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DESIGN AND EVALUATION OF A FILTER SPECTROMETER CONCEPT FOR FACSIMILE CAMERAS

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16. Abstract

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SUMMARY

The facsimile camera is an optical-mechanical scanning device which has been selected as the imaging system for the Viking '75 lander missions to Mars. A concept which uses an interference filter-photosensor array to integrate a spectrometric capability with the basic imagery function of this camera has been proposed for possible application to future missions. This paper is concerned with the design and evaluation of critical electronic circuits and components that are required to implement this concept. The feasibility of obtaining spectroradiometric data is demonstrated, and the performance of a laboratory model is described in terms of spectral range, angular and spectral resolution, and noise-equivalent radiance.

INTRODUCTION

The facsimile camera has been selected to provide imagery data for the Viking '75 lander missions to Mars (ref. 1), primarily for reasons of size, weight, power, and radiometric and photogrammatic accuracy. The Viking facsimile cameras use silicon photodiode detectors and, in addition to black and white imagery, have the ability to image in six spectral channels over the silicon-response range from 0.4 to 1.0 μm. Reference 2 proposed a filter-photodiode array concept in order to increase spectral resolution and, hence, augment the facsimile camera with a spectrometric capability. This technique utilizes individual interference filters positioned over elements of a photodiode array which, in turn, is alined along the line of the camera scanning mirror. Any picture element (pixel) in the scene can be electronically sampled on command as it is scanned along the array; thus a spectral signature of that pixel is provided. This approach utilizes the existing scanning mirror servosystem of the facsimile camera and, therefore, offers mechanical simplicity over the commonly used rotating wedge filter. (See refs. 3 and 4.)

Reference 5 predicted the potential performance capabilities and constraints of this concept using silicon and lead sulfide detectors to cover the spectral range from 0.4 to 2.7 μm. The performance trade-offs between spectral and spatial resolution, spectral range, and sensitivity were defined, and performance predictions were made for the Viking camera design parameters and the Martian environment. This paper presents the design and evaluation of a laboratory model of this concept. The model uses a silicon photodiode array to provide 29 spectral channels over the spectral range from 0.53 to 0.96 μm. The performance of this laboratory model is described in terms of angular and spectral resolution and noise-equivalent radiance to verify performance predictions and to define system performance limits.

SYMBOLS

A	detector area, m^2
C_f	feedback capacitance, F
D	lens diameter, m
f	frequency, Hz
H_λ	spectral irradiance, $\frac{W}{m^2\text{-}\mu m}$
I_{dc}	photodiode dark current, A
I_N	root mean square (rms) noise current, A
i_{jn}	rms Johnson noise current, A
i_{sn}	rms shot noise current, A
K_m	filter-detector calibration constant, A/W
k	Boltzmann's constant
N_λ	spectral radiance, $\frac{W}{m^2\text{-}\mu m\text{-}sr}$
NER	noise equivalent radiance, $\frac{W}{m^2\text{-}sr}$

n	number of samples
q	electronic charge, C
R_f	feedback resistance, Ω
R_λ	spectral responsivity of detector, $\frac{A}{W\text{-}\mu m}$
S/N	average ratio of signal to rms noise
S_λ	solar irradiance above atmosphere, $\frac{W}{m^2\text{-}\mu m}$
T	absolute temperature, K
V	voltage, V
β	angular resolution, rad
Δf	bandwidth
λ	wavelength, μm
ρ_λ	spectral reflectivity of surface (normal albedo)
τ_f	peak transmissivity of optical filter
τ_λ	spectral transmissivity of atmosphere
$\tau_{\lambda,f}$	spectral transmissivity of optical filters
$\tau_{\lambda,l}$	spectral transmissivity of optics
ϕ	illumination scattering function

DESIGN

This section presents the electronic design for the integrated imagery and spectrometry concept and an analysis of the expected spectrometry performance.

Concept

The basic operation of a facsimile camera as imager and spectrometer is illustrated in figures 1(a) and 1(b), respectively. (See also ref. 6.)

The imagery function is accomplished as follows: radiation from the scene is reflected by the scanning mirror, captured by the objective lens, and projected onto a plane which contains the photosensor aperture. The radiation falling on the aperture is converted into an electrical signal which is amplified and sampled for data transmission. As the mirror rotates, the imaged scene moves past the aperture and permits the aperture to scan vertical strips (elevation scan). The entire camera is rotated slowly in azimuth until the complete scene of interest is scanned.

A spectrometer capability can be added to the facsimile camera, as shown in figure 1(b), by placing an array of photodetectors, in addition to the imaging detector, in the aperture plane alined along the direction of image motion. Individual narrow-band interference filters mounted over the separate photodetectors allow a pixel to be spectrally resolved as it moves down the filter-detector array. Electronic pulses derived from the servo which controls the scanning mirror position are used to provide proper synchronization for multiplexing the detector array outputs.

Pixel Selection and Tracking

The general operation of the facsimile camera-spectrometer is based on first obtaining an image of the scene and then selecting particular pixels in the image for spectral investigation, one pixel at a time. The azimuth coordinate for the selected pixel is determined from the camera azimuth position information. (The Viking lander cameras, described in ref. 7, transmit this information every line scan.) This digital coordinate then defines the azimuth location of the selected image pixel relative to the imaging detector, which may or may not be positioned along the filter-detector array.

The vertical coordinate of the pixel of interest is determined from the imagery data by counting the image elements along the scan line. The absolute vertical position, relative to the imaging detector, is determined as a function of the imaging data sample pulses, provided that the imaging detector and the first element of the filter-detector array are properly spaced at a multiple interval of a pixel. More specifically, if the spacing corresponds to a mirror rotation angle which is an integral number of encoder bits, then the encoder output can be counted to the predetermined value at which the spectrometry data acquisition is to be initiated.

The implementation of this technique is shown in figure 2. Information on both vertical and azimuth position is compared with the selected pixel position information. When the image of the selected pixel reaches the first spectral channel, a binary counter is enabled. Pulses are then counted to address the proper channel of the multiplexer to sequence down the filter-detector array in synchronism with the motion of the selected pixel.

As noted in reference 5, equal spacing of detector elements results in a pixel tracking error since the axis of mirror rotation and the principal point of the lens are displaced. This pixel tracking error can be eliminated by altering the video sampling pulse train from a constant interval to a variable interval or by varying the spacing between detectors. This latter approach should not require a complex fabrication procedure, because a photomask technique is generally used to define detector array geometry. The electronic solution offers more flexibility if camera geometry is not fixed.

Generation of Video Data

Each of the successively sampled photodiodes generates a photocurrent proportional to the incident radiant flux. This photocurrent develops a voltage across the feedback resistor of an operational amplifier; this voltage is then applied to the input of the multiplexer. As the imaged scene moves down the filter-detector array, the proper multiplexer switch is closed to apply the voltage output of the desired channel to the buffer amplifier as shown in figure 3. The final summing amplifier provides signal amplification prior to digitization.

The important characteristics of the photodiode and preamplifier have been presented in reference 8. Both the photodiode and preamplifier should have low leakage currents, and the preamplifier feedback capacitance should be minimized; thus the largest feedback resistance for a given bandwidth application is allowed. To obtain the highest possible signal-noise ratios necessitates preamplification prior to multiplexing. This otherwise undesirable complexity avoids two problems. First, the leakage current of the field effect transistor (FET) switch in the multiplexer is of the order of the signal current and a large offset would be produced. Second, the gate-source capacitance of the FET switch allows switching transients to couple into the video signal and subsequent amplification would result in amplifier saturation. In the electronic design presented here, some transients of reduced amplitude are present; however, a timing delay is provided to allow these transients to diminish before data is sampled for digitization.

The technique used for acquiring spectral information and calibration includes the following steps: First, the output produced by the dark current in each channel is sampled, either while the vertical scanning mirror is turned toward the darkened interior of the camera or, as in the Viking lander cameras, while a flag is inserted into the optical path. This dark sample of each channel is stored in the camera-spectrometer for subsequent subtraction from the calibration and spectral data to remove offsets. Next, the spectrometer is directed to scan a calibration target of known spectral reflectance mounted on the lander, for example, and the information is stored. Finally, the selected pixel is scanned and the data are stored.

Data processing consists of subtracting the stored value of dark current offset from each channel and, if desired, a commandable offset may also be subtracted to better utilize the encoding range. Data taken from the calibration target may be transmitted in addition to the raw spectral data or used for onboard normalization of the raw data prior to transmission.

Sensitivity

Since one objective of the spectrometer concept is not to interfere with the imaging mode, many major camera design variables will be determined chiefly by the imaging requirements. Consequently, the spectrometric capability can be optimized primarily by concentrating design efforts on the detector-preamplifier signal-noise ratio and optimization of filter characteristics.

A performance trade-off analysis of the filter-detector array concept, which has been presented in reference 5, accounts for signal-noise ratio, angular resolution, and spectral range. The signal-noise ratio for any channel in the facsimile camera-spectrometer configuration is given by

$$\frac{S}{N} = \frac{\pi\beta^2 D^2 \sqrt{n}}{16 I_N} \int_0^\infty N_\lambda \tau_{\lambda,l} \tau_{\lambda,f} R_\lambda \, d\lambda \tag{1}$$

where N_λ is the spectral radiance of the object.

The camera performance and design parameters are the ratio of signal to rms noise S/N, instantaneous field of view or angular resolution β, the objective lens diameter D, the lens transmittance $\tau_{\lambda,l}$, the filter transmittance $\tau_{\lambda,f}$, the photosensor spectral responsivity R_λ, the system noise current I_N, and the number of repeated samples n. The lens diameter is determined by the angular resolution and the depth of field requirement for the imagery mode. (See refs. 5 and 6.) The number of repeated samples is determined by the time available to acquire information on each pixel.

A related performance parameter is the noise-equivalent radiance (NER)

$$\text{NER} = \frac{N}{S} \int_0^\infty N_\lambda \, d\lambda \approx \frac{I_N}{\left(\frac{\pi}{4}\right)^2 \beta^2 D^2 \sqrt{n} \int_0^\infty \tau_{\lambda,l} \tau_{\lambda,f} R_\lambda \, d\lambda} \tag{2}$$

The approximation assumes narrow band filtering and provides a more convenient measure of instrument sensitivity because it is independent of the scene spectral radiance.

An analysis of system noise in reference 5 has shown that two noise sources are dominant: shot noise and Johnson noise. Shot noise is generated by the leakage currents of the photodiode and the field effect transistor (FET) amplifier input according to

$$i_{sn} = \left(2qI_{dc}\Delta f\right)^{1/2} \tag{3}$$

where I_{dc} is the leakage current. The small area photodiodes necessary for the spectrometer-detector array have leakage currents on the order of 10 pA and thus are low noise devices. Input leakage currents of a few picoamperes are attainable for the preamplifier; therefore the preamplifier does not contribute significantly to the system noise. The feedback resistor generates Johnson noise

$$i_{jn} = \left(\frac{4kT\Delta f}{R_f}\right)^{1/2} \tag{4}$$

which may become significant since the preamplifier bandwidth is also a function of R_f. For bandwidths on the order of 20 Hz (which corresponds to the slow-scan rate of the Viking lander camera), a feedback resistance of 1 GΩ can be used with the resulting Johnson noise dominating the photodiode shot noise by a factor of approximately two.

The filter-detector array is fabricated by dicing the interference filters to the desired size, mounting them over the detector elements, and positioning an array of apertures over the filter elements to reduce the possibility of optical crosstalk. This procedure allows pretesting and selection of optimum filters for each channel prior to mounting so that, for example, regions of poor detector spectral response can be compensated for by increasing the spectral bandwidth. Also, the position along the detector array of each spectral filter can be altered according to the off-axis performance of the optics.

EXPERIMENTAL EVALUATION

This section presents the evaluation of an experimental laboratory model facsimile camera-spectrometer which was fabricated to demonstrate the feasibility of the technique and to determine performance characteristics.

Laboratory Model

The laboratory model facsimile camera-spectrometer is illustrated in figure 4 and its characteristics are listed in table I. General design considerations were based on the analysis performed in reference 3, which resulted in 29 spectral channels, each consisting of an interference filter-silicon photodiode. The spectral resolution is approximately

0.025 μm; the spectral range is 0.53 to 0.96 μm; and the angular resolution is 0.2°. The remaining performance parameter is signal-noise ratio or noise-equivalent radiance.

TABLE I. - LABORATORY MODEL CHARACTERISTICS

Angular resolution, deg	0.2
Spectral channels	29
Spectral range, μm	0.53 to 0.96
Half-power spectral bandwidth (typical), μm	0.025
Peak transmission of interference filters (typical)	0.60
Lens aperture, cm	1
Lens focal length, cm	7.5
Lens transmission	0.92
Angle off axis of extreme detector, deg	5.1
Mirror position information	14-bit optical shaft encoder
Photodiode leakage current, pA	3
Preamplifier	Teledyne model 2740
Feedback resistance, GΩ	0.5
Multiplexer	Siliconix DG-125
Detector-preamplifier bandwidth, Hz	70

An optical shaft encoder is used to monitor the vertical mirror position to provide servo information similar to that of the Viking lander cameras. The selection of the vertical location of a particular imaging pixel is performed with switch inputs to the vertical comparator.

A linear photodiode array with equally spaced elements, shown in figure 5, was used with a predictable pixel tracking error of approximately one pixel at each end of the array. Each spectral filter was designed for 0.025-μm half-power bandwidth; as a result, the performance in each channel was not optimized by the selection of specific filter characteristics.

Detector Preamplifier

Dark leakage currents of 3 pA obtained from the manufacturer's data on the photodiode array result in calculated detectivity values of 17 $\mathrm{Gm\text{-}Hz^{1/2}/W}$, a factor of approximately three higher than the values assumed in analytical predictions of system performance. (See ref. 3.) A feedback resistance of 0.5 GΩ was used to provide low Johnson noise, but allowed a bandwidth of approximately 70 Hz. This bandwidth is sufficiently wide for the present Viking slow scan rate and thus requires no change in servomechanical design. This feedback resistance yields a Johnson noise current of approximately 5 $fA/Hz^{1/2}$, about five times the contribution of the photodiode shot noise. The system's rms noise voltage was measured over the entire video bandwidth and agreed with the calculated value where Johnson noise was used as the dominant source.

Acquisition of Spectral Data

In order to evaluate the performance in each spectral channel and to account for differences in filter transmission characteristics and detector spectral response, a calibration factor was determined for each spectral channel. The entire array was illuminated with a calibrated National Bureau of Standards (NBS) tungsten lamp, and the output signal voltage for each element is given by

$$V = AR_f \int_0^\infty H_\lambda \tau_{\lambda,f} R_\lambda \, d\lambda \approx AR_f K_m \int_0^\infty H_\lambda \, d\lambda \tag{5}$$

where K_m is the calibration factor corresponding to the narrow band filter-detector response

$$K_m = \int_0^\infty \tau_{\lambda,f} R_\lambda \, d\lambda \tag{6}$$

The calibration factor K_m agrees with anticipated values based on the spectral response of silicon and the manufacturer's filter characteristics.

To test the facsimile camera-spectrometer under operating conditions, a test target of known reflectance illuminated with the NBS lamp was scanned a single time with the spectrometer. The signal-noise ratio expression was used to predict the signal voltage in each channel for comparison with the experimental results; this was done in order to test the ability of the spectrometer to obtain absolute radiometric data under conditions of known illumination. Predicted values of voltage output, calculated with the respective values of K_m for each channel, are shown in figure 6 along with measured data. Two channels (at 0.75 and 0.94 μm) showed less agreement with predicted values, and examination revealed that noise was introduced by switching transients, which were due to the arrangement of circuit components. In all other cases, measured values agreed with calculated values to within 11 percent.

Spectroradiometric Performance

Calculated values of noise-equivalent radiance are plotted in figure 7 for a single scan of the laboratory model by using the system characteristics listed in table I and the values of the calibration constant K_m for the filter-detector response in each channel. Variations in filter characteristics and the wavelength dependence of the detector response account for the different NER values in each channel, which range in value from 6 to 12 $\frac{nW}{m^2\text{-sr}}$. The sensitivity of the laboratory model is a factor of approximately two lower than that predicted in reference 3. The lower sensitivity results from the Johnson noise contribution to the system noise current. Performance in all channels can be improved by broadening spatial resolution, increasing the number of samples, or decreasing the video bandwidth requirement.

CONCLUDING REMARKS

This paper has presented the electronic design of a technique which utilizes interference filters and a solid-state photodiode array to integrate a spectrometry capability with the basic imagery function of facsimile cameras. The electronic design for selecting and tracking a picture element was described along with the technique for acquiring and processing spectral data. The design was implemented and evaluated in a laboratory model facsimile camera by using a silicon photodiode array with 29 spectral channels covering the range from 0.53 to 0.96 μm.

Spectroradiometric data were acquired from a calibration target, and results showed good agreement with predicted values. The angular resolution of the laboratory model was 0.2° and the spectral resolution was approximately 0.025 μm. For a lens aperture diameter of 1.0 cm, the resulting NER (noise equivalent radiance) ranged from 6 to 12 $\frac{nW}{m^2\text{-sr}}$, depending on variations of silicon response with wavelength and filter transmission characteristics.

It must be noted that the sensitivity of the laboratory model as presented here does not represent any particular limitation of the performance capability of the facsimile camera-spectrometer concept. Instead, it confirms a specific result for the trade-offs (spatial and spectral resolution, spectral range, and signal-noise ratio) which must be made for any specific application of this concept.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., June 20, 1974.

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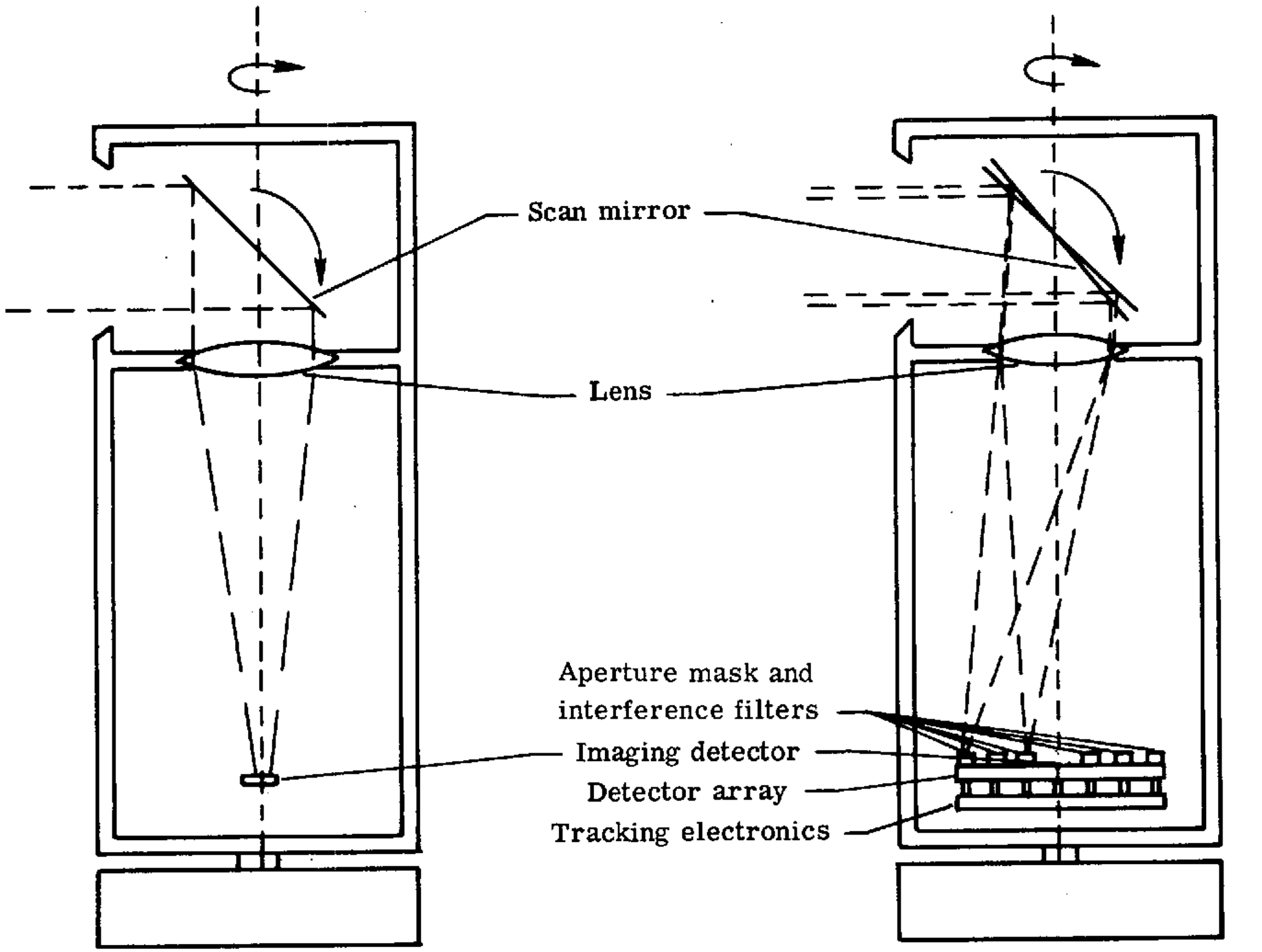


(a) Imager.

(b) Imager and spectrometer.

Figure 1.- A basic configuration of the facsimile camera as an imager and a spectrometer.

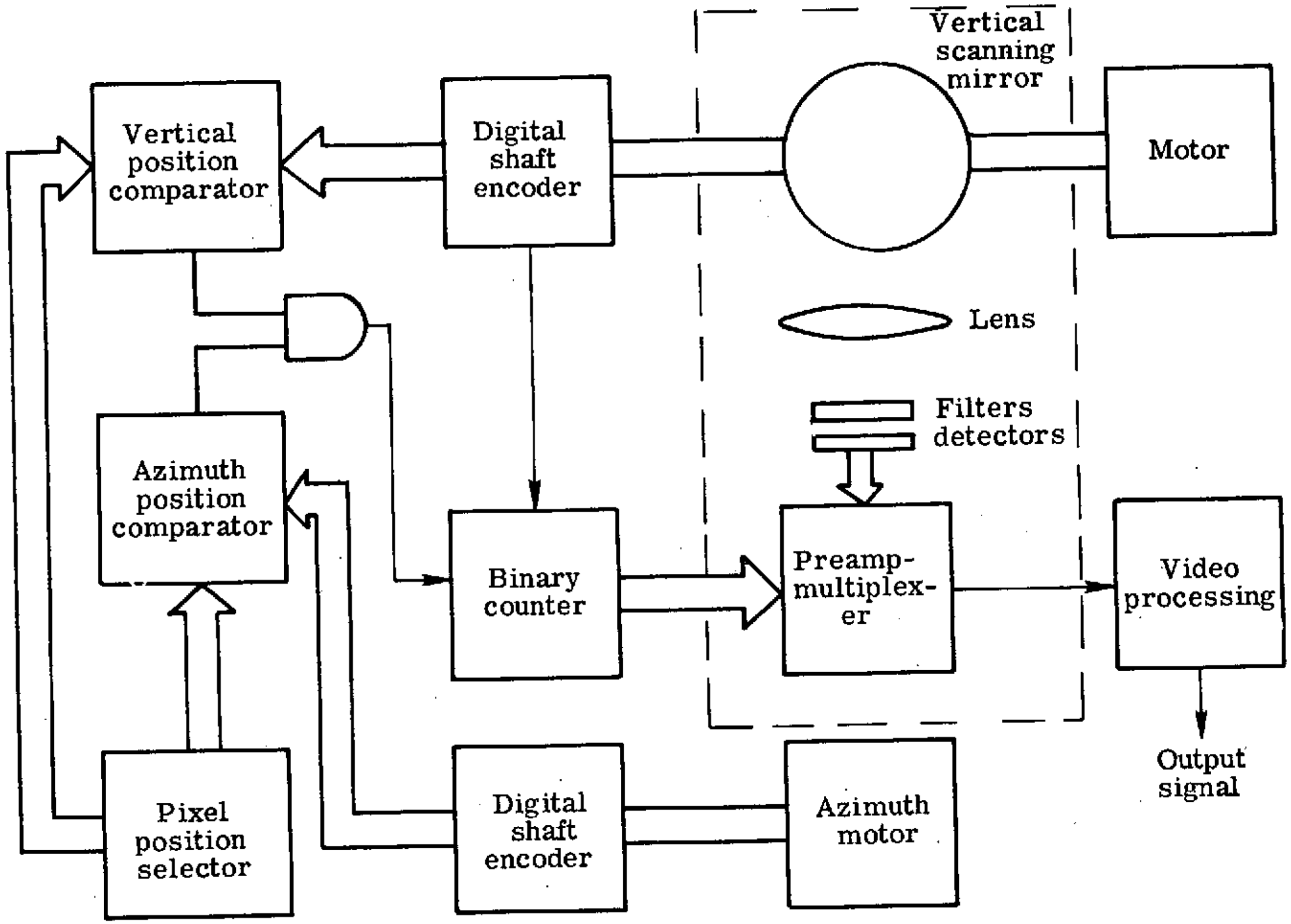


Figure 2.- Block diagram of pixel tracking electronics.

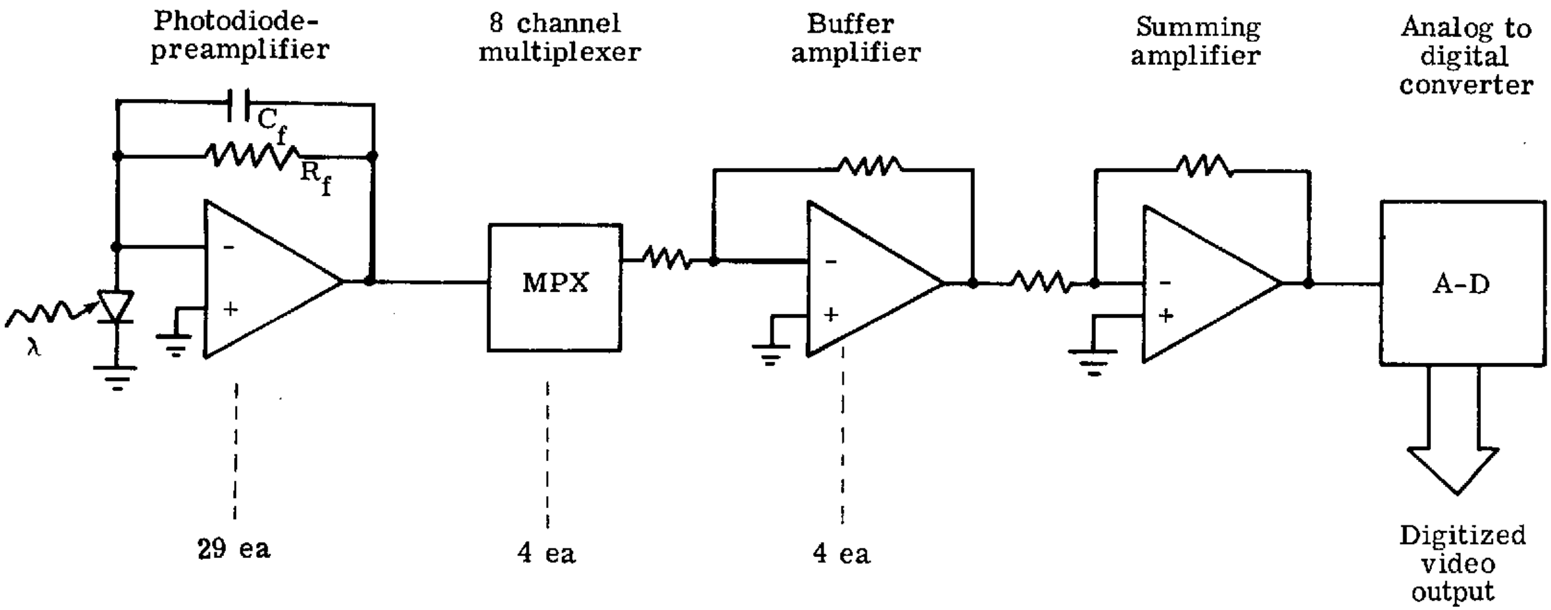
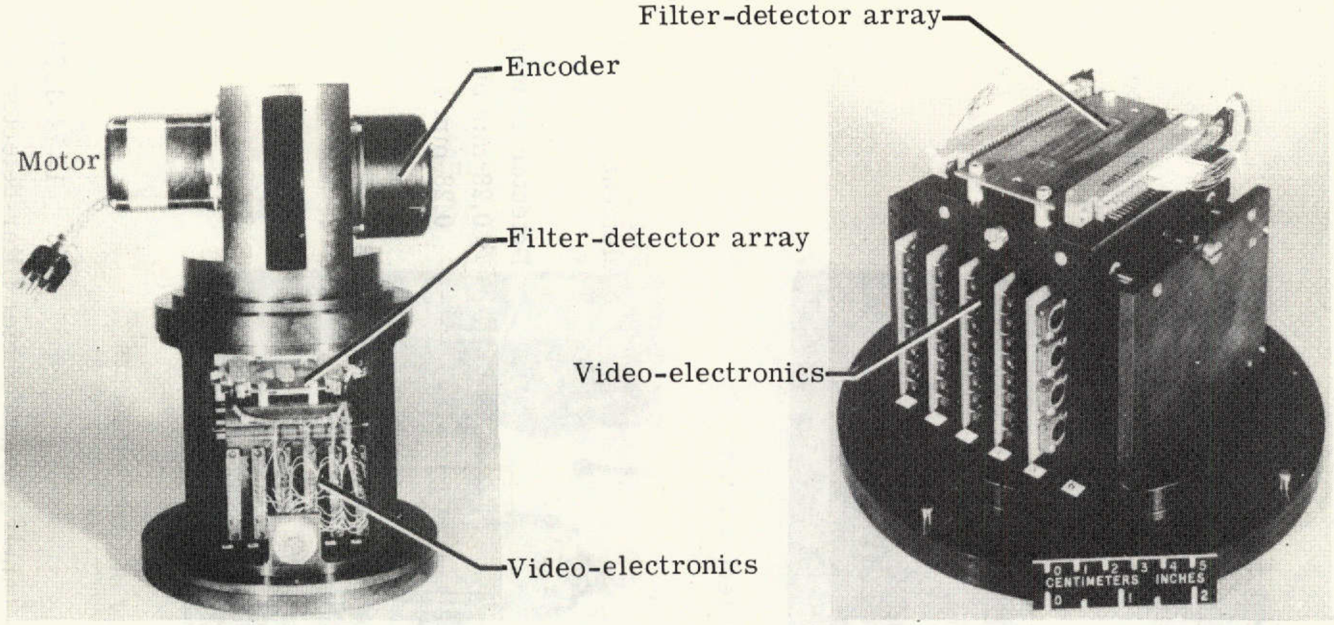


Figure 3.- Data acquisition electronics.



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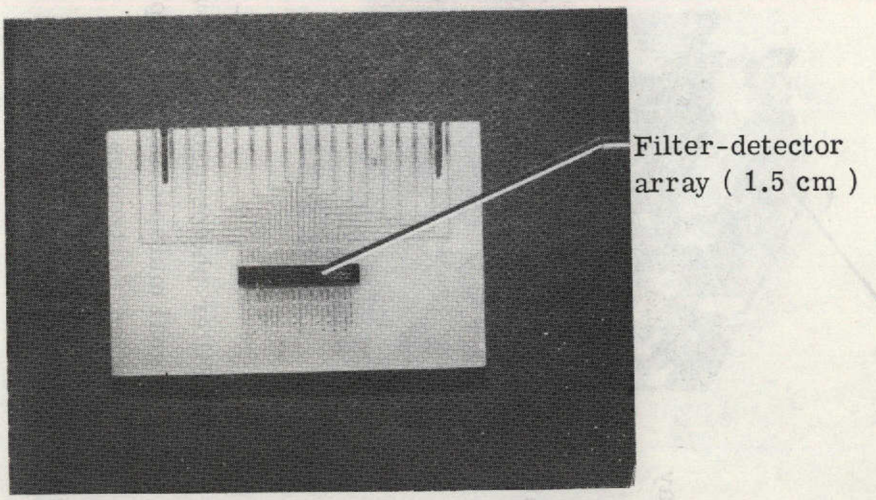
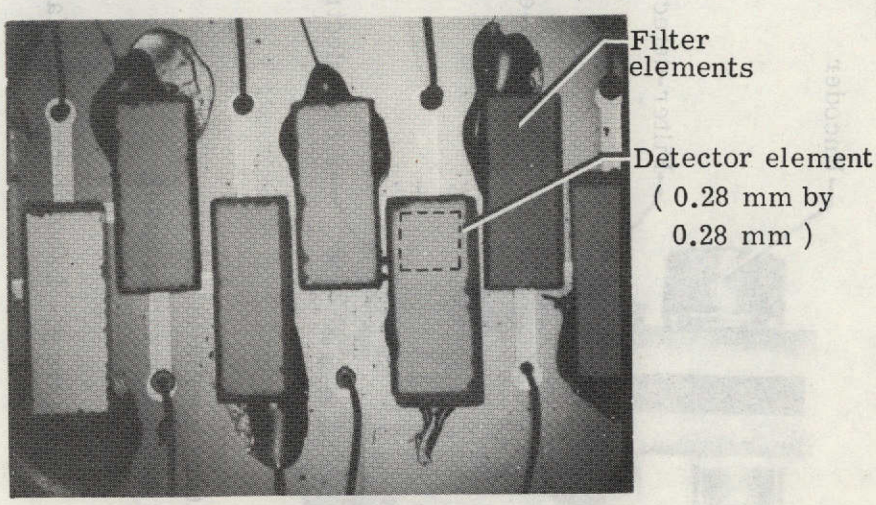
(a) Laboratory facsimile camera (without azimuth rotation base).

(b) Filter-photosensor array with signal multiplexing and amplification electronics.

Figure 4.- Laboratory model facsimile camera-spectrometer.



Filter-detector array



Magnified view of filter elements

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Figure 5.- Facsimile camera-spectrometer filter-detector array.

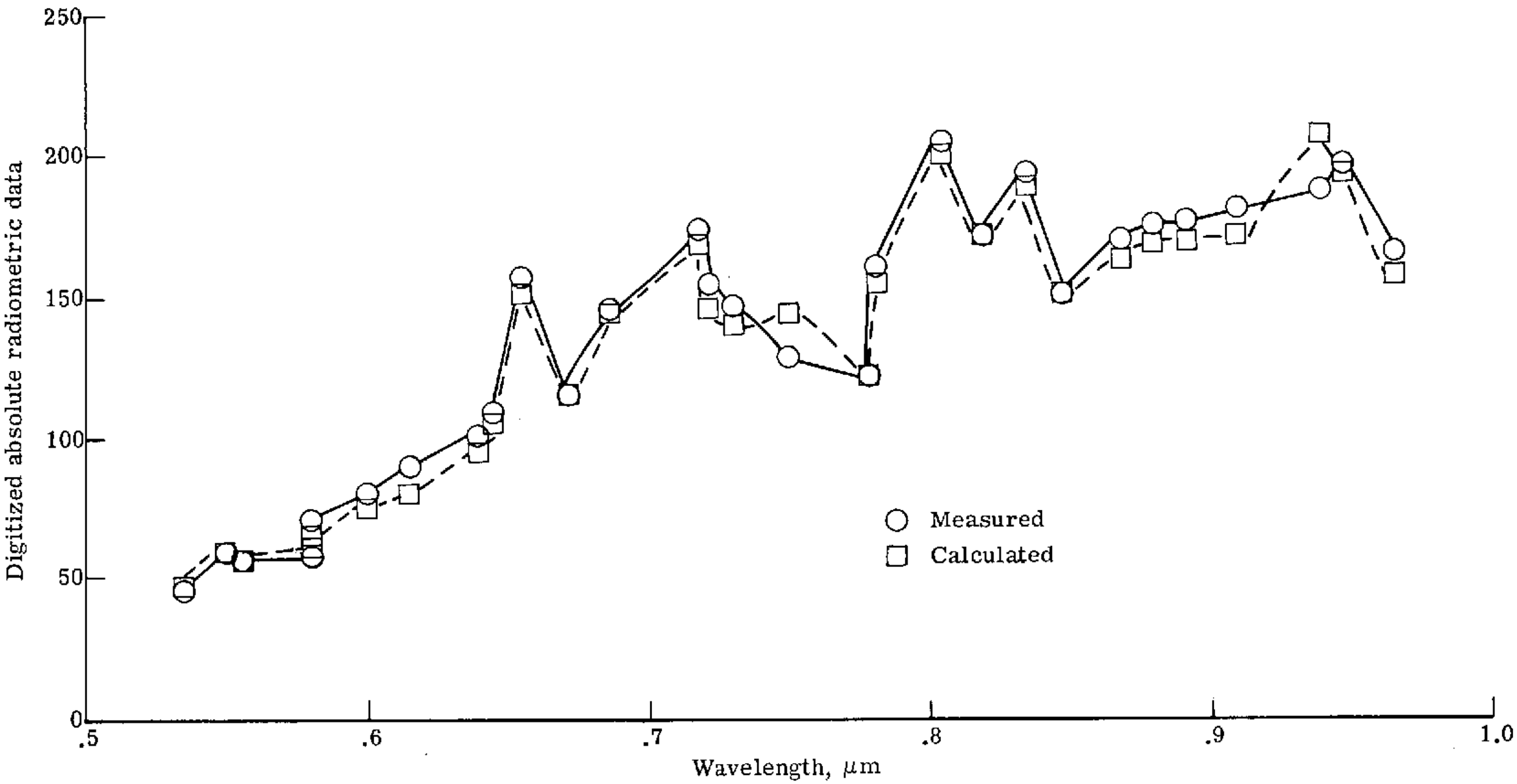

Figure 6.- Digitized radiometric data with known illumination.

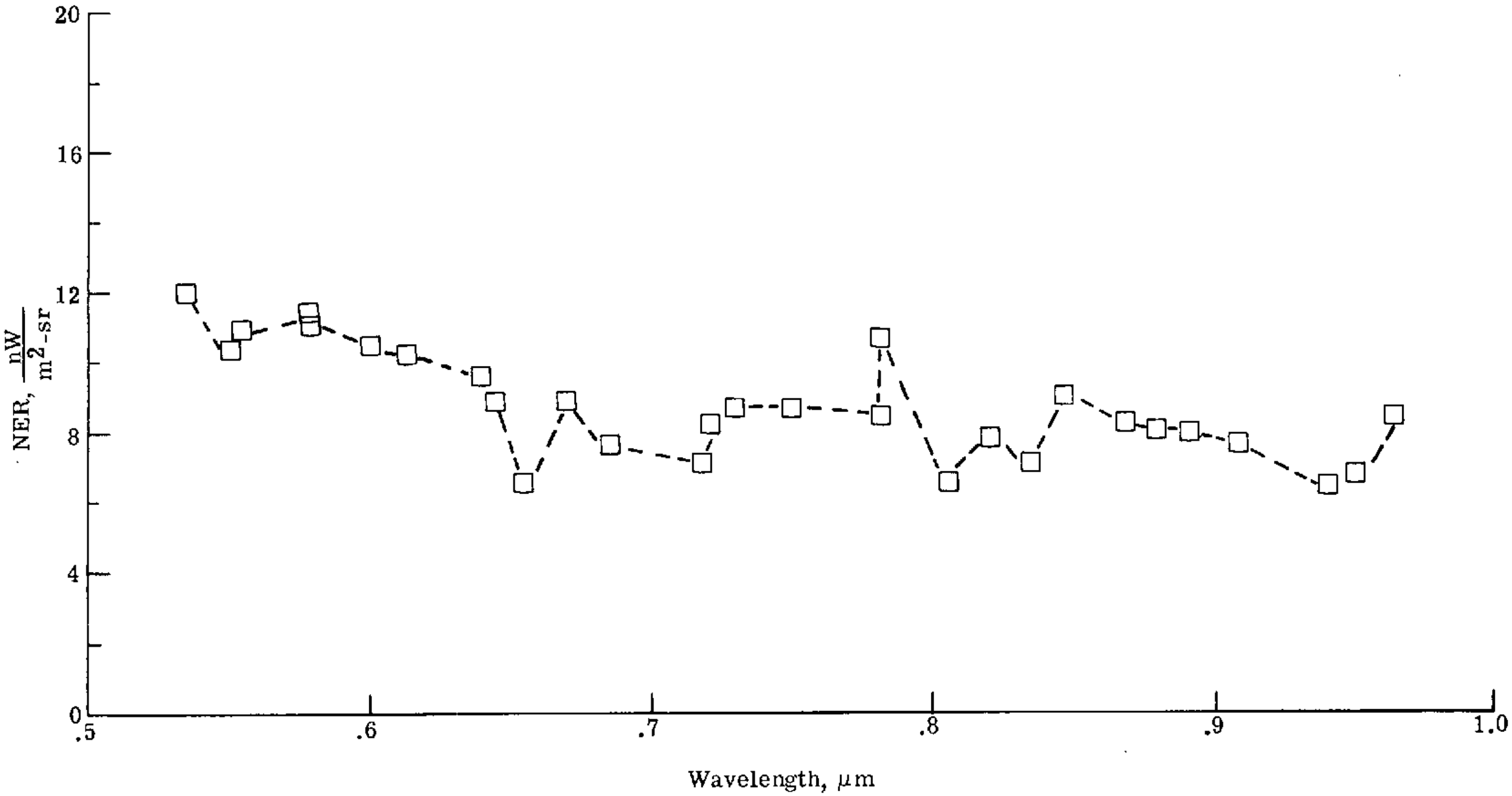

Figure 7.- Noise equivalent radiance of laboratory model facsimile camera-spectrometer.