The characteristics of the vidicon cameras used in the DODGE satellite and the electronic system used for information processing are presented. Considerations that affect the electronic and mechanical design philosophy are emphasized. The article concludes with a discussion of results obtained on a test monitor facility.

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DESIGN and PERFORMANCE of the DODGE CAMERAS

Remote sensing from a stationary satellite platform can be a very powerful observational tool. Aside from the direct measurement of satellite attitude, the DODGE cameras are capable of providing valuable information on global cloud structure and dynamics on the sunlit portion of the earth. For such meteorological observations, the camera system can be considered as an imaging photometer. To obtain some measure of the quality of the camera system and its associated ground receiving equipment, we may compare a picture taken and transmitted through the entire satellite camera system with a picture taken through the lens of a simple still camera.

Imagine the camera looking down ($-Z$ axis) at the Earth from a synchronous, equatorial orbit. The brightness distribution of the projected Earth can be described in terms of two angles θ and φ using the normal convention for spherical coordinates. The image transmission system translates the brightness distribution $B\,(\theta, \varphi)$ of a projected scene into a serial form of electrical signal (e.g., a time varying frequency difference at an antenna) for transmission from the spacecraft. The signal, upon being received on the ground, is translated again using a display device into a spatially varying brightness $B'\,(\theta, \varphi)$. A perfect image transmission system will produce an output $B'\,(\theta, \varphi)$ which exactly corresponds to the input $B\,(\theta, \varphi)$. If we write $B'\,(\theta, \varphi) = \eta\, B\,(\theta, \varphi)$, η can be loosely interpreted as a multidimensional variable whose deviations from unity provide a measure of system quality. If $\eta = \eta\,(B)$, then the output brightness is a non-linear function of the input brightness. Moreover, if η is a function of θ, or of $\frac{\partial B}{\partial \theta}$, then the system is geometrically distorted or resolution limited, respectively. A noisy system can be represented by letting η take the form of a random variable. The ultimate goal of image system design is, very simply, to make η independent of all system parameters and time.

This article will treat the design of the satellite portion of the camera system, or more specifically, the translation of $B\,(\theta, \varphi)$ into a serial analog voltage capable of modulating a transmitter.

Characteristics of the Storage Vidicon

The heart of the DODGE cameras is a one-inch-diameter vidicon tube whose photosensitive "target" is capable of storing a charge pattern corresponding to an image for very long times (many minutes). This unique quality of the tube allows a short exposure time (to establish the charge pattern), and a relatively long readout time. Figure 1 shows the essential features of the vidicon. An electron beam is formed at the cathode and is then accelerated, focused, and deflected before it impinges upon the photoconductor at the front of the tube. The voltage on the control grid provides an effective means of controlling the flow of electrons in the beam. In the DODGE cameras, this voltage is pulsed periodically to form bundles of electrons traveling toward the signal electrode. This particular mode of "beam modulation" has certain advantages over using a continuous beam. These advantages will be discussed later in the article.

The electron beam is deflected in a regular pattern to gradually scan out the entire photoconductor surface in a manner similar to reading a page from a book. The beam travels through a highly porous mesh to charge the photoconductor according to the charge pattern image stored on its surface, as explained in the previous article.

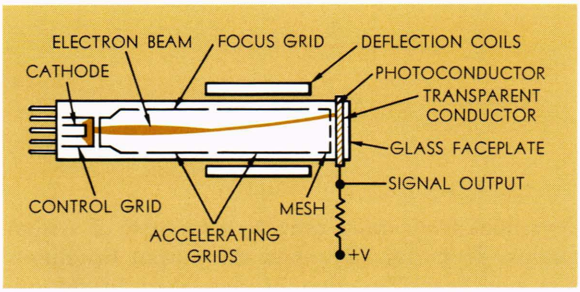

Fig. 1—Outline of a storage vidicon.

The resolution of the vidicon is limited by the finite area of the electron beam cross section and (for longer storage times) by lateral leakage of the photoconductor charge pattern. The resolution is usually measured by imaging black-and-white line patterns of varying spatial frequency (lines/inch) on the face of the tube. As the line spacings become of the same order as the beam cross section, some of the beam "spills over" onto adjacent lines and the difference between black and white levels decreases. Figure 2 shows the resolution characteristics of the DODGE vidicon. The abscissa is normalized to the "quality square" of the vidicon of 0.44 inch. The ordinate represents black-and-white differences normalized to a low frequency response. Mathematically, the contrast curve represents the Fourier transform of the cross-correlation of the beam spread function with the line pattern intensity profile.

If we designate the beam spread function by $f(x)$, and the line pattern intensity profile by $g(x)$, then the contrast curve is defined by

$$H(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} h(X)\, e^{-j\omega X}\, dX, \quad \text{where}$$

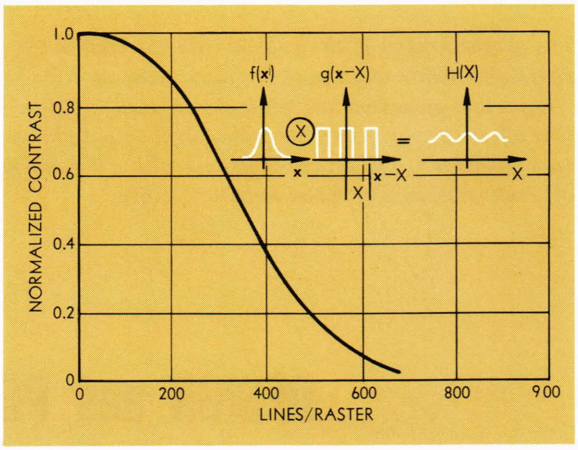

Fig. 2—Transfer function of the DODGE vidicon.

$$H(X) = \int_{-\infty}^{\infty} f(x)\ g(x-X)\ dx\ .$$

The square wave line intensity profile actually tends to accentuate the low frequency response somewhat due to the presence of higher order harmonics. For this reason, many workers prefer to use a line pattern with sinusoidally varying densities. The contrast curve is exactly analogous to the transfer function of an electronic filter. Knowing the spatial frequency components of an arbitrary input image and the tube transfer function, the output image information can be predicted. Moreover, the response can be "corrected" by computer to yield unity over all useful frequencies of the image tube.

Another tube parameter of interest is the variation of output signal with incident light level. Figure 3 shows this dependence for a typical DODGE vidicon. The amount of discharge of an element roughly the size of a beam cross section depends upon the incident light level at that point. The electron beam, upon recharging the element, will produce a corresponding signal current which can be made to flow through a load resistor. The

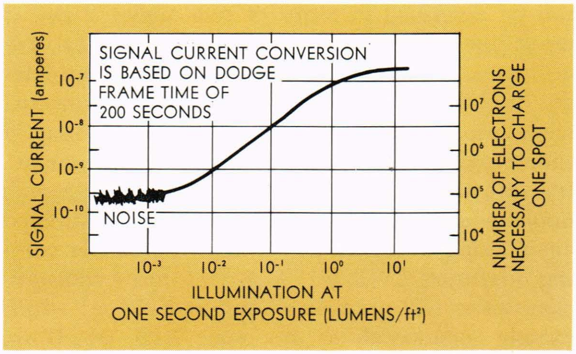

Fig. 3—DODGE signal current versus illumination.

signal current will depend upon the beam "dwell time" per resolution element, which in turn depends upon the frame time and the number of elements per frame. In the DODGE camera, the frame time is 201.3 seconds and the image is sampled 512 times in each direction. The dwell time therefore is 768 μsec. The electron beam amplitude is adjusted to fully recharge the target at maximum illuminations. Excess electrons at the lower light levels are captured by the mesh. Figure 3 indicates that the tube is fairly linear over about two decades of input illumination. Useful information is present over nearly three decades and is usually limited on the low side by thermal noise in the load resistor. The upper knee of the curve is adjusted in the DODGE cameras by use of a variable f-stop lens and neutral density filters to correspond to a brightness of 10^4 foot-lamberts, which in turn corresponds to Earth highlight brightness.

Electronics

The camera electronics extracts and arranges the image information from the tube in a manner suitable for transmission. The extraction is done by video processing circuitry in which prime consideration is given to minimizing the introduction of noise.

The principal source of noise in the cameras arises from Johnson noise in the load resistor and from noise in the first stages of amplification. The Johnson noise voltage across a resistor, R, is given by

$$e_n = \sqrt{4kTR\Delta f} \; ,$$

where k = Boltzmann constant = 1.38×10^{-23} joules deg^{-1}

T = Absolute temperature, °K

Δf = Bandwidth.

Since the vidicon is essentially a source of current, the signal-to-noise ratio is given by

$$\frac{e_s}{e_n} = \frac{i_s R}{e_n} = i_s \sqrt{\frac{R}{4kT\Delta f}} \; .$$

In practice, R is increased until stray vidicon output capacitance decreases the bandwidth Δf just to that point where only useful image information is passed; Δf is related to the dwell time Δt by

$$\Delta f = \frac{1}{2\Delta t} = \frac{1}{2\text{x}768\ \mu\text{sec}} = 650\ \text{cps} \; .$$

As mentioned previously, in the DODGE cameras the electron beam is modulated by pulsing the control grid once per dwell time. This modulation centers the video information around a carrier of 1300 cps, and removes the requirement for DC response in the preamplifier.

Figure 4 shows the modulation scheme used in DODGE. As the beam is linearly deflected (1) across the image profile (2) at a rate of about one beam width per "dwell time" Δt (768 μsec), the beam is pulsed on (3) for 40 μsec, and the corresponding signal current (4) flows through the load resistor. The image profile is thus effectively sampled by the beam spread function (5) at a series of discrete points. A capacitively coupled amplifier can now be used to raise the signal level for further processing.

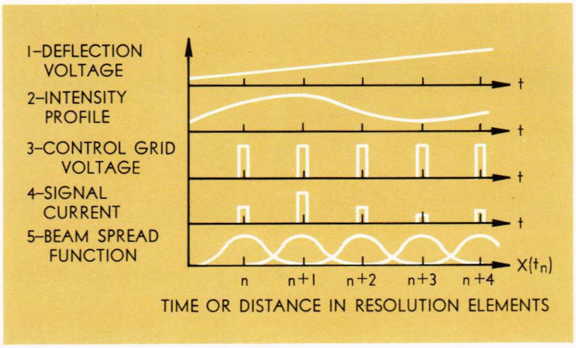

Fig. 4—Beam modulation in the DODGE cameras.

The major parts of a camera are included in Fig. 5. All timing information is derived ultimately from the 5 Mc/s satellite oscillator, including shutter pulses, sweeps, beam modulation synchronization, and camera sequencing. A satellite programmer automatically initiates a sequence of pictures at hourly intervals.

The particular parameters used in the DODGE beam modulation technique (i.e., pulse duty cycle and number of samples per resolution element) are not necessarily optimum. The noise in the video signal emanates from several sources, and the final choice of parameters must necessarily represent some compromise. The Johnson noise equation dictates a high value of R. The decision to modulate the beam, however, implies an extension of the upper cutoff frequency and thus a small R. The sampling theorem, moreover, places a lower limit on the modulation frequency. Because the tube is capable of storing some information up to about 700 lines per raster width (see Fig. 2) and the sampling takes place at 512 lines, the sampling theorem is slightly violated. In practice, however, the modulation level is down sufficiently beyond 500 lines that only an image with very strong frequency components above 500 lines would be appreciably contaminated.

The beam is modulated at a low duty cycle of

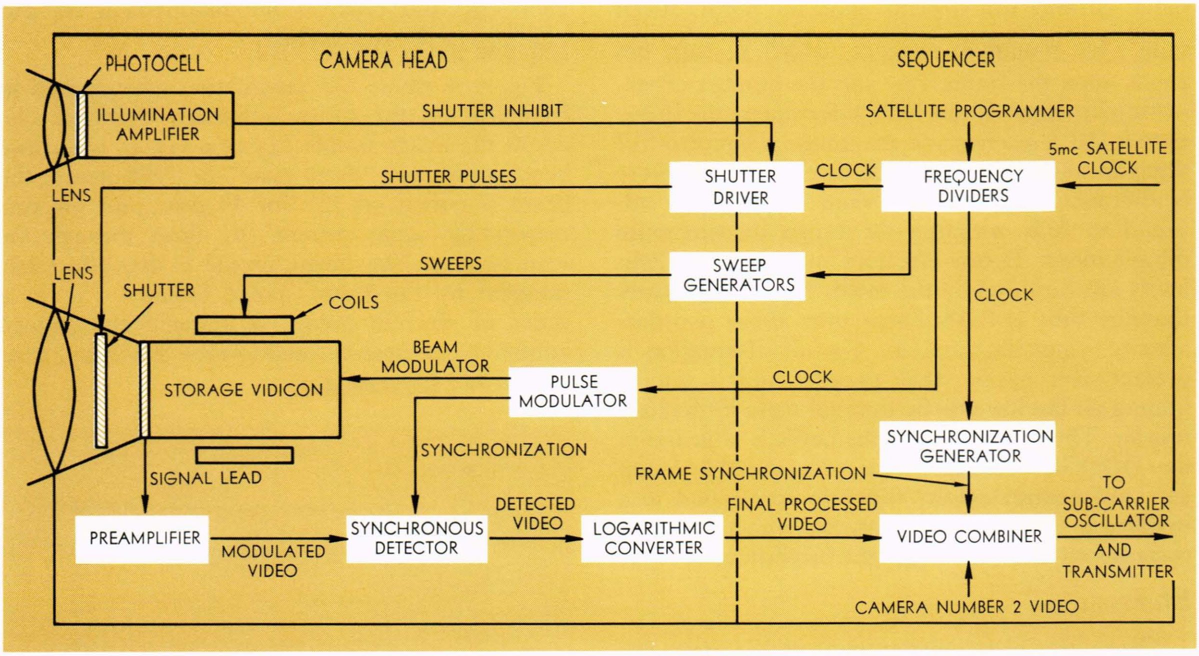

Fig. 5—Functional block diagram of camera electronics.

approximately 5 percent to reduce the noise contributions from the tube due to the statistical variations present in collected electrons. These variations can be caused by field emission or by random thermal carriers in the target itself. By grouping the electron beam into accurately controlled bundles, the amplitudes of which can be detected synchronously, this component of noise can be reduced. There is a price to be paid, of course, in terms of increased bandwidth leading to greater Johnson noise. Studies are presently underway to attempt to determine empirically the optimum modulation duty cycle.

The synchronously detected and filtered video signal is passed through a logarithmic amplifier. The function of the logarithmic amplifier is to make the output signals approximately proportional to brightness ratios, rather than to brightness directly. The eye is inclined to discern brightness steps in equal ratios rather than in equal differences. This is exactly analogous to the behavior of the ear in which differential thresholds measured in decibels tend to be independent of level. A logarithmic camera output, then, tends to have its information distributed evenly over its total dynamic range, and thus is uniformly immune to transmission noise at all levels.

From the log amplifier, the video signal from each camera is fed sequentially through a video combiner which provides proper synchronization and camera identification for interpretation at the ground station.

The cameras are protected from direct exposure to the sun by automatically inhibiting the shutter electronics when the sun is in the field of view. A simple lens coupled to a photocell and having a field of view identical with that of the camera generates the inhibit signal.

Hardware Implementation

For packaging purposes, the camera system is broken into four parts: a 22° field of view camera head, a 60° field of view camera head, a "half-book" sequencer, and a "full-book" DC/DC converter. Figure 6 is a photograph of the completed camera system. The circuits in each camera head are concerned in the main with extracting image information from the vidicon and with the subsequent processing of the video. The sequencer, on the other hand, is concerned mainly with directing the

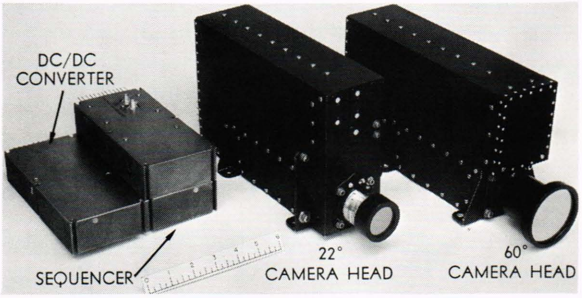

Fig. 6—DODGE camera system.

cameras through a meaningful cycle and with arranging the video information into a form interpretable by the ground station. The DC/DC converter supplies a series of voltages from 4 volts to 500 volts which allows the cameras to operate from the satellite battery voltage of +10.7 volts. The separate packages are essentially independently testable.

This independence of testing is carried one step further in the camera heads. Each camera head is composed of a vidicon housing assembly to which is attached an associated framework to house the electronics. An inner housing assembly contains a vidicon, a set of deflection coils and a mu-metal shield. The inner housing fits inside a solid aluminum block which provides the fundamental reference plane for the camera. The inner cylinder can be rotated with respect to the outer housing to accurately align a reticle pattern on the tube face. The recticle pattern allows accurate interpretation of pictures regardless of biases in the electronic scanning circuitry. Each shutter (adequately described in the following article in this issue) is mounted on the front of the outer housing and is driven by discharging a bank of capacitors through a solenoid. The capacitors are slowly recharged from the DC/DC converter between exposures. Figure 7 shows a 22° camera head assembly with cover removed. The low level video signal passes out of the tube through the shielded lead and into a shielded preamplifier. After being amplified approximately 60 db, the signal passes on to the video processor module where it is synchronously detected, passed through a third-order Butterworth filter, and then through a logarithmic amplifier. The output of the video processor appears at one of the pins on the back of the camera head. The third module in view in Fig. 7 at the rear of the camera head provides the various voltages necessary to operate the vidicon, including the proper amplification of the beam modulation pulse. One of the three shielded wires at the rear of the module carries the modulation pulse. The other two wires protect especially sensitive grids in the tube from the modulation pulse. Not visible on the other side of the camera head are a deflection amplifier module and a shutter driver module.

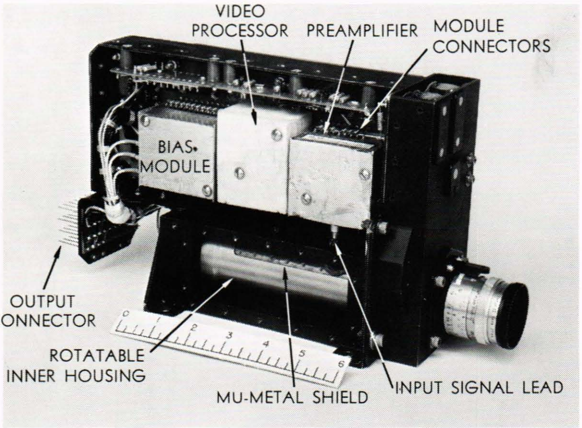

Fig. 7—60° camera head assembly with cover removed.

Each vidicon is subjected to a series of tests prior to installation in the camera head. These tests include measurements of resolution, illumination sensitivity, deflection sensitivity, and variations of beam current with control grid voltage. In addition, each tube is operated continuously at 50°C for 100 hours to expose possible manufacturing defects. Each module is tested and tailored to a particular vidicon prior to assembly. The modular construction thus minimizes the probability of having to disassemble a camera head.

Figure 8 shows an unpotted video processor module with tailored components, typical of the modular construction used throughout the camera heads. The modules use a welded cordwood construction which affords a high density package. Extensive use is made of integrated circuits, both in the camera head and in the sequencer. The module shown in Fig. 8, for instance, contains seven operational amplifiers in addition to a host of logic elements, switches, and associated components.

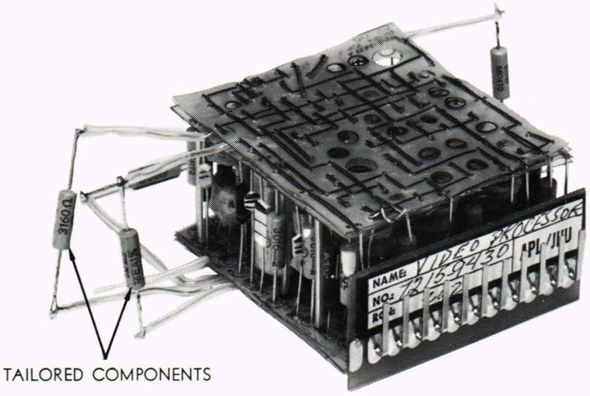

Fig. 8—Unpotted video processor module with tailored components.

System Performance

It would be misleading to imply that the DODGE camera system testing went smoothly. Several problems arose at the system level which would have been impossible to localize during earlier testing phases. Generally, the most sensitive indicator of a problem is a final photograph taken by the camera and reproduced by a monitor. Paradoxically, this is also one of the most sensitive indicators of monitor limitations. The majority of the camera evaluation is performed by imaging both camera heads on a screen upon which is projected a 35 mm transparency. The camera system is operated in a continuous mode alternately shifting from one camera to the other every 200 seconds. The combined video output from the sequencer goes directly to a monitor facility where it is displayed on a cathode ray tube (CRT). The sweeps of the cathode ray tube are synchronized to the sweeps of the camera. Figure 9 is a reproduction of a 200-second polaroid exposure of the CRT display taken with the 22° camera. The photograph is taken from a projected transparency of the Governor's Mansion at Williamsburg, Virginia. The small crosses that are visible are the calibration marks on the tube and are only two resolution elements wide. Several comments should be made about the photograph. First, it should be clear that in order to be published in the *Digest*, several steps of reproduction that do not occur in practice were necessary. These steps invariably degrade the quality of the picture. Second, the resolution of the CRT is no better than that of the cameras and thus the CRT adversely affects picture quality. Adjustment of the monitor video gain and centering is a very critical and time consuming task with a 200-second readout time. The very slightest change from the proper video windows greatly reduces the gray scale rendition in the pictures, even though all of the image information is present in the video. It also should be noted that the test facility used to evaluate the cameras exhibited limitations which will not be present in the ground station facility. The resolution capability of the ground station monitor, for example, is much better than that of the cameras.

Probably the most serious objections to the picture quality shown in Fig. 9 are the horizontal and vertical white lines running through the picture. These lines result from an imperfect digital deflection system, partly caused by the monitor and partly by the camera. The 200-second vertical sweep in the camera is generated by feeding a resistive ladder chain with binarily related inputs. If any of the binary inputs has an unequal weight compared with the average, then it will produce unequal steps at well specified points in the staircase. This will cause the vidicon electron beam to overlap more in some places than in others, leading to more signal and thus the bright lines. This is a very sensitive effect that persists in spite of efforts to precisely match the weighted binary inputs. Vertical white lines are caused by the monitor, which has digital sweeps in both horizontal and vertical directions. The actual DODGE ground station will be free from digital scan problems and presumably will be able to eliminate the horizontal white lines from the camera by proper processing.

Fig. 9—Photograph taken by TV camera system.

Producing color pictures with the 22° camera is an interesting exercise worthy of a few comments. (A thorough description of the DODGE color capability is given in the following article.) To produce a color photograph on polaroid film, the procedure described above is repeated three times, once for each of the primary colors. The final result, being a superposition of three separate frames, takes nearly 17 minutes (1000 seconds) to produce. The criticalness of adjustments, moreover, is compounded by the fact that proper color balance becomes a prime consideration, and that one inaccurate setting during a color sequence can easily cost 20 minutes. The problem of color balance in the satellite will be alleviated somewhat by the use of a color pattern painted on one of the DODGE end masses which will be in the field of view of the camera. The final color balance will be obtained by matching the colors in the end mass with a standard pattern retained on the ground.

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