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A SYSTEM FOR LUNAR PHOTOGRAPHY AND DATA TRANSMISSION

John R. Scull

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FIGURES

FIGURES (Cont'd)

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John R. Scull

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

ABSTRACT

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At the time the first United States Lunar Photographic Vehicle was being developed, data from Explorer IV indicated the presence of high-intensity ionizing radiation surrounding the Earth. As a result, an alternate approach was developed, using a slow scan vidicon television camera in conjunction with 2000:1 bandwidth compression by means of a special 650 gm low power tape recorder. The performance of the prototypes along with the engineering philosophy which led to their development is presented in some detail. Special attention is given to the development of methods for generating, storing and transmitting video information over long distances using low power and subaudio bandwidths.

Author

[1]This paper presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. NASw-6, sponsored by the National Aeronautics and Space Administration.

[2]Presented at the International Symposium on Rocket and Astronautics, Tokyo, Japan, May 24-28, 1960.

In the early part of 1958, the United States announced that the Advanced Research Projects Agency would attempt a series of instrumented lunar probes as a part of the United States participation in the International Geophysical Year. The responsibility for these probes was turned over to the National Aeronautics and Space Administration (NASA) in October 1958, shortly after its formation. This paper will discuss the design of a system for lunar photography and data transmission developed for but not flight tested with Pioneer IV, the second space probe fabricated by the Army Ballistic Missile Agency and the Jet Propulsion Laboratory for NASA.

Pioneer III, the first of the ABMA-JPL space probes, contained two radiation counters, two temperature sensors, and a test of two devices to be used in later lunar photographic experiments, a despin system and a shutter-trigger mechanism which would be tripped as the probe passed the illuminated surface of the Moon.

The next space-probe experiment, Pioneer IV, was originally intended to photograph the unseen side of the Moon and to send back the pictures by radio telemetry. The initial design for this camera used 35mm film, a focal-plane shutter, a thixotropic developer and fixer system, and a photoelectric scanning mechanism similar to facsimile for data readout. By September 1958, the design of this system was complete and portions of it were under development testing.

At this time, data from Explorer IV, the latest in the series of United States IGY satellites, indicated the presence of a belt of high-intensity radiation surrounding the Earth. There were insufficient data to determine the relative proportion of protons or electrons in this radiation or their respective energy distribution. On the basis of the data available, it was decided to initiate an alternate approach to the film camera which would be undamaged by radiation.

It was decided that the system most likely to receive no permanent damage from radiation would be a vidicon television camera (Ref. 1). The Radio Corporation of America had recently designed a lightweight vidicon TV camera to use in a meteorological satellite (Ref. 2). This TV system was relatively lightweight but had the disadvantage of requiring fairly high signal bandwidth for transmitting the picture to the ground station. For the long communication distances of the Moon or farther and the limited transmitter and battery weight available, it was necessary to develop a system for bandwidth reduction and to optimize the relationship of bandwidth, power, signal-to-noise ratio, the number of shades of grey, the time of transmission, and the resolution of the picture. The following portion of this paper describes the development of this television, recording, and data-transmission system.

The largest single factor influencing the development of the Pioneer IV spacecraft was the weight limitation, 14 lb (6.35 kg). The effect of this weight limitation was to restrict not only the weight and size of the scientific instrumentation, but also to limit the amount of power available for transmission of the data to the Earth. Since the largest problem seemed to be that of communication bandwidth, the combined weight of TV camera, recorder, and transmitter was minimized and the remaining weight put into power-supply batteries. Due to the increased efficiency of mercury batteries when used at low drain levels over large discharge times, the fact that the weight of the transmitter was proportional to its output power, and the desire to track the probe to as great a distance as possible, the weight optimization of the over-all system resulted in a low-power (180-mw) transmitter capable of telemetering information bandwidths of 2 cps from the Moon's distance and beyond.

The complete transmitter consisted of a crystal-controlled oscillator, transistor frequency multipliers, and a vacuum-tube output stage operating at 960 mc. The spacecraft antenna had a 3-db gain in the direction of the Earth. The scientific measurements were frequency-modulated on subcarriers which, in turn, phase-modulated the partially carrier-suppressed transmitter. The modulation index was adjusted so that the threshold of the telemetry subcarrier detectors would be 1-2 db higher than the threshold of the carrier detector so that telemetry would be lost just prior to loss of RF carrier lock.

Since the upper stages of the Juno II launching vehicle were spin-stabilized, it was necessary to slow down the spin rate in order not to blur the pictures. This was accomplished by means of a "yo-yo" system. Two 6-gm weights were fastened to the ends of wires about 2 meters long. Prior to the launch, these wires and weights had been wrapped around the payload and secured. At about 10 hr after launch, the weights were released and centrifugal force caused them to unwind and release themselves upon reaching the end of their travel. Their release caused a change in the angular momentum of the spacecraft and reduced the spin rate from 400 rpm to 10 rpm.

In order to actuate the shutter of the camera, a photoelectric shutter-trigger was developed. This sensor, shaped like a pistol, contained a lens system and a pair of photoelectric cells. The spacing of these cells was adjusted so that an image of the size of the Moon would excite both cells simultaneously. Since the shutter-trigger could have been set off by the Earth shortly after launch, it was armed by a timer after 20 hr of flight. The attitude of the spin-stabilized probe was such that, after arming, only the Moon would trigger the camera.

The output signals of the two photocells in the shutter-trigger were connected to a coincidence and time delay circuit. A continuuous series of coincidence pulses from the Moon for 30 sec would turn on the TV system for warmup. The next pulse which occurred would operate the shutter, take a picture, and turn on the tape recorder. After the tape recorder reached the end of its reel of tape, the camera would shut off and the recorder would begin to play back the pictures at reduced bandwidth until the batteries were depleted. Since the 10-w power drain of the TV camera system was considerably higher than the average power level, high-discharge-rate nickel cadmium cells were used for its operation.

The entire TV system, including lens, shutter, vidicon, deflection and focus yokes, video amplifiers, power supplies, and regulators, weighed slightly under 6 lb (2.7 kg). The half-inch (1.2-cm) vidicon used in this camera used a "sticky" or long-time-constant photoconductor. As a result, the presistence of the image was such that the entire frame of the picture could be read out over a 2-sec period. This long readout time results in a bandwidth reduction by almost a factor of a hundred over a conventional TV system. The disadvantage of this long time constant is that the vidicon tube must be shuttered instead of being continuously exposed to the object being photographed. In order to stop the motion due to the spin of the spacecraft, a 1.5-msec focal-plane shutter was used. The lens system for the TV camera was a conventional f/2 50mm lens used for 16mm movie cameras. The focal length was chosen in order to have the Moon just fill the frame at its closest expected approach. The complete camera shown in Fig. 1 was adjusted to have 200-line resolution with 100-cps horizontal sweep and 2-sec vertical sweep. The 6kc video from the vidicon was amplified by a cathode follower and a series of transistor amplifiers. Vertical and horizontal sync pulses along with blanking and dc restoration was accomplished by semiconductor circuits. A block diagram of the complete TV system appears in Fig. 2. Figure 3 shows a typical composite video signal as it appears at the output of the TV camera system.

An important consideration of system philosophy centers around the quality of the picture to be obtained from a video communication channel containing noise. Some indication of the picture quality at low signal-to-noise ratios can be obtained from Fig. 4. This Figure shows a video test pattern and white noise at a signal-to-noise ratio of 2:1. The picture quality can be improved significantly by integrating several frames, in that the signal is correlated but the noise is not. Figure 5 shows the same signal-to-noise-ratio picture averaged 50 times. These experiments indicated that it is better to transmit one image as many times as possible rather than to attempt recovery of many images.

The video output of the TV camera was connected to the tape recorder. This tape recorder was required to record two continuous vertical scans of the picture over a 4-sec period with a bandwidth of 6 kc. On playback, the stored video information was played back at a 2.5 cps bandwidth over a period of slightly more than two hours. The speed ratio or reduction in bandwidth was 2000:1. In order to recover the information from the tape at the low speed of 0.01 inches per second with frequency components as low as 0.005 cps, several alternate approaches were tried.

In the first approach, several different flux-responsive playback heads were evaluated. The second-harmonic flux-modulator heads evaluated include several commercially available double-core and crossed-field types. A crossed-field magnetic-bridge type developed at JPL for this program is shown in Fig. 6. The flux-responsive system was set aside when development tests showed sensitivity to stray magnetic fields and no appreciable improvement in over-all bandwidth over conventional rate-of-change-of-flux types.

Since the frequencies and recorded wavelengths involved were too long for direct recording, both AM and FM carrier systems were tried. Using 6 kc video bandwidth, several carrier frequencies were tested to determine the lowest possible. Figure 7 shows a test using AM and four different carrier frequencies with no carrier filtering. Based on this test, it was determined that a carrier of 20 kc was adequate for a 200-line image. Although an AM system seemed desirable from the standpoint of simplicity and lack of accurate speed control, it was decided to use an FM technique in order to minimize incidental amplitude modulation from dropouts and poor tape-to-head contact.

During the evaluation of the AM carrier system, a novel method of recording was discovered. Instead of requiring a separate carrier oscillator, modulator, and magnetic recording amplifier with ac bias, the technique of "carrier erase" was investigated. In this system, the carrier is prerecorded on the tape after adequate erasure. The video modulation is then simply "dc" recorded over the prerecorded carrier with no additional bias. The essence of this technique is that the original recording of the carrier is partially erased in accordance with the level of the video signal, thus achieving amplitude modulation of the carrier. The simplicity of this technique may be noted by the fact that, for a laboratory-prerecorded carrier on the tape, no electronics are required between TV camera output and magnetic recording head, the dc-restored video from the camera supplying all the current required. Figure 8 shows a "carrier erase" amplitude-modulated envelope with a typical test-pattern modulation signal after recovery from a tape recorder.

The FM system developed had several simplifications over the conventional methods used in that no bias or erasure signal was required if a sufficiently large amplitude of carrier was used. Its comparative insensitivity to recorded signal amplitude variations was regarded as a further advantage. Speed control, a requirement for FM, was not considered an added complication since it was required for adquate video line synchronization. Tests were conducted to determine the shortest recorded wavelength which would produce satisfactory results using a wide deviation (±30%). The results shown in Fig. 9 for high-output tape and a small commercially available head indicate the optimum wave length and recording current. The minimum playback level at 0.01 inches per second was 7 microvolts or -90 dbm. The tuned-carrier playback amplifiers required 160 db amplification before use as motor speed control or for output to the transmitter modulator.

The mechanical characteristics of the tape transport mechanism were dictated primarily by the playback system and control mode requirements. The total tape length required for the storage of two frames of video information was a minimum of 80 in. (200 cm). Tests of methods to use as motive power for the 2000:1

speed ratio between playback and record led to the development of a spring-driven motor for high speed and a dc servo-controlled motor with large speed reduction for low speed. The spring motor chosen for recording was based on the use of a Neg'ator constant-force spring and a viscous-damped speed governor. Since a stable reference carrier was recorded on the tape for playback speed control, the slight speed variations due to the spring-powered record motor were outweighed by the simplicity of the system. Torque- and speed-vs-temperature curves for the record system are shown in Fig. 10 and 11.

The playback tape transport used a high-efficiency miniature low-power dc motor developed specially for this application. The characteristics of this motor are as follows:

Output shaft speed	0-2000 rpm
Output shaft torque	0.05 in.-oz
Input voltage	7.2 v
No-load current	2 ma
Weight	3 oz
Size	1 1/4 in. D x 1 1/4 in. high

Measured motor efficiencies of this motor were in excess of 80% and the no-load losses were quite low. This motor drove the tape reel through an 8000:1 reduction. The reduction was originally by precision gearing but was later changed to a rubber puck drive to minimize speed variations. After the tape was completely rewound during the playback cycle, a cam-operated switch released the record spring (but without any record electronics operating) and the cycle repeated itself until battery depletion.

During playback, the accurate speed control required for proper FM demodulation and line synchronization was provided by a "speed lock" technique. A stable 20-kc reference carrier was recorded on one track of the recorder at the same time as the FM video carrier was recorded on the other. When played back at 0.01 inches per second the reference carrier was at 10 cps. This low-frequency carrier was amplified and compared to a 10-cps stable oscillator in a phase detector, and the resulting dc signal was used to operate the playback motor. Over-all timing and speed accuracy was demonstrated to be better than 0.1% over a 10-hr period. A block diagram of the entire recorder is shown in Fig. 12 and photographs of the complete recorder are shown in Fig. 13 and 14. The weight of the complete recorder including the record and playback amplifiers and motor speed control system was just under 1.5 lb (650 gm). The over-all size was about 8 in. in diameter and about 1 in. thick.

Several FM demodulation techniques were investigated during the development of this system. Due to the low level of the signal recovered from the tape, coupled with amplitude variations, the detector was required to have a very high discrimination against amplitude modulation. The original attempts at demodulators used simple slope detectors preceded by two stages of limiting. Figure 15 shows a typical video signal at the output of the camera. Figure 16 shows the same signal after high-speed recording and slow-speed playback using a slope or integrating detector. In order to improve the signal-to-noise ratio, several pulse-counting techniques were tried. The most successful of these were the full-wave one-shot multivibrator and the boxcar discriminators. The circuit designs for these two detectors are shown in Fig. 17. Both of these pulse-counting detectors offer about an 8 db improvement over the simpler slope detector, as shown in Fig. 18 and 19.

On assembling the complete system, shown in Fig. 20, it was found that a large part of the total signal bandwidth was required to supply adequate horizontal synchronization pulses. In addition, subsequent investigations revealed that sync disturbances caused by wow and flutter in the ground recorder were a source of major difficulty. To eliminate these defects, a different approach to synchronization was developed. In this system, shown in Fig. 21, the vidicon horizontal sweep signal is derived from the airborne tape recorder's reference pilot tone through a frequency divider which supplies reset pulses to the horizontal-rate generator. The pilot tone is carried through the airborne tape recorder as the motor-lock signal, and transmitted to the ground over a very-low-bandwidth telemetry subcarrier. Bandwidth and subcarrier power requirements are determined by the frequency stability of the motor-lock oscillator. In any case, a net reduction in total bandwidth results. In the ground system, the pilot tone and the video information are both impressed on the low-speed recorder. When the ground tape recorder is played back at high speed to recover the data, the video information is discriminated, amplified, and applied to the intensity grid of the monitor kinescope. The pilot channel is fed to a frequency divider whose ratio is identical to that of the flight unit and the resulting pulse resets the monitor horizontal-sweep generator. The pilot channel is also discriminated to provide the rate signal for the horizontal-sweep generator and wow and flutter compensation for the video channel. Figure 22 shows a scale of five shades of grey fed to the input of the airborne tape recorder. The corresponding signal at the output of the ground tape recorder is shown in Fig. 23.

The signal-to-noise ratio for the entire airborne and ground bandwidth-compression system is 15 db (not including cosmic noise). The picture on the ground monitor kinescope for this same system is shown in Fig. 24. This photograph was taken after approximately 10,000 replays of the picture on the ground.

In December 1958 when this TV system was in the prototype-evaluation stage, the Pioneer III space probe was launched. This probe, which reached an altitude of 63,580 miles above the Earth, discovered the second or outer radiation belt surrounding the Earth. This discovery was deemed so important that it was decided to defer the flight of the television camera to some later time and to repeat the radiation measurement experiment. Additional shielding was added around one of the radiation detectors to modify its sensitivity and to allow a measurement of the relative energy level of the radiation.

Pioneer IV, with this experiment, was successfully launched on March 3, 1959, and provided excellent new radiation data. The Pioneer IV lunar probe was tracked to a distance of 407,000 miles, setting a record which has only recently been broken by the USA space probe Pioneer V.

The television camera developed for this probe, with some modification in packaging, resolution, and bandwidth, was used in recently successful United States meteorological satellite, Tiros I. It is intended to use the same or similar television systems for future satellites and space probes.

I wish to acknowledge the special assistance on the development of the television camera and tape recorder to H. C. Vivian and R. C. Heyser of the Jet Propulsion Laboratory and E. A. Goldberg and M. H. Mesner of the Radio Corporation of America.

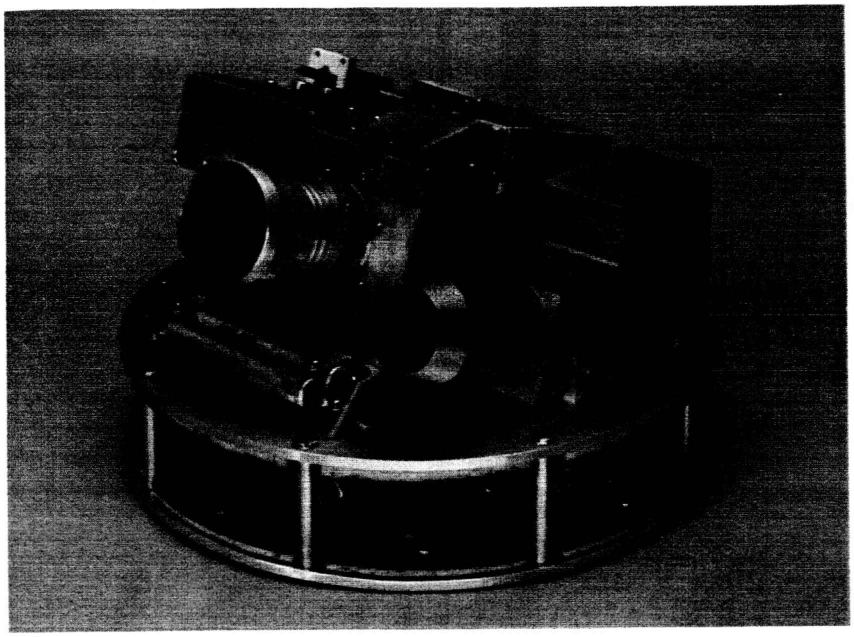


Fig. 1. Vidicon camera with shutter-trigger.

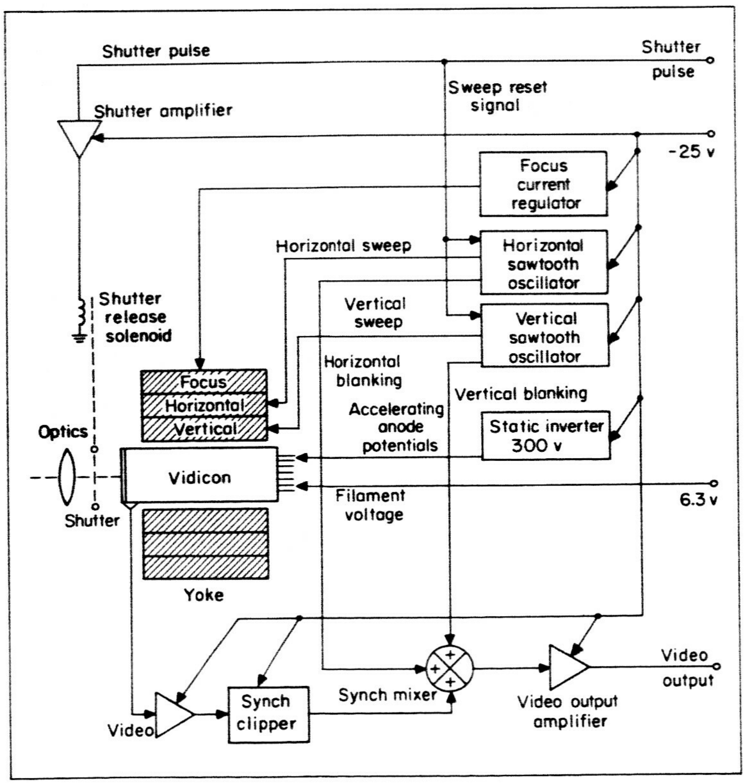


Fig. 2. Vidicon camera unit.

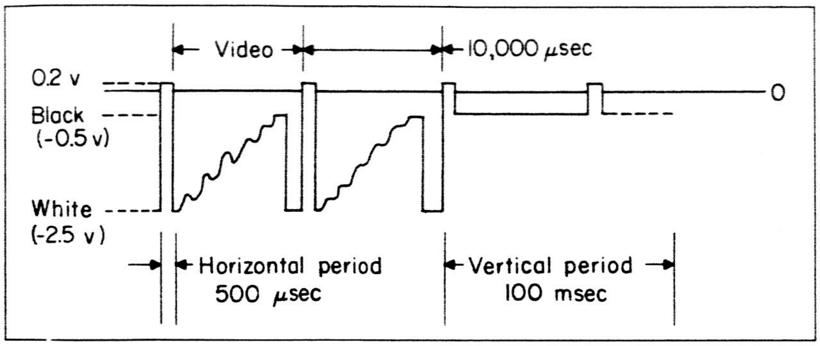


Fig. 3. Typical composite video signal.

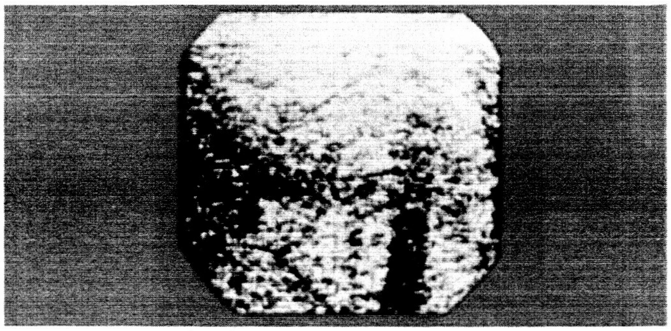


Fig. 4. Single transmission of composite video and white noise.

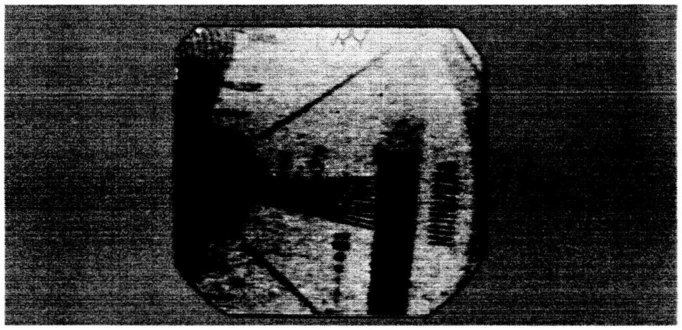


Fig. 5. Random noise reduction by repeated transmissions of a single picture, average of 50 transmissions.

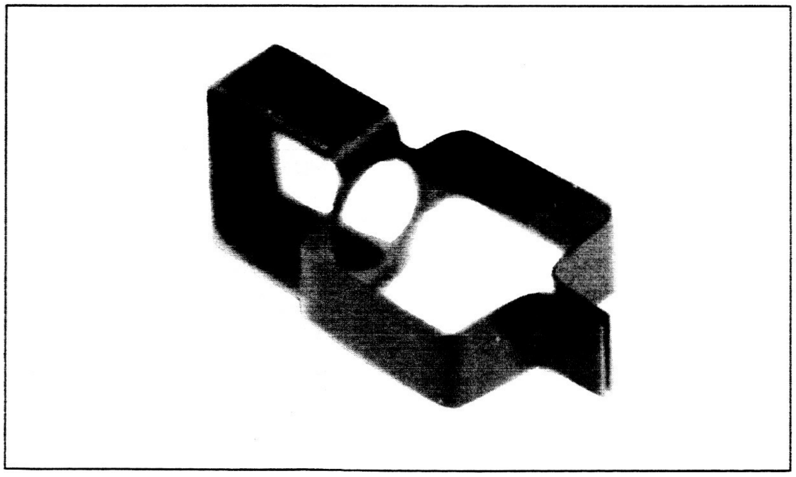


Fig. 6. Magnetic configuration of experimental flux-responsive head.

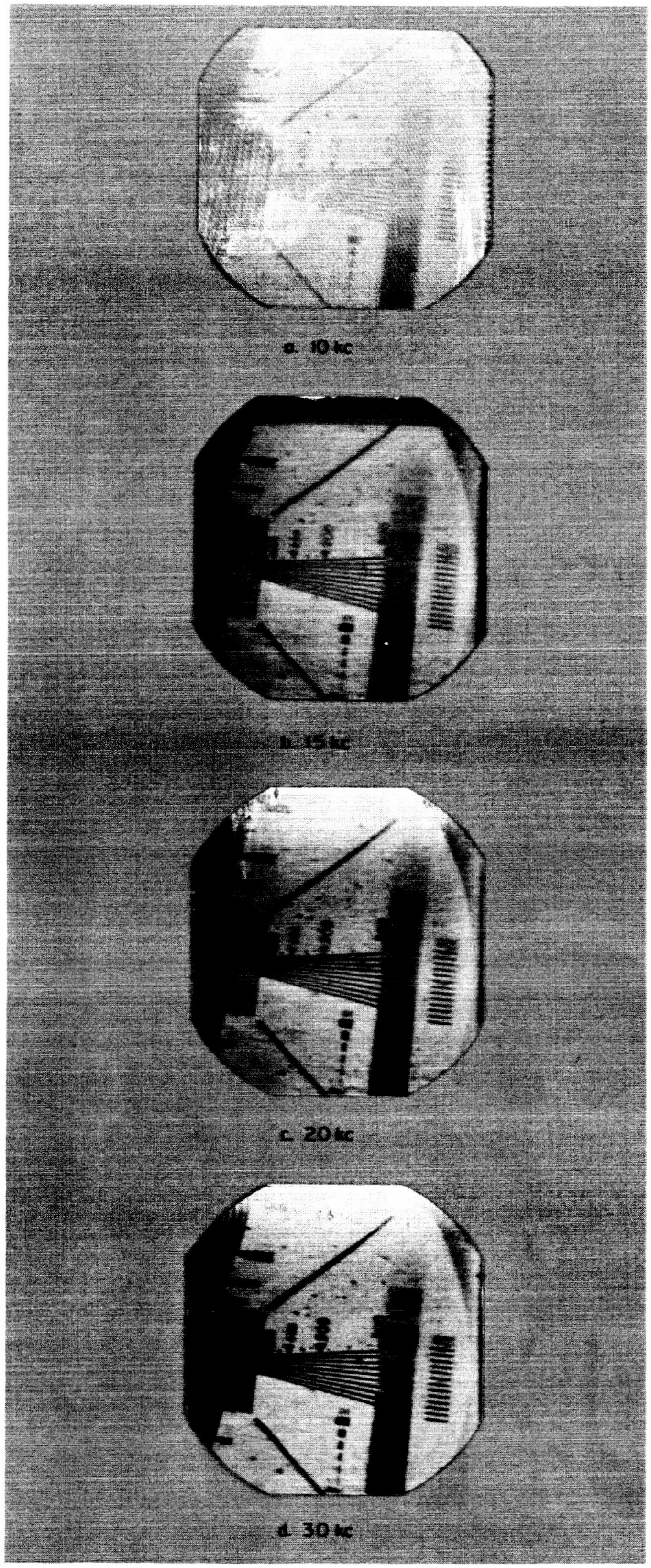


Fig. 7. Demodulated AM video with carrier.

Fig. 8. Modulation pattern of carrier erase system.

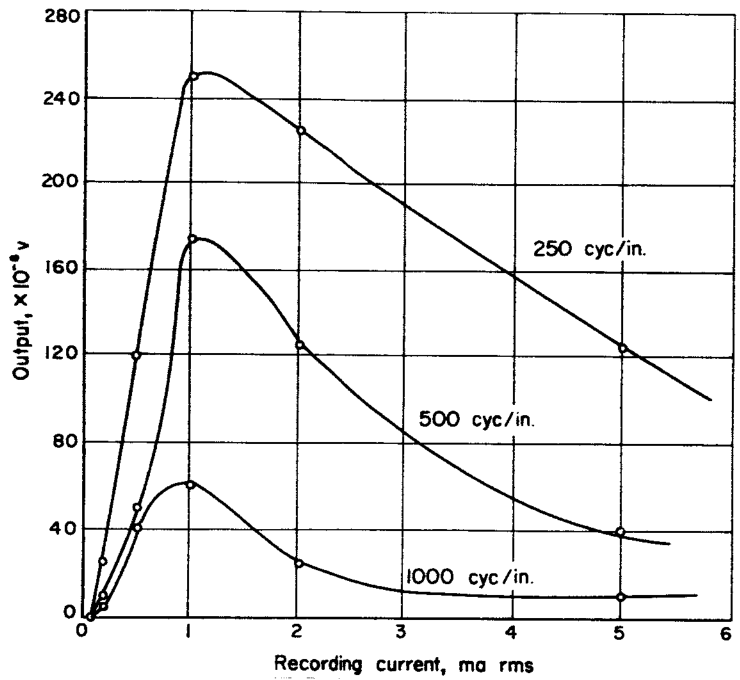


Fig. 9. Optimization curves for high-output tape with dynam-mu head.

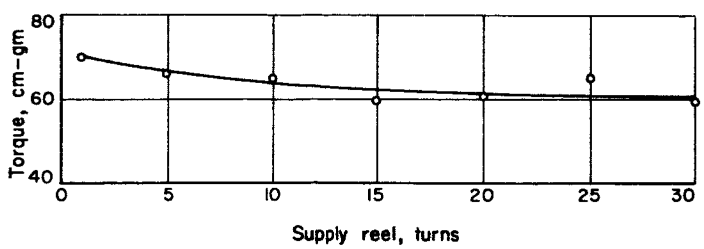


Fig. 10. Torque curve of Neg'ator spring motor.

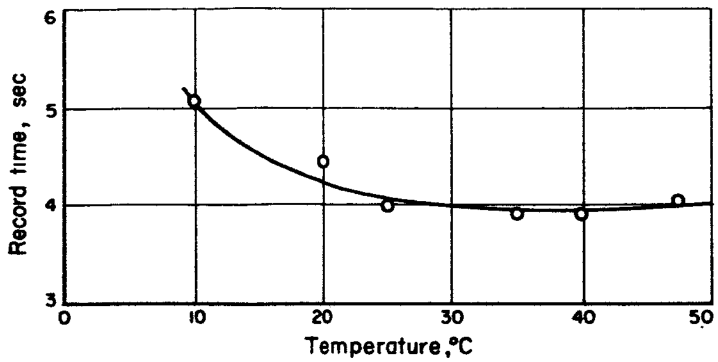


Fig. 11. Speed curve of Neg'ator spring motor.

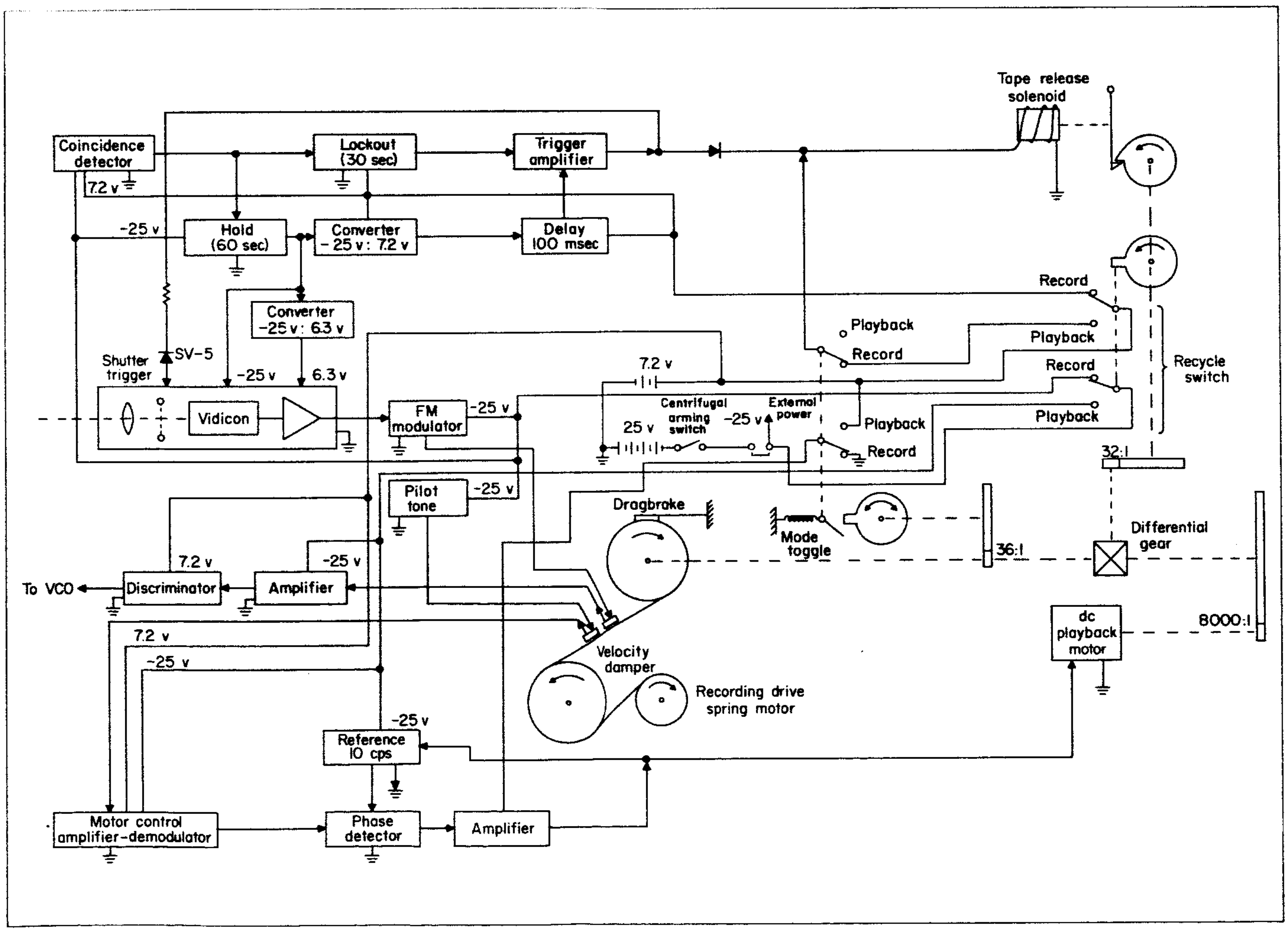


Fig. 12. Complete camera system.

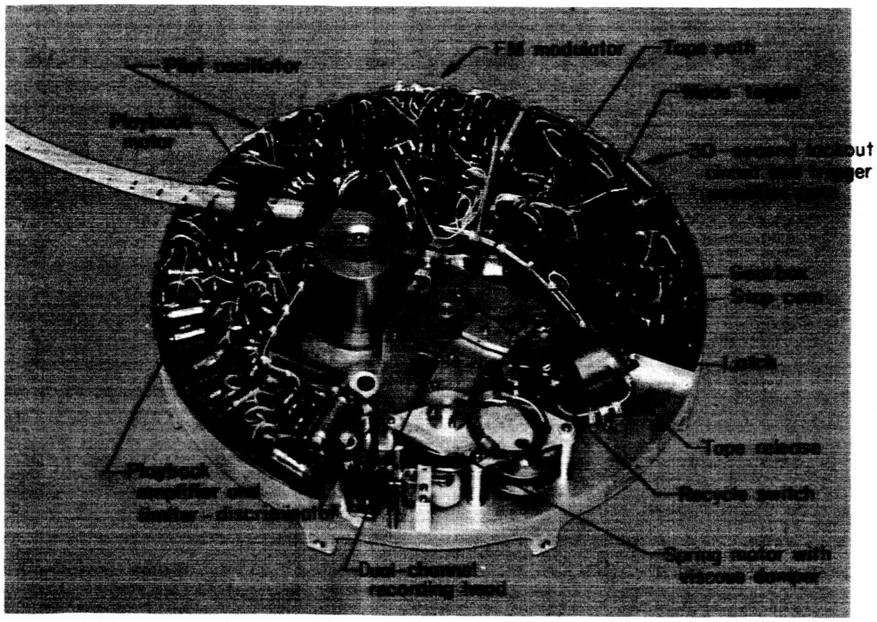


Fig. 13. Tape recorder, top.

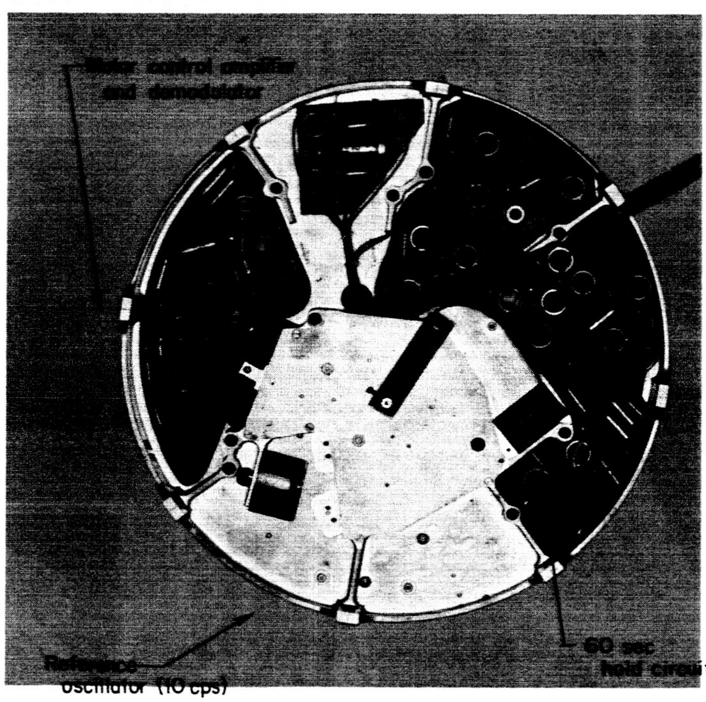


Fig. 14. Tape recorder, bottom.

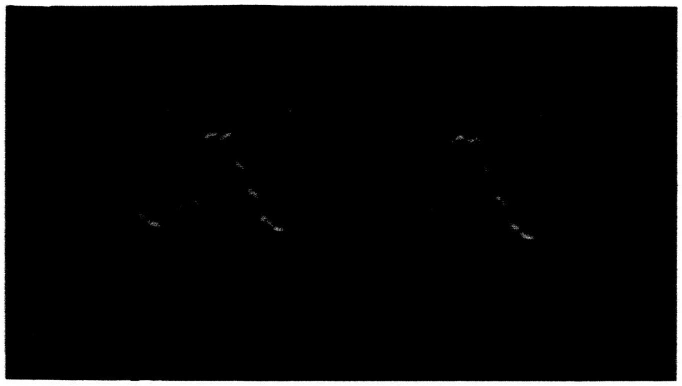


Fig. 15. Video camera output signal.

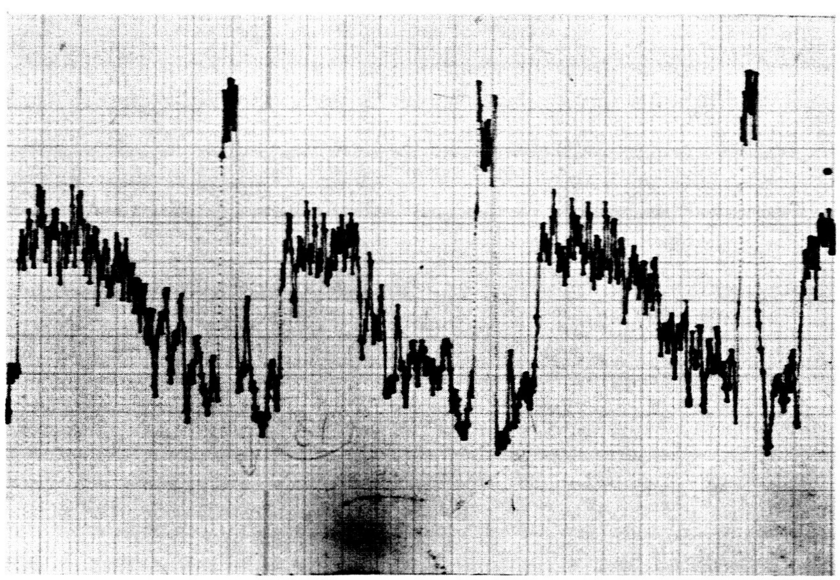


Fig. 16. Video output of tape recorder.

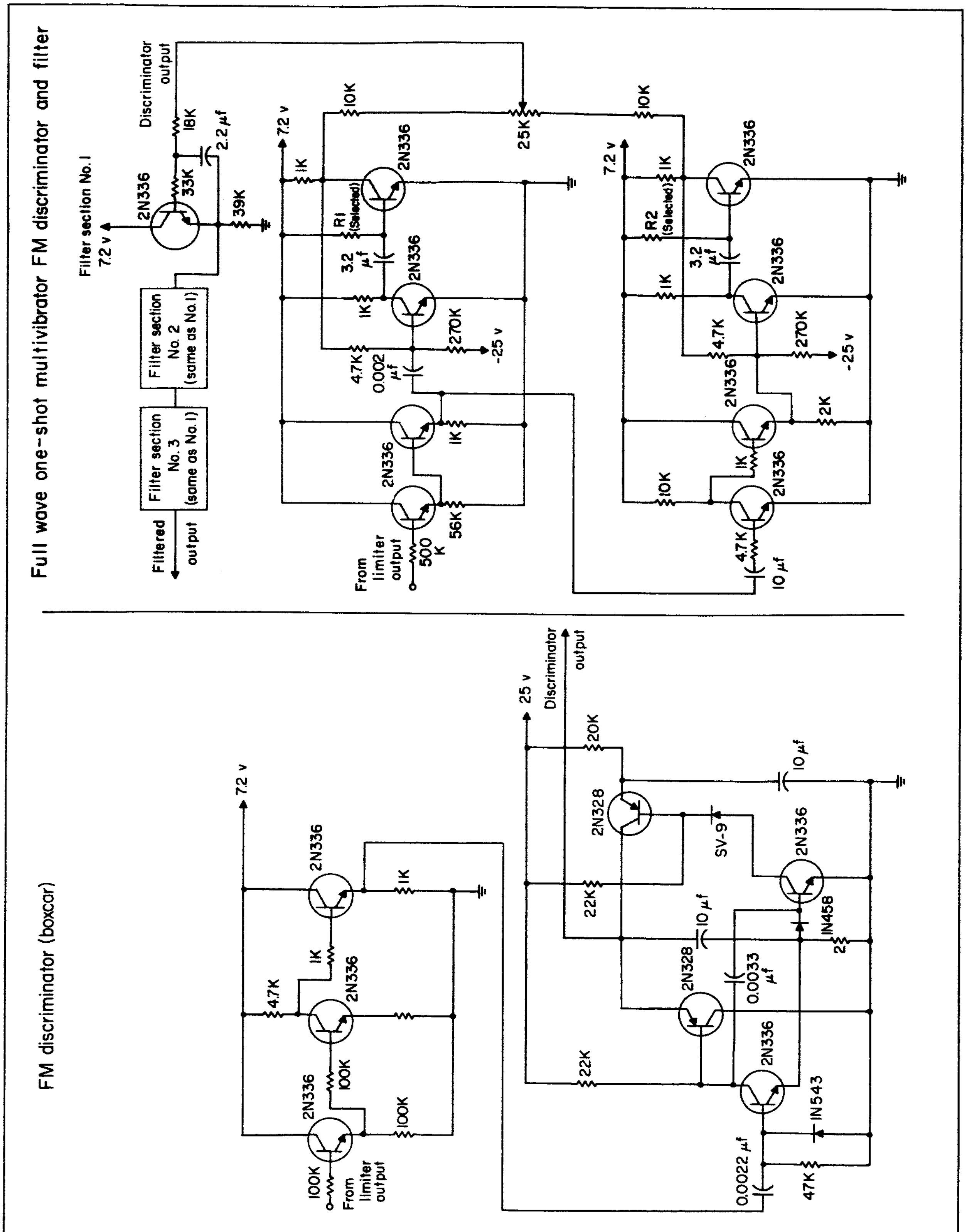
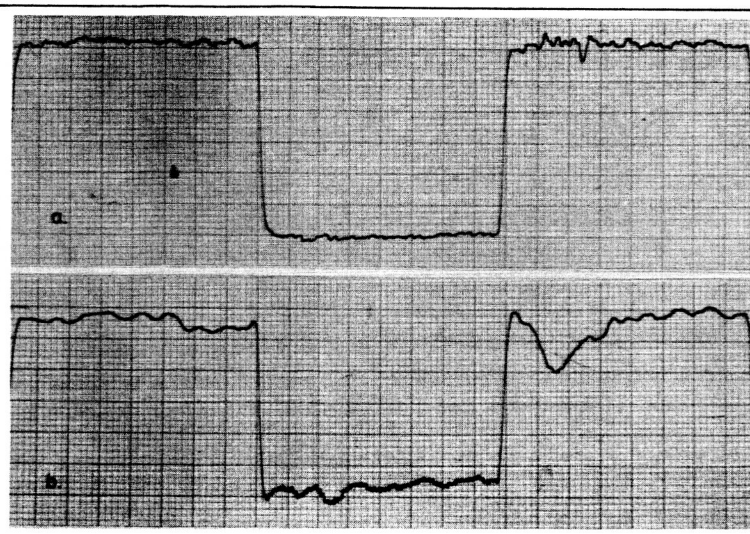


Fig. 17. Boxcar and one-shot-multivibrator FM discriminators.



a. One-shot discriminator b. Integrating-type discriminator

Scale sensitivity:	a. 500 mv/cm	b. 250 mv/cm
Discriminator sensitivity:	a. 250 mv/cyc	b. 125 mv/cyc
Total voltage swing:	a. 1.5 v	b. 625 mv
Peak-to-peak noise:	a. approximately 10%	b. approximately 30%

Modulating signal frequency: 100 cps
Tape packing density: 500 cyc/in. Carrier frequency: 18 kc
Sanborn recorder speed: 5 mm/sec Recording current: 0.5 ma (rms)
Applied square-wave amplitude: 4 v peak-to-peak

Fig. 18. Discriminator response to 100 cps square-wave modulating signal.

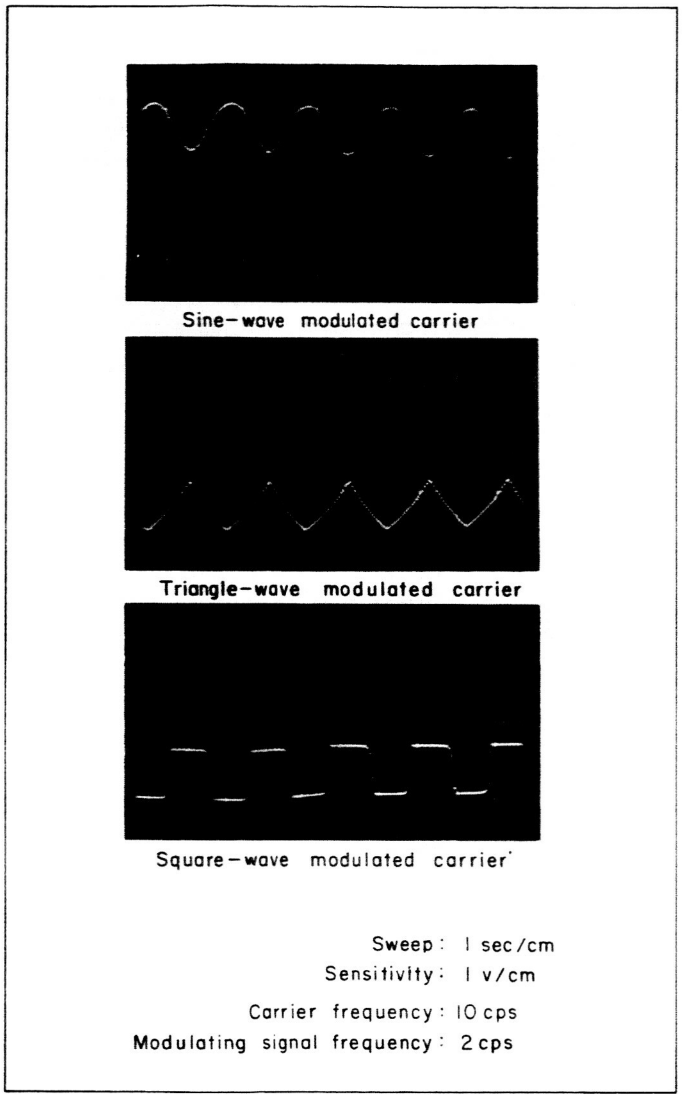


Fig. 19. Boxcar discriminator response to various modulating signals.

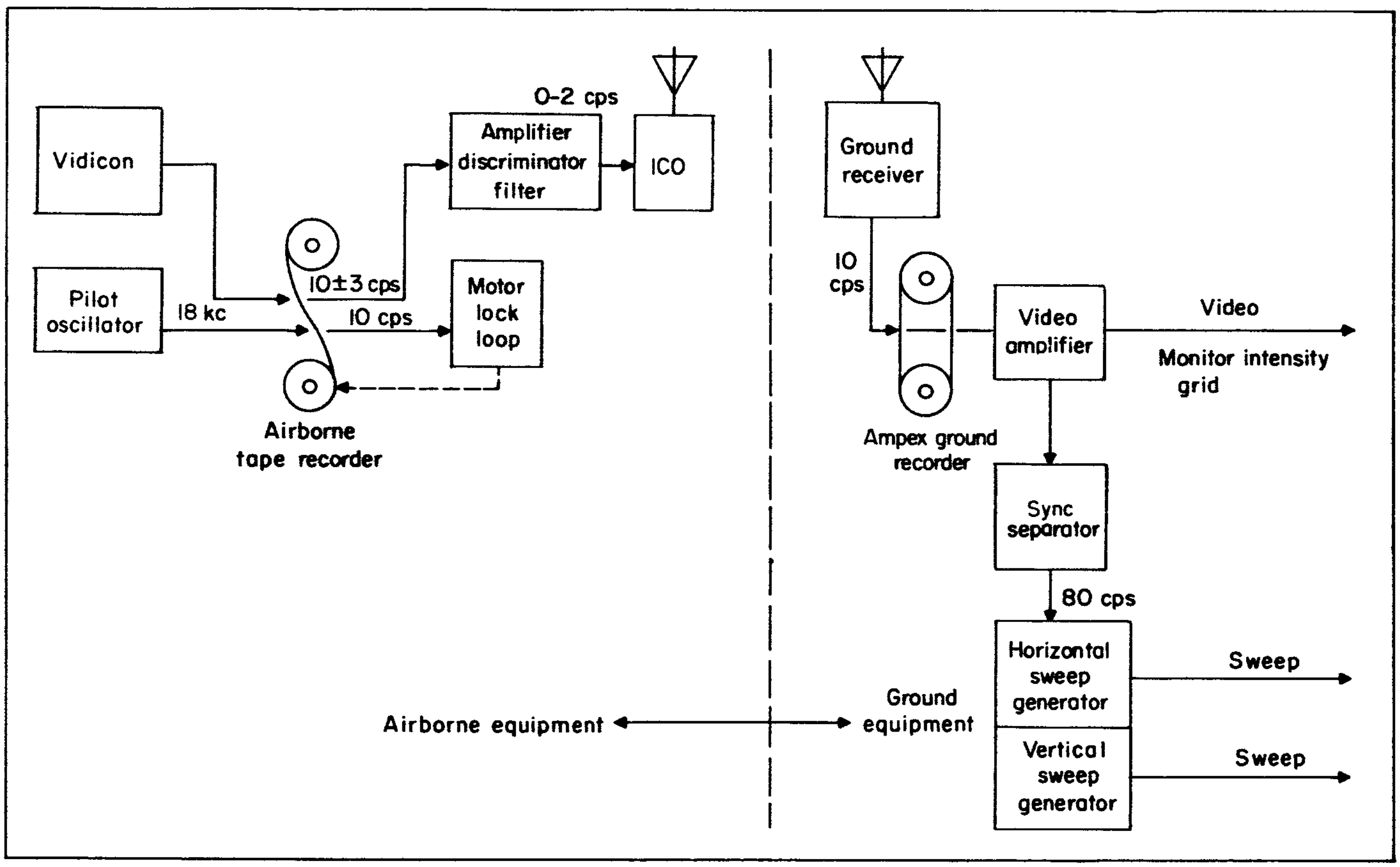


Fig. 20. Airborne recording and ground recovery systems.

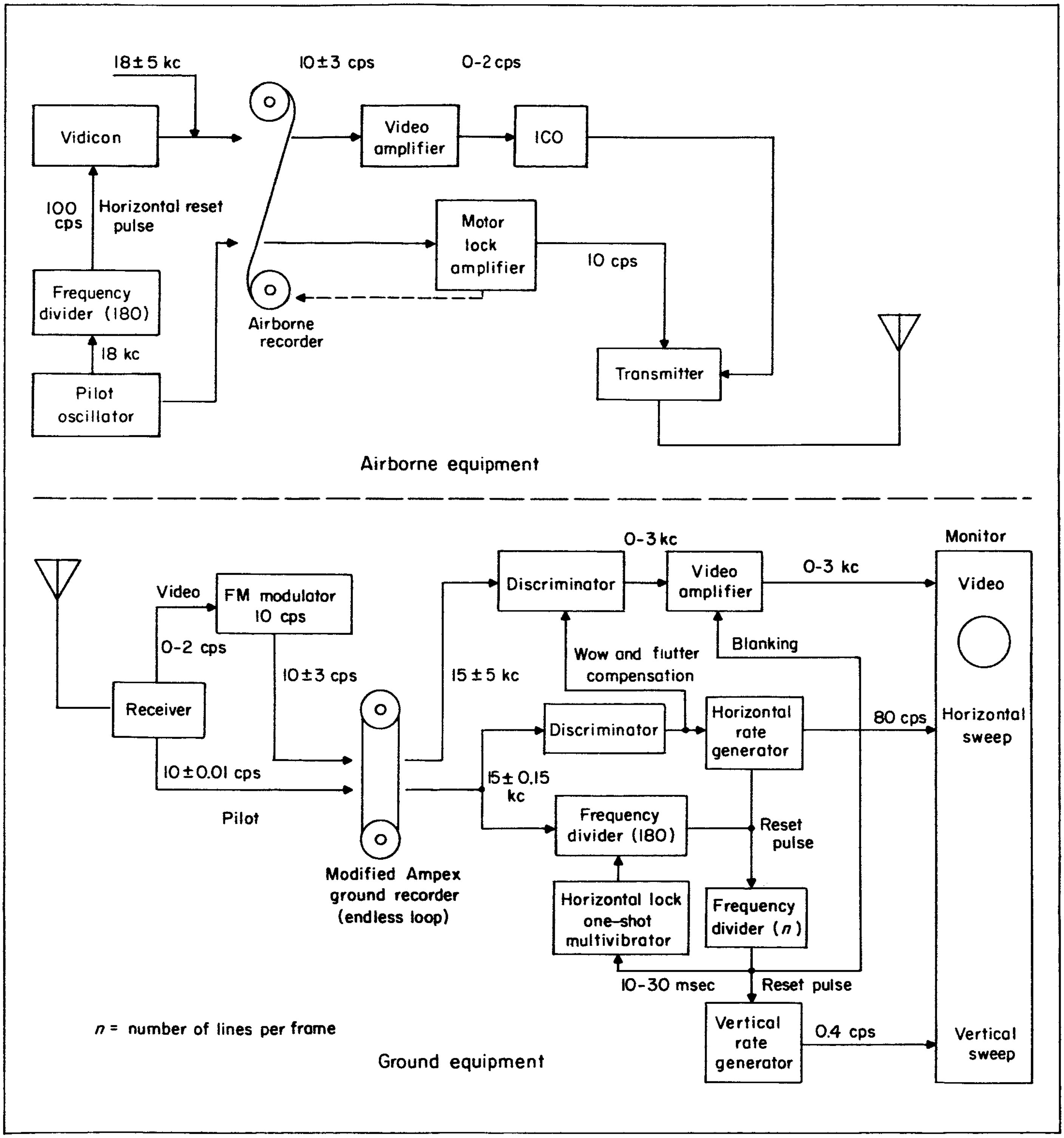


Fig. 21. Modified block diagram of airborne and ground systems.

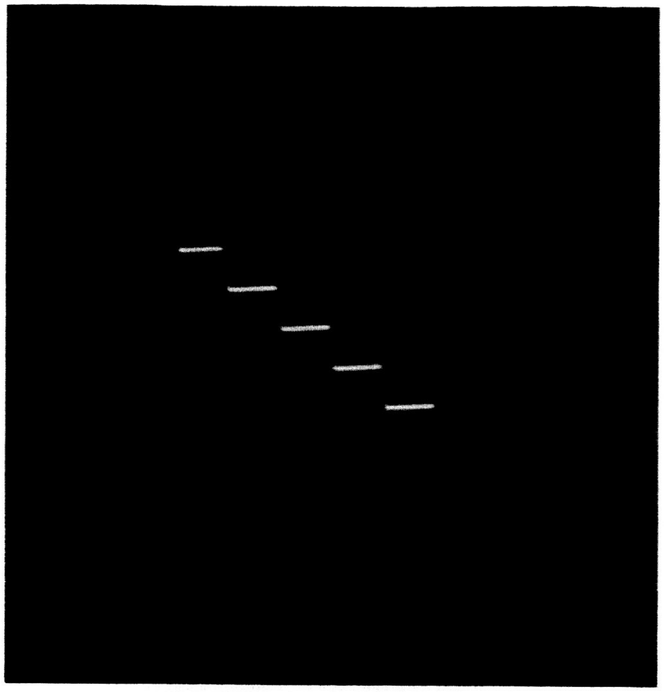


Fig. 22. Grey scale simulated video signal.

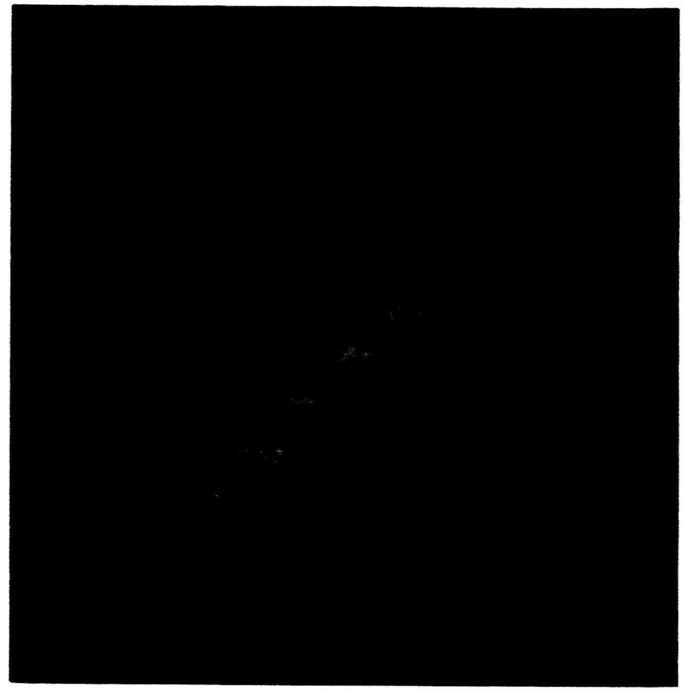


Fig. 23. Ground tape recorder output for simulated video signal.

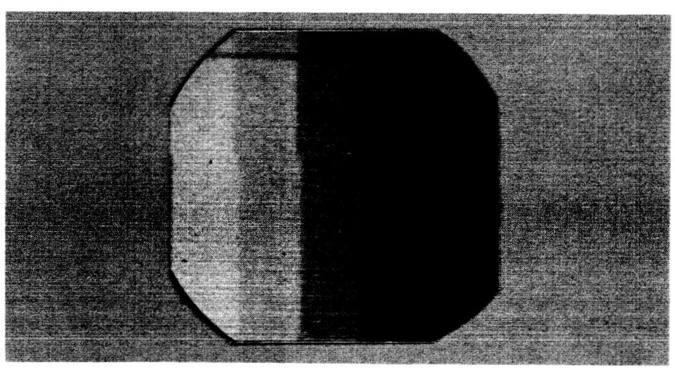


Fig. 24. Grey-scale sync pattern.

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