A discussion is presented on the photometric and optical aspects of the DODGE TV cameras. The photometric analysis is based upon black and white plus color picture transmission. The scheme used for color picture transmission is treated in detail. Some unique problems in the camera optics are discussed.

PHOTOMETRIC and OPTICAL CONSIDERATIONS in the DODGE SATELLITE TV CAMERA DESIGN

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The DODGE satellite carries two TV cameras, one having a 60° field of view (FOV) and the other having a 22° FOV. However, the main discussion of this article will be centered around the 22° FOV camera since it possesses a color capability and is more complex. The black and white operation of the 60° FOV camera is identical to that of the 22° camera.

Both cameras use a special slow scan vidicon pickup type of the type 1339-23X supplied by General Electrodynamics Corporation. The cameras are designed to operate with a one-second exposure time as determined by a shutter. Since the 60° FOV camera is a black and white only type it uses a simple blade-type shutter. The 22° FOV camera is much more elaborate in that it uses an eight-channel color wheel, which also provides shuttering action. Three of the channels are equipped with blue, green, and red filters, one channel is left blank and the remaining four have different blue cutoff (haze or Rayleigh) filters. Figure 1 shows this shuttering-type color wheel.

The availability of color adds to the usefulness of the pictures by making it easier to identify natural objects in the field of view. Desert areas yield a characteristic reddish hue. When viewing the Earth's horizon, cloud altitude may be inferred by associating the color bands of atmospheric scatter with altitude. Auroras may also be viewed from DODGE-type altitudes.

Color Separation and Reconstruction

The approach to be used is based upon the basic principles of standard color separation techniques and color film photography. Frame sequential color information of the three basic additive primaries, i.e., red, green, and blue is transmitted to an earth bound station. A normally black and white picture-taking camera, having a storage capability as in the slow scan vidicon target, is used in conjunction with a three-color channel color wheel. A different primary color filter is introduced into the optical path of the camera for each frame. A total of

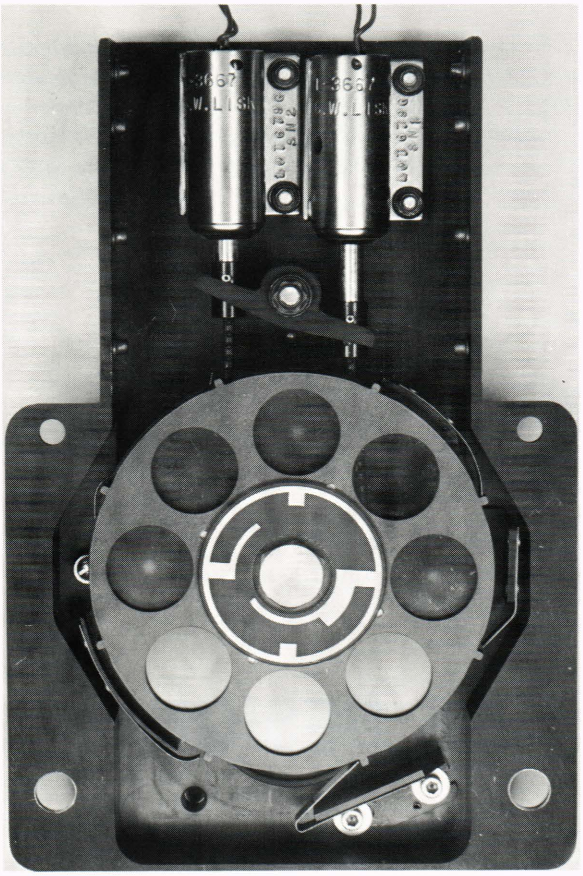

Fig. 1—Color wheel shutter.

three frames is required to yield a composite color picture. Color picture reconstruction at the ground station is accomplished by displaying the transmitted video information on a flying spot scanner system and recording the three color frames on a separate black and white film plate. The three film plates are used as color separation negatives. Standard photographic procedures apply in making a composite color reproduction. The color reproductions can take the form of a transparency or a print. The three color separation negatives are optically registered with respect to each other and indexed with a precision hole punch. The individual negatives with their corresponding color filters are then used in succession to expose a color transparency or form a color print. Figure 2 illustrates the steps involved in the color separation and picture reconstruction process.

As mentioned earlier, a storage-type pickup tube is being used. The picture-taking sequence involves exposure of the camera tube and information readout for one color channel, during which time the second color channel filter is moved into place. At the end of the first color frame readout the camera tube is re-exposed to the same scene with the new color filter in place. At the conclusion of this exposure, camera tube target readout again commences. This procedure is repeated for the third color channel. The TV camera exposure time is dependent upon the type of optics selected, available illumination levels, and required resolution. The camera readout time is determined by the tube storage capability, transmitter system bandwidth, and available transmitting power.

Satellite drift and/or libration may cause a shift of several resolution elements between the start and completion of the three-color frame sequences. This is usually not serious since the use of a color separation technique permits precise mechanical registration of the negatives to be made at the ground station to form a composite color picture.

A black and white picture can be obtained from any of the color separation frames in addition to the standard black and white channels of the color wheel.

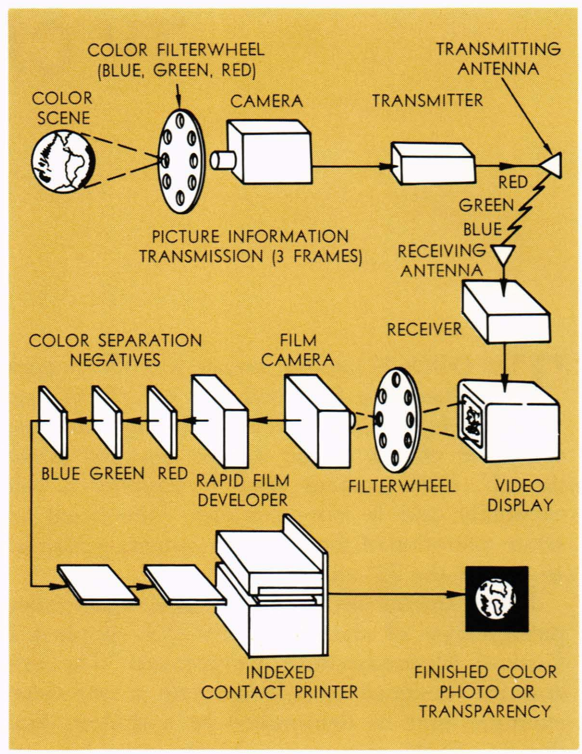

Fig. 2—Diagram illustrating color separation and reconstruction scheme.

Viewing Through the Atmosphere

The short wavelength portion of the sun's energy is scattered by the atmosphere which acts as a diffuse reflector as viewed from the space camera. Likewise, short wavelength intelligence information in the form of reflected light from the earth is scattered by the lower portion of the atmosphere. The presence of this scattering results in reduced picture contrast when viewing into or through the earth's atmosphere from space. This phenomenon, termed Rayleigh scattering, is inversely proportional to the fourth power of the wavelength, λ, of the light. In the 22° FOV camera it was decided to include various short-wavelength cutoff filters. Figure 3 illustrates the spectral characteristics of the cutoff filters selected, designated $B(\lambda)$ 90. These filters are all thin films formed on quartz substrates to withstand radiation environments encountered in a synchronous or near-synchronous orbit. Also shown in Fig. 3 are the spectral characteristics of the vidicon camera tube, $D(\lambda)$, the solar spectrum, $S(\lambda)$, and the composite effects of the various filters in combination with the vidicon, designated by the product $D(\lambda)B(\lambda)S(\lambda)$.

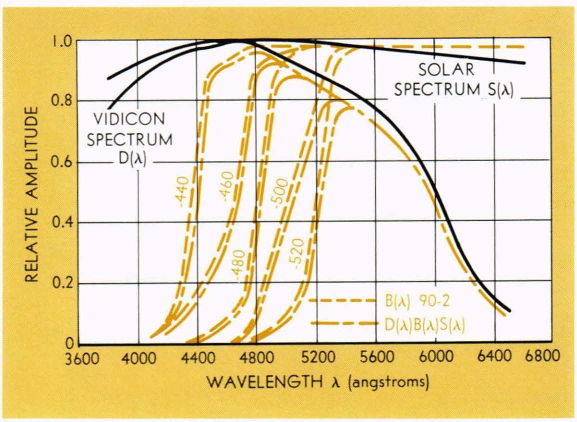

Fig. 3—Relative spectral characteristics.

Since the camera will be operating under natural lighting conditions outside the Earth's atmosphere, it is essential to relate these composite characteristics to some measurable laboratory photometric quantities to which the vidicon camera tube has an established transfer characteristic. Without the establishment of this relationship it would not be possible to determine the values of the required neutral density[1] filtering for adjustment of the operating light levels for the vidicon tube. The transfer characteristic of the vidicon is given in terms of visual photometric quantities, i.e., exposure is given in foot candle seconds with a tungsten light source operating at 2870°K. In actual usage there will be solar illumination. Therefore, some correction must be applied to retain the meaningfulness of the vidicon transfer characteristic. Mathematically, this compensation can be represented by the factor R given by

$$R = \frac{\int_0^\infty D(\lambda)S(\lambda)B(\lambda)\,d\lambda \int_0^\infty V(\lambda)W(\lambda)\,d\lambda}{\int_0^\infty V(\lambda)S(\lambda)\,d\lambda \qquad \int_0^\infty D(\lambda)W(\lambda)\,d\lambda}$$

where
$D(\lambda)$ = Vidicon spectral characteristic.
$S(\lambda)$ = Solar spectral characteristic.
$B(\lambda)$ = Rayleigh filter spectral characteristic.
$W(\lambda)$ = Tungsten light source spectral characteristic.
$V(\lambda)$ = Visual spectral characteristic which is that of the standard measuring instrumentation to which the vidicon transfer characteristic is related.

Figure 4 illustrates the spectral characteristics of the eye, tungsten, and solar illumination sources in addition to the composite characteristics of the vidicon or the eye with either solar or tungsten illumination. The integrals are obtained by taking the areas under the respective composite curves in

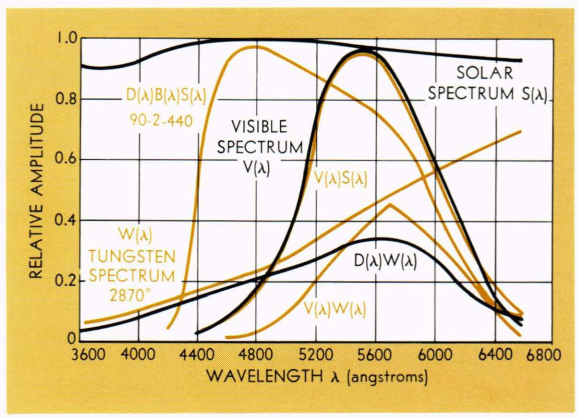

Fig. 4—Relative spectral characteristics.

TABLE I

COMPUTED VALUES FOR R FOR EACH OF THE RAYLEIGH FILTERS

Filter Type	*R Value*	*Light Flux (ft. cd.) at Filter Output*	*Neutral Filter Density*
90-2-440	1.06	424	2.627
90-2-460	0.883	353	2.548
90-2-480	0.752	301	2.479
90-2-500	0.608	243	2.386
90-2-520	0.504	202	2.305

[1] A neutral density filter is one having a flat spectral characteristic over a desired range of optical wavelength.

Figs. 3 and 4. It may be noted that the value of R will be different for each of the five black and white channels in the camera depending upon the particular Rayleigh filter. See Table I.

The light flux available at the output of the camera lens has been computed to be 400 foot candles for an earth scene highlight brightness of 10^4 foot lamberts with an f/2.5 lens. The light flux must be modified for each channel by the corresponding R value for the respective Rayleigh filter. Table I lists the light flux available at the output from each of the Rayleigh filters, for solar input illumination.

Based upon a vidicon exposure index,[2] camera exposure time and scene highlights, the required total neutral density filtering in each of the channels is given by

$$T = \frac{\text{Exposure Index}}{E_F \times \tau}$$

where T = Filter transmission
τ = Camera exposure time
E_F = Available light flux (ft. cd.) for a given Rayleigh filter.

and the optical density, D, of the neutral density filters is given by

$$D = \log \frac{1}{T}.$$

Table I also lists the required neutral density filters for each of the black and white channels of the camera for a one foot-candle-second exposure index and a one-second exposure time.

Color Equalization

To reproduce a quality color picture having good color rendition and a capability of yielding white tones, it is essential that some form of equalization of the three color channels be accomplished. This color equalization is performed by optical means right at the camera by the addition of the appropriate neutral density filters in the blue and green channels. These neutral density filters are in the form of a thin film nickel-chromium deposit on a high purity quartz substrate.

To obtain the response of the camera system relative to each of the spectral bands as defined for the primary color separations it is essential to consider the spectral characteristics of the vidicon camera tube $D(\lambda)$, the primary color filters $F_1(\lambda)$, $F_2(\lambda)$, and $F_3(\lambda)$, the Rayleigh cutoff filter $B(\lambda)$, and the solar spectrum $S(\lambda)$. The maintenance of the three color system places some limitation on the degree of blue energy rejection by the Rayleigh cutoff filter. In the DODGE 22° FOV camera a cutoff at 4400 Å was arbitrarily selected.

It may be readily observed from Fig. 5, that the available energy as represented by the respective areas under the curves for each of the color channels is different for each channel. Integration of the areas under the respective composite curves for each of the three color channels yields a basis

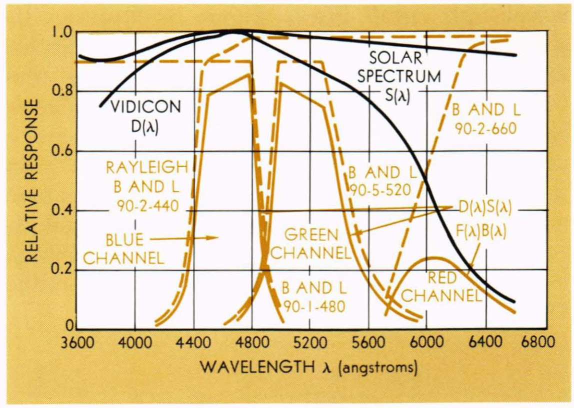

Fig. 5—Color channel spectral characteristics.

for color-equalization. Table II lists the neutral density equalization filters which must be applied to the different color channels for equal signal output from the camera.

TABLE II

NEUTRAL DENSITY EQUALIZATION FILTERS

Channel	*Filter Transmission*	*Filter Density*
Blue	0.352	0.453
Green	0.307	0.512
Red	1.0	0.0

As in the Rayleigh filter computations, an R value is established for the color channels. Since the color channels have already been equalized, the same "R" value will govern all three channels. Using the red channel as a base, the color "R" value is computed to be 0.105. The Bausch and Lomb filter type 90-2-440 which has a 4400 Å cutoff has been selected for use with all three color channels. Therefore, a combined (RR) value of 0.111 is used for the color system. Based on a one foot-candle-second vidicon exposure index and a one-second exposure time, a reduction by a factor of 44 in light flux is required. This means a neutral density filter of optical density of 1.642. A filter having a density of 1.0 is located in the camera view port on the satellite skin. The additional filter of 0.64 is located in the lens hood. Since these neutral filters of optical density are common to all color and black and white channels alike, 1.642

[2] Exposure index may be defined as the product of camera illumination and exposure time. The units are foot-candle-seconds.

can be subtracted from the neutral density values listed in Table I to yield the desired filter value to be coupled with each of the Rayleigh filters.

Optics

The selection of a lens for a particular camera application is governed by several parameters, i.e., the sensor or camera tube usable format, the desired field of view, resolution, weight, ruggedization, etc. Reflective optics or catadioptric optics may be very desirable for weight and size reduction in long focal length systems. Since both DODGE TV cameras require the use of a relatively short focal length optics, refractive optics were used. It is intended in the following paragraphs to bring out some of the more subtle points which can have an appreciable affect upon the camera.

Effects of Plane Parallel Refractors

In the DODGE TV cameras it is necessary to provide protective covers over the optical filters. A high purity quartz cover plate is used for protection against radiation damage. The front surface of the cover plate is used for the vacuum deposition of a thin film neutral density filter for light level attenuation. Likewise, a Rayleigh (haze) filter is placed in front of the lens in both the 60° FOV camera and 22° FOV camera. The 22° FOV camera, in addition, has quartz filters inserted between the lens and the vidicon pickup tube. All of these elements are plane parallel refractors and have a definite affect on the operation of the overall camera system.

If the protective cover plates and neutral density filters were lumped into one, it is possible to arrive at an overall refractor thickness of 0.4 inch. A skew ray at an angle of 11° would experience a path deviation of 0.026 inch. The effect of this path deviation appears as an effective change in the angular field of view.

Placement of a refractor of this type between the lens and the image plane would cause a similar ray path deviation, d, of a skew ray at an angle, α, but more significant would be the change δ, in the effective back focal length of the lens. This is illustrated in Fig. 6. In the case of the color TV camera, the color wheel is placed between the lens and image plane. The quartz filters in this color wheel have a thickness of 0.1 inch. The shift, δ, in effective back focal length due to the color wheel is about 0.034 inch for a typical lens. Usually the lens is set to infinity focus for distant objects. However, the shift in the focal plane due to a plane parallel refractor requires the lens to be focused for an object at a much closer distance. This may be at several feet rather than at infinity, depending upon the lens.

Camera Calibration

The photometric calibration of the DODGE TV cameras is a straightforward procedure using a standard tungsten filament lamp operating at a black body color temperature of 2870°K. The incident light flux on the camera is measured using a standard foot-candle meter. As a further check

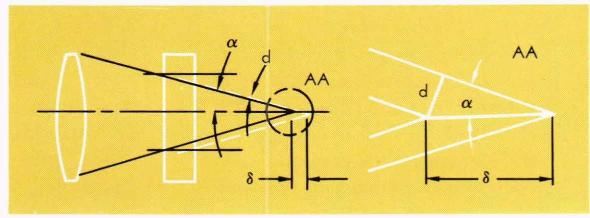

Fig. 6—Sketch showing effects of a plane parallel refractor.

on operation in a naturally lighted environment, the cameras are operated outdoors where cloud brightness can be measured and used as a reference.

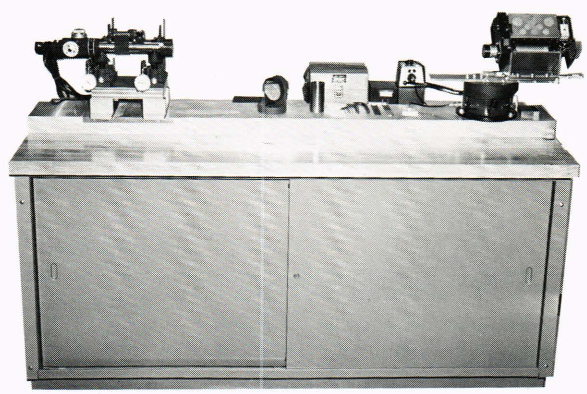

Fig. 7—Optical calibration equipment.

The geometrical calibration of the cameras to establish the precise angular displacement of each of the reticle markings on the face of the vidicon pickup tube with respect to an established optical axis is more involved. Figure 7 shows the optical arrangement used to perform the alignment and calibration. The alignment telescope-autocollimator and optical rotary table shown have a direct readout capability of one second of arc. The DODGE TV cameras were calibrated to an optical axis perpendicular to a plane defined by the front surface of the camera housing and parallel to a plane determined by the precision ground mounting feet on the camera housing. The 22° FOV camera is calibrated to an accuracy of 0.05° and the 60° FOV camera is calibrated to 0.1°. The limiting factor in the camera calibrations is the electronic resolution that was selected as 512 elements per line in the digital sweep generator.