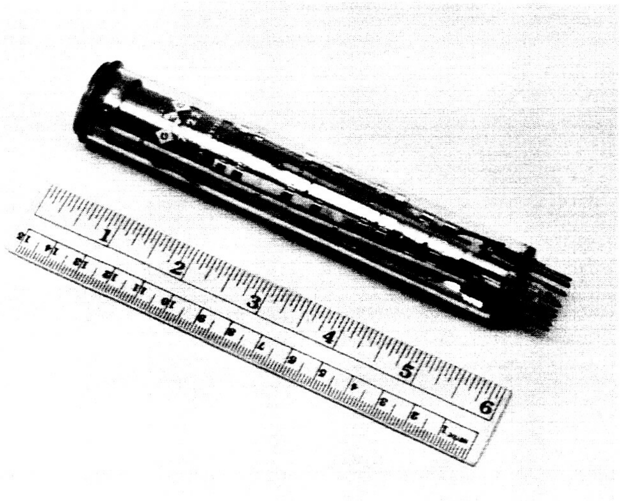

Fig. 7. Electrostatic Vidicon

JPL and subsequently used in *Ranger* spacecraft cameras.) The resultant output signal now takes the form of a modulated RF signal with the video spectrum transferred from dc to RF. If the beam-chopping oscillator is set at 125 kc there is a simple binary relationship, ×8, to the 1-mc clock frequency.

C. Preamplifier

The usable output signal of the Vidicon $I_s = I_o - I_d$ where I_s is the signal current and I_d the dark current. The transfer characteristics are shown in Fig. 8. Low values of output current, of a few millimicroamperes, require an amplifier with a correspondingly favorable SN ratio. A completely transistorized system is greatly to be desired particularly to secure the lowest possible primary-power consumption. Fortunately the design of low-noise transistor amplifiers has been alleviated by the recent introduction of high-gain, passivated surface, low-noise transistors exemplified by the 2N2049.

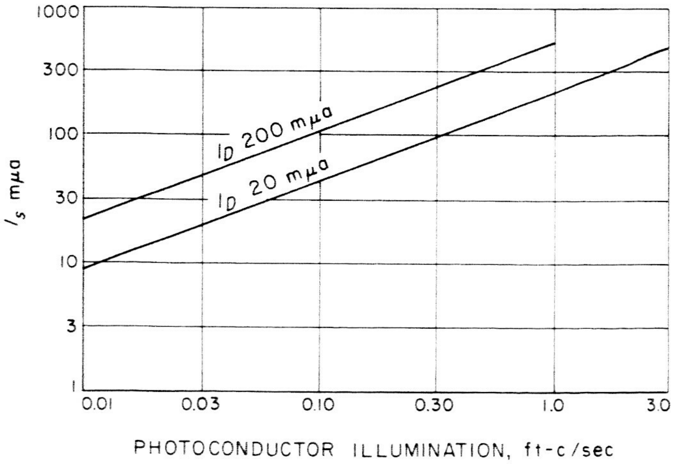

Fig. 8. Vidicon light transfer characteristics (from General Electrodynamics Corporation data)

The Vidicon signal-output circuit for a 125-kc carrier system is shown in Fig. 9. The photoconductive target corresponds to an extremely high impedance generator (>>10 megohms) so that the signal output for usable resistance values varies directly as R. The highest SN ratio will be realized by maximizing R as the noise voltage is a function of $R^{1/2}$. In this case the effective output load

$$R = \frac{Q}{\omega C}$$

Therefore, R is maximized by minimizing C and operating with the highest possible Q for the tuned transformer.

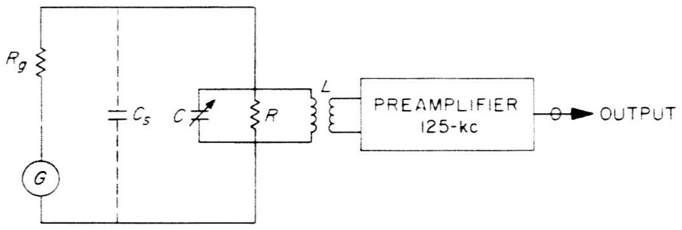

Fig. 9. Vidicon signal output circuit for beam modulation

Figure 10 shows the noise spectrum for a typical transistor (Ref. 5). Operation at 125 kc clearly obviates the flicker noise. However, $f\alpha_b$ must be considerably higher than 125 kc because of the term $(1 - \alpha_0)^{1/2}$. The 2N2049 has a specified $f\alpha_b = 800$ kc with I_c at 10 μa for which $f\alpha_b(1 - \alpha_0)^{1/2} = 112$ kc. However, for lowest noise the recommended collector current is in the 300-μa

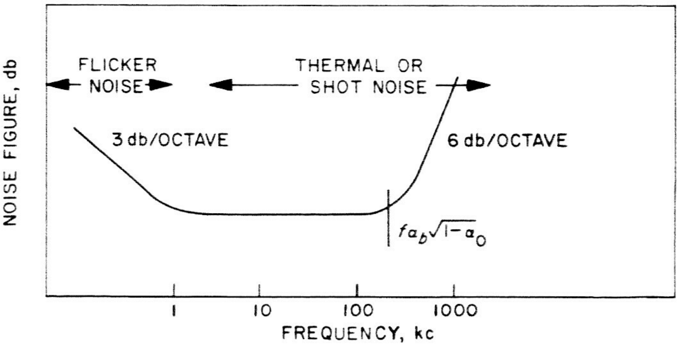

Fig. 10. Noise spectrum of a transistor

region for which f_{α_b} is expected to be much higher than 800 kc. This would place the carrier frequency well within the lowest noise figure region. The optimum required source impedance for the transistor of between 500 and 1500 ohms is readily obtained by adjustment of the transformation ratio of the input transformer.

Figure 11 illustrates a technique for evaluating the video amplifier using an amplitude-modulated signal from an R-F signal generator to simulate Vidicon highlight signal of a few millimicroamperes. Data so obtained is presented in Table 1 where it will be noted that a -40 db signal (100:1 ratio) at the 5 mμa level has a signal-to-noise ratio of 15 db. A measured noise figure for this same amplifier indicated a NF of 3 db which is close to the best obtainable with vacuum-tube devices.

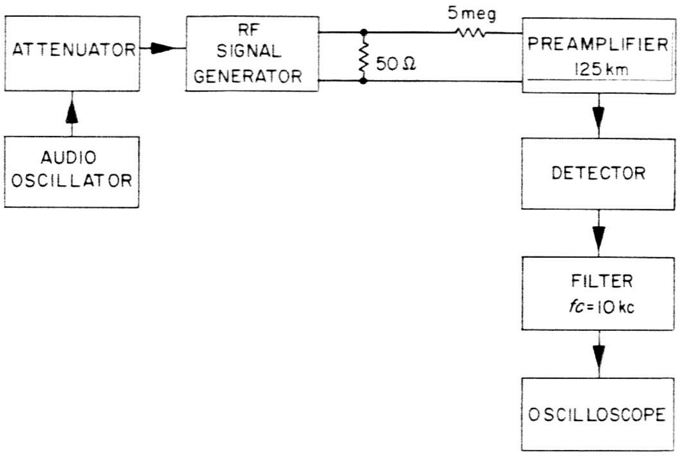

Fig. 11. Measurement of amplifier SN ratio simulating Vidicon characteristics

D. Camera Assembly

An experimental, wide-angle, space-flight television camera assembly that uses the techniques discussed above is shown in Fig. 12. The Vidicon, preamplifier, and shutter are enclosed in an assembly that includes the lens. The associated control electronics is connected by a 12-ft cable to the camera. The lens is a 55 mm Takumar Asahi f1.8 lens in a Pentacon mount with an electrically operated 15-ms shutter. A similar electronic assembly operates the narrow-angle camera which would then use a 100-cm f6 telescope with a 20-cm objective. A thermally-stabilized housing for the narrow-angle camera is illustrated in Fig. 13.

Table 1. Measured video-amplifier system performance data for a simulated 5-millimicroampere Vidicon signal

Modulation intensity, db (30% = 0 db)	P-P video output signal, mv	RMS noise, mv	S/N, db
0	1900	3.3	55
-10	600	3.3	45
-20	190	3.3	35
-30	60	3.3	25
-40	19	3.3	15
-50	6	3.3	5

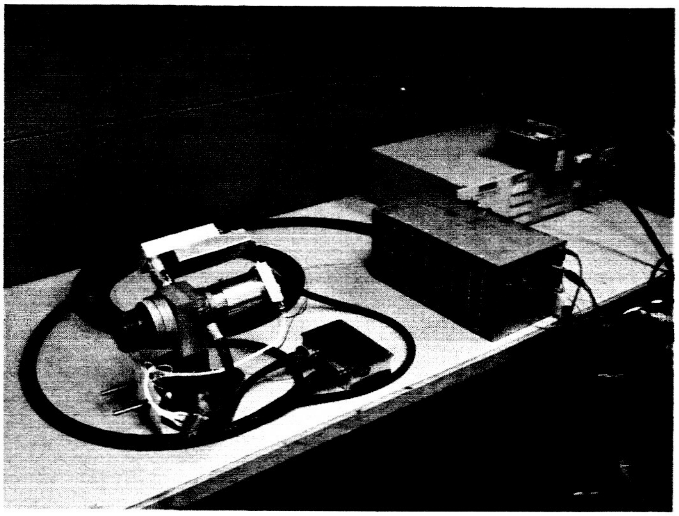

Fig. 12. Experimental flight television camera

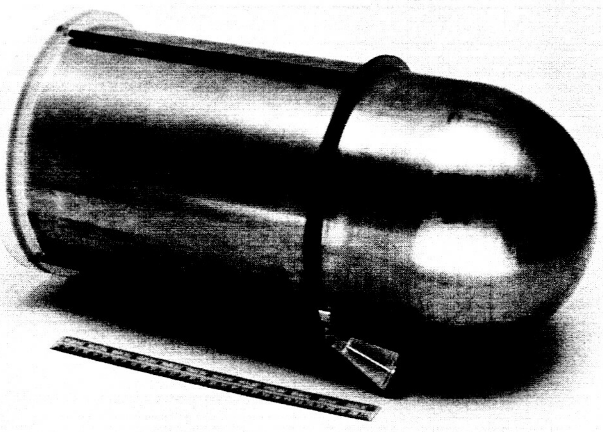

Fig. 13. Narrow-angle television camera housing

E. Performance

A test pattern photographed with the system described above is shown in Fig. 14. To illustrate the digital process a signal respresenting a coded line scan is compared with the analog signal, first before filtering of the digital signal and second after filtering (Figs. 15 and 16). The almost imperceptible effect of the digital process on the picture is illustrated in Fig. 17. Displayed in the upper part of the picture is the digital signal and in the lower part the analog encoded picture following the decoding process. These pictures were taken with a Polaroid camera using a slow-scan presentation on an oscilloscope monitor having a P15 long-persistence screen.

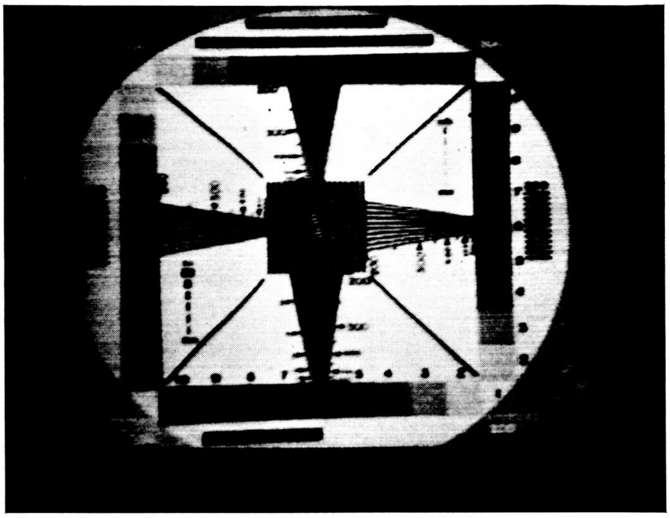

Fig. 14. Test pattern taken with television camera

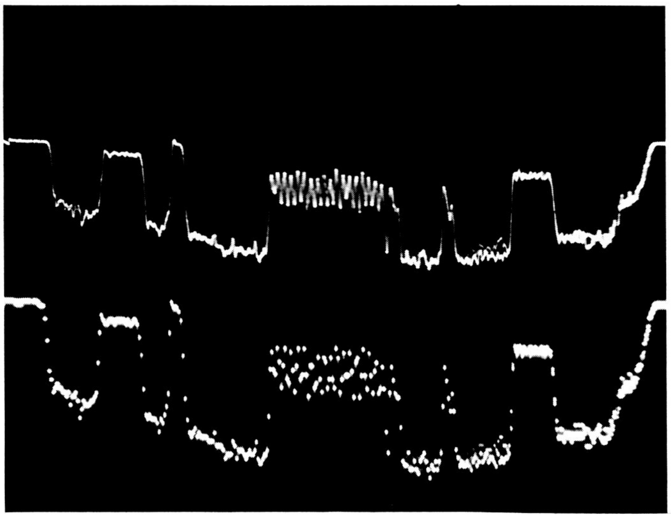

Fig. 15. Digitally encoded signal before filtering

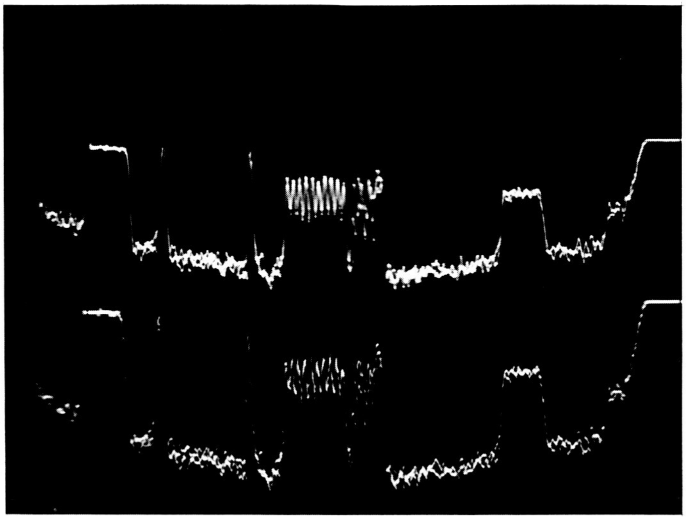

Fig. 16. Digitally encoded signal after filtering

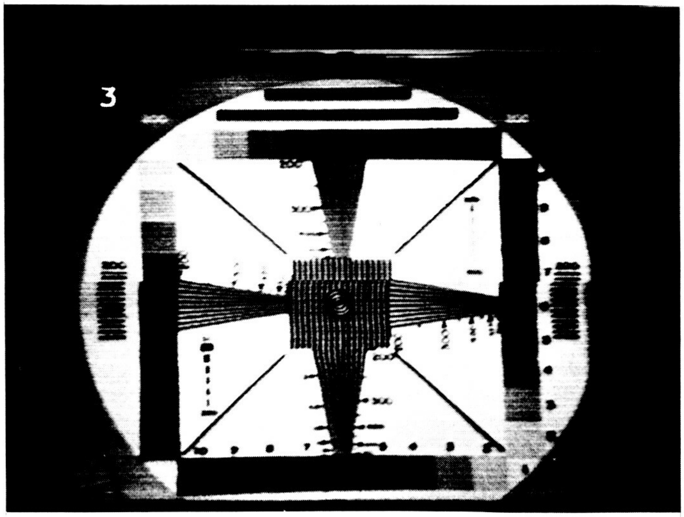

Fig. 17. Comparison of analog and digital process

VI. CONCLUSION

It appears that the electrostatic Vidicon camera tube meets the requirements for a planetary space camera. When this tube is combined with a suitable information encoder, a capability is then established for transmitting pictures over a narrow-band communication system back to Earth over planetary distances.

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