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INVESTIGATION OF FACSIMILE CAMERA-SPECTROMETER CAPABILITY IN THE 1.0 to 2.7 MICRON SPECTRAL RANGE

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16. Abstract

The capability of the facsimile camera augmented with a filter-spectrometer to provide scientifically valuable information in the 1.0 to 2.7 um spectral range is investigated for a future planetary lander mission to Mars. A computer model is used to evaluate tradeoffs between signal-to-noise ratio, spatial and spectral resolution, and the number of spectral channels. Spectral absorption features resulting from water and chemical variations found in pyroxenes are used to represent scientific information of interest to biologists and geologists. Expected output data from a filter-spectrometer is illustrated which indicates that important information pertaining to water content and chemical composition can be obtained using six to eight spectral channels with 0.3 degree spatial resolution.

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SUMMARY

The capability of the facsimile camera augmented with a filter-spectrometer to provide scientifically valuable information in the 1.0 to 2.7 um spectral range is investigated for a future planetary lander mission to Mars. A computer model is used to evaluate trade-offs between signal-to-noise ratio, spatial and spectral resolution, and the number of spectral channels. Spectral absorption features resulting from water and chemical variations found in pyroxenes are used to represent scientific information of interest to biologists and geologists. Expected output data from a filter-spectrometer is illustrated which indicates that important information pertaining to water content and chemical composition can be obtained using six to eight spectral channels with 0.3 degree spatial resolution.

INTRODUCTION

Telescopic observations of Mars have provided spectral information over the spectral region from .3 to 2.5 μm, appreciably contributing to the basic understanding of the Martian surface (ref. 1). Spectral investigation of Mars from Earth is made difficult by effects introduced by the Earth's atmosphere and by the low Mars surface resolution. Neither of these problems will be encountered in the summer of 1976 when the Viking Mars lander cameras return multispectral imagery data to Earth. In addition to high and low resolution black and white images, the Viking cameras feature six spectral channels over the silicon detector spectral range (.4 to 1.1 μm). Data from three spectral channels in the visual region can be used to produce color images of the surrounding terrain, thus greatly enhancing opportunities for identifying surface constituents.

It has been widely recognized that spectral measurements in the 1.0 to 2.5 μm region can significantly add to information about surface chemical composition (ref. 2). Many rock forming minerals can be identified on the basis of their wavelength absorption bands (ref. 3). Pyroxenes, which have been identified as important to the interpretation of reflectance spectra of solar system objects, such as Mars, exhibit strong absorption features near 1 and 2 μm. In addition, bound water, whose presence is of extreme interest to geologists and biologists, produces absorption features near 1.4 to 1.9 μm.

A concept which allows the incorporation of spectrometry capability in the 1.0 to 2.7 μm range into a Viking-like camera has been proposed, analyzed, and tested in references 4, 5, and 6, respectively. This filter-spectrometer concept utilizes lead sulfide photodetectors with interference filters, and does not interfere with the imaging capability of the camera.

The purpose of this paper is to illustrate the scientific capability which could be provided by a facsimile camera filter-spectrometer for a Viking-like mission to Mars. A computer model is used to evaluate the trade-off between spatial and spectral resolution by illustrating expected output data for several filter-spectrometer designs. The computer model includes pertinent Viking camera parameters, Martian irradiance, and input reflectance spectra representative of pyroxenes and Montmorillonite, a clay-like mineral containing bound water. From this data both the scientific capability of the filter-spectrometer and preliminary design goals for the filter-spectrometer are indicated.

SYMBOLS

D	lens diameter, cm
D^{*}_{λ}	spectral detectivity of photodetector, cm-Hz$^{1/2}$/W
ℓ	lens focal length, cm
N_q	quantization noise
S/N	ratio of signal to rms noise
S_{λ}	solar spectral irradiance above planetary atmosphere, W/cm^{2}µm
α	quantization level, V
β	instantaneous field of view, deg
λ	wavelength, µm
ρ_{λ}	spectral albedo of surface
τ_{λ}	spectral transmissivity of atmosphere
$\tau_{\lambda,f}$	spectral transmissivity of filter
$\tau_{\lambda,\ell}$	spectral transmissivity of lens
ϕ	illumination scattering function of surface
ω	angular velocity of vertical mirror, rad/S.

SCIENCE GOALS

Because the number of spectral channels that can be included in a facsimi-le camera-spectrometer is limited, the location and bandwidth of the spectral channels must be carefully chosen. Several target characteristics which have been recognized as important parts of a Mars geological model are described here both to illustrate the science value of the spectrometry capability and for use in preliminary instrument design and evaluation. Hopefully, the interpretation of Viking images will provide a firmer basis for design decisions and further increase the value of a spectrometry capability.

The preliminary definition of science goals described here is based on telescopic spectral reflectance data obtained from solar objects, particularly the Moon. Comparisons between laboratory spectra of lunar samples and telescopic data have demonstrated that - at least for the Moon - reflectance spectroscopy is a reliable means of remotely obtaining mineralogical and chemical information. Laboratory studies of terrestrial and lunar rocks and meteorites, as well as telescopic spectra of the Moon, Mars, Mercury, and some asteroids have reported absorption bands attributed to pyroxenes (ref. 3). This mineral group is important as accessary minerals in most igneous rocks and some metamorphic rocks. Pyroxenes may be principle rock forming minerals in basic and ultrasonic igneous rocks (ref. 7).

The spectra of two varieties of the pyroxene group are illustrated in figure 1. Augite is found chiefly in dark colored igneous rocks rich in iron, magnesium, and calcium. Another common pyroxene, enstatite, may be rich in iron and is then called hypersthene. The hypersthene band at 1.85 μm is due to the ferric ion and clearly illustrates the effect of chemical composition on the reflectance spectra.

The presence of water in any form is of great interest to biologists and mineralogists, both in connection with possible life forms and in defining the mineralogical history during periods of crystalization. In the spectra of minerals and rocks, whenever water is present, two chracteristic bands appear at 1.4 μm and 1.9 μm. These bands result from overtones and combinations of fundamental vibrational modes of the water molecule. The presence of both bands is diagnostic of undissociated water molecules in the structure (i.e., water or hydration of water trapped in the lattice). The presence of the 1.4 μm band alone indicates that hydroxyl groups other than those in water are present in the material. A combination tone is formed in some cases by the combination of the hydroxyl ion stretching mode with the lattice or vibrational modes, resulting in two bands, which can be observed at approximately 2.2 and 2.3 μm. The spectra of montmorillonite, a clay-like group of minerals, is presented in figure 2 to illustrate the water bands.

The spectra shown in figures 1 and 2 are in no way intended to represent the entire scientific goals for which a spectrometry capability could be useful. In fact, they represent only the most obvious features of interest; however, these features are sufficient to illustrate the design trade-offs and typical expected performance from the facsimile camera-spectrometer.

FILTER-SPECTROMETER CONCEPT

Imaging Function

The basic operation of a facsimile camera as an imager is illustrated in figure 3(a) (ref. 8). The imaging 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 narrow strips in elevation. The entire camera is rotated slowly in azimuth until the complete scene of interest is scanned.

The versatility of the Viking cameras is greatly improved by using twelve photodetectors in the image plane which can be electronically selected. Five channels are designated for black and white imaging (one for low resolution survey and four for high resolution imaging). Six channels are spectrally filtered to provide spectral data over the silicon detector response range from .4 to 1.1 μm. The three spectral channels in the visual region can be used to produce color images of the surrounding terrain, and the spectral data can be used to construct spectral reflectance curves which can then be matched to laboratory standards to aid in the identification of surface materials.

Filter-Spectrometer

An improved spectrometry capability can be added to the facsimile camera by placing an array of lead sulfide photodetectors, in addition to the imaging detectors, in the aperture plane alined along the direction of image motion as shown in figure 3(b). Spectral filters positioned over the lead sulfide elements allow spectral data to be acquired for a selected picture element over the spectral range from 1.0 to 2.7 μm. This is accomplished by using electronic pulses, derived from the servo which controls the scanning mirror position, to sample the appropriate detector output synchronous with the image movement down the array. The sampled detector outputs are then digitized, stored and transmitted, similar to the imaging data.

General operation in the spectrometer mode consists of first obtaining an image of the scene and selecting particular pixels for spectral investigation one at a time. Using information from the vertical and azimuth servo systems, the camera can be directed to position the image of the selected pixel over the spectrometer filter-detector array and spectral data pertaining to the selected pixel can be acquired.

ANALYTICAL MODEL

The performance of the facsimile camera as a radiometer has been analyzed in reference 8. Most of the important performance and design parameters are included in the signal-to-noise ratio expression

$$\frac{S}{N} = \frac{\pi \, \beta^2 D^2 \Delta\phi}{\ell \sqrt{\frac{\pi}{8} \; \beta\omega}} \int_0^\infty S_\lambda \tau_\lambda \rho_\lambda \tau_{\lambda,\ell} \tau_{\lambda,f} D^*_\lambda \; d\lambda \qquad (1)$$

Since the principal instrument function will be to image, camera parameters such as lens diameter and focal length, and mirror scanning rate, are assumed here to be the same as the Viking design. Using these values, as summarized in Table I, the signal-to-noise ratio can be written as

$$S/N = .156\ \beta^{3/2} \int_0^\infty S_\lambda \tau_\lambda \rho_\lambda \tau_{\lambda,\ell} \tau_{\lambda,f} D^*_\lambda \ d\lambda \qquad (2)$$

This expression refers to the analog signal-to-noise ratio at the detector output. The rms noise which limits performance at this point arises from the photodetector-preamplifier.

Three other design variables in addition to signal-to-noise ratio must be considered to optimize the scientific information which is generated:

(1) High spatial resolution (low value of β) allows spectral data to be obtained from smaller targets consisting of only a few image elements. Data interpretation difficulties resulting from the mixture of minerals and the effect on their combined spectra are reduced with high spatial resolution. The detector sensitivities, and lens diameter requirements imposed by the imaging design, result in spatial resolutions sufficiently low to provide acceptable depth of focus for the spectrometry mode (see ref. 8).

(2) The spectral bandwidth should be minimized whenever possible to allow spectral absorption features to be detected and accurately reconstructed. An ideal rectangular filter characteristic is desirable with minimum signal contamination from out-of-band radiance. The selection of the location of each spectral channel is determined by the specific spectral features of most interest to the scientist.

(3) The number of spectral channels is the most significant factor determining the complexity and cost of the filter-spectrometer addition to the facsimile camera. The electronic complexity associated with selecting each

channel and processing its output, along with the image field requirements imposed on the optical system, necessitate that only a few channels be used. However, a sufficient number of spectral channels must be available to adequately sample the target spectral features.

ILLUSTRATION OF PERFORMANCE

The analysis presented here illustrates the design trade-offs which can be made to meet the science goals previously mentioned. A computer model of the signal-to-noise ratio expression is used to illustrate typical output data for selected target spectra using several spectrometer designs compatible with the present Viking imaging system.

Assumptions

The following assumptions are made:

1. The Viking lander camera parameters, as summarized in Table I, were used to define design parameters pertinent to the imaging system. Not shown in the table is the assumption that the performance of the optical system can be extended to 2.7 μm, and that image field limitations do not significantly restrict the number of spectral channels. The Viking camera slow-scan rate was used to define the video bandwidth requirements.

2. A 50 percent peak transmissivity and a Gaussian shape were assumed for the spectral filters, thereby allowing some out-of-band signal associated with nonideal filters.

3. Figure 4 illustrates the spectral detectivity for lead sulfide detectors. The noise spectrum of lead sulfide detectors often exhibits a 1/f

dependence, and hence may require the input radiation be mechanically chopped to optimize the signal-to-noise ratio. The effects of mechanical chopping have not been included here.

4. A signal-to-noise ratio goal for each channel under maximum illumination conditions (i.e., $\rho = 1$, $\phi = 1$) was set at 256, so that the electronic noise would be appreciably lower than a quantization interval for six bit encoding, as used by Viking.

5. For the convenience of data interpretation, the spatial resolution in a given design was assumed to be the same for each channel.

6. The solar spectral irradiance for Mars is shown in figure 4. The transmissivity of the Martian atmosphere is assumed here to be unity although the atmosphere is known to contain CO_2 and water vapor, both of which have absorption bands in the 1.0 to 2.7 μm spectral range. Further investigation of the Martian atmosphere will allow a more accurate model to be defined and incorporated into the analysis.

Performance Evaluation

The computer model was used to define the limits for spectral resolution as a function of wavelength and spatial resolution under the maximum input signal condition ($\rho = 1$, $\phi = 1$). Spatial resolution values of $\beta = 0.1$ degree, which is similar to the Viking low-resolution mode, and $\beta = 0.3$ degree considered. The output signal-to-noise ratio was calculated for various center wavelengths to define the spectral bandwidths necessary to achieve the signal-to-noise goal, thus defining the minimum spectral resolution limits for the respective design as shown in figure 5.

These resolution limits were used as design parameters to illustrate typical output data for target surfaces represented by the spectral curves shown in figures 1 and 2. Several designs were considered to illustrate the trade-off between spectrometer design parameters and to illustrate the importance of optimizing the design for the science goals. The output data is shown in figures 6 through 9 along with the input curves to indicate how well the input information could be reconstructed. Experience gained by the scientist in evaluation of laboratory data could aid in constructing spectral curves from the output data. Several observations concerning the filter-spectrometer design can be made.

Spectral position of channels - Since the number of spectral channels is severely limited by engineering constraints, the position of each channel has a dramatic effect on the accuracy of defining the position and depth of absorption bands as is illustrated in figure 6. Figure 6(a) shows results for equally spaced spectral channels and figure 6(b) shows channel positions selected specifically to quantify the absorption bands. To be observed in figure 6(b) is the accurate quantification of the water and iron bands.

Spatial and spectral resolution - The trade-off between spectral and spatial resolution is shown in figure 7. To increase spatial resolution, the spectral resolution must be decreased to provide sufficient radiant energy in each spectral channel to maintain the signal-to-noise goal (see figure 5). The 0.3° spatial resolution represents a factor of three decrease from the Viking low resolution imaging capability, and provides significantly more accurate quantification of the narrow absorption bands. Not shown in figure 7 is the possible masking of absorption bands due to viewing larger surfaces and possible mineral mixtures. Such effects must be examined experimentally and would depend greatly on the particular surface under consideration.

Number of spectral channels - Since the number of spectral channels may be limited for engineering reasons, results with six channels are compared to eight channels in figure 8. The channels are selected to define the more pronounced water and iron bands, with the water band at 1.43 μm no longer adequately sampled. The six channel design sacrifices some capability, since only one spectral channel is located between 1.0 and 1.8 μm. Scientifically interesting spectral features located in this region could therefore go undetected with the six channel design.

Important to recognize in figure 8 is the accuracy of the spectral representation of surface material characteristics offered by both the six and eight channel designs, and also the significance of the scientific capability provided by the filter-spectrometer.

CONCLUDING REMARKS

An analytical study of the performance capability of the facsimile camera filter-spectrometer was presented. The well recognized science goals of water detection and determination of the chemical composition of pyroxenes were used to represent the spectral information of primary importance to biologists and geologists in the spectral region from 1.0 to 2.7 μm. Several filter-spectrometer design configurations were considered to illustrate the effects of number and position of spectral channels, and spectral and spatial resolution.

Results demonstrate that valuable scientific information pertaining to the chemical composition of mineralogical materials could be obtained using the filter-spectrometer. Under severe engineering constraints a six channel design with a 0.3 degree spatial resolution could detect water bands at 1.9 μm and 2.25 μm and variations in chemical composition of pyroxenes. The inclusion of two additional channels allows observation of the 1.4 μm water band and increases instrument capacity for investigation of science goals not considered here.

These results should serve as preliminary design objectives for augmenting the facsimile camera with a spectrometry capability in the 1.0 to 2.7 μm spectral range. Improved design criteria should be based on interpretations of Viking '75 imagery data, the resulting more inclusive definition of science goals, and experimental investigation of fabrication, calibration, and the effects of spatial resolution on spectral data interpretation.

TABLE I

Assumptions Used For Computer Model

Of Facsimile Camera-Spectrometer

Lens focal length (V)	5.3 cm
Lens diameter (V)	1.0 cm
Lens Transmissivity (V)	.70
Mirror Scanning rate (V)	7×10^{-2} rad/sec
Quantization (V)	6 Bits
Peak Transmissivity of Gaussian Spectral Filters	.50
Illumination Scattering Function	1.0
Martian Atmospheric Transmissivity (1.0 → 2.7 μm)	1.0

(V) Viking lander camera design parameters.

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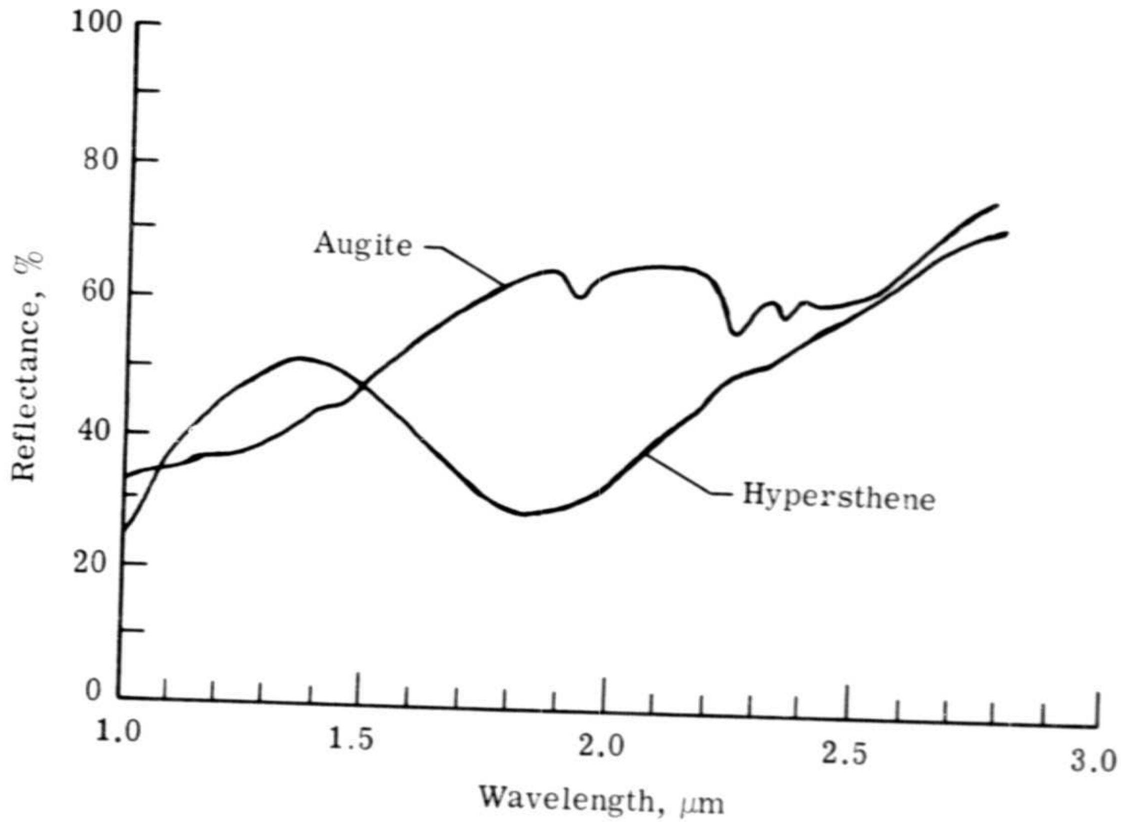


Figure 1.- Spectral reflectance of two pyroxenes.

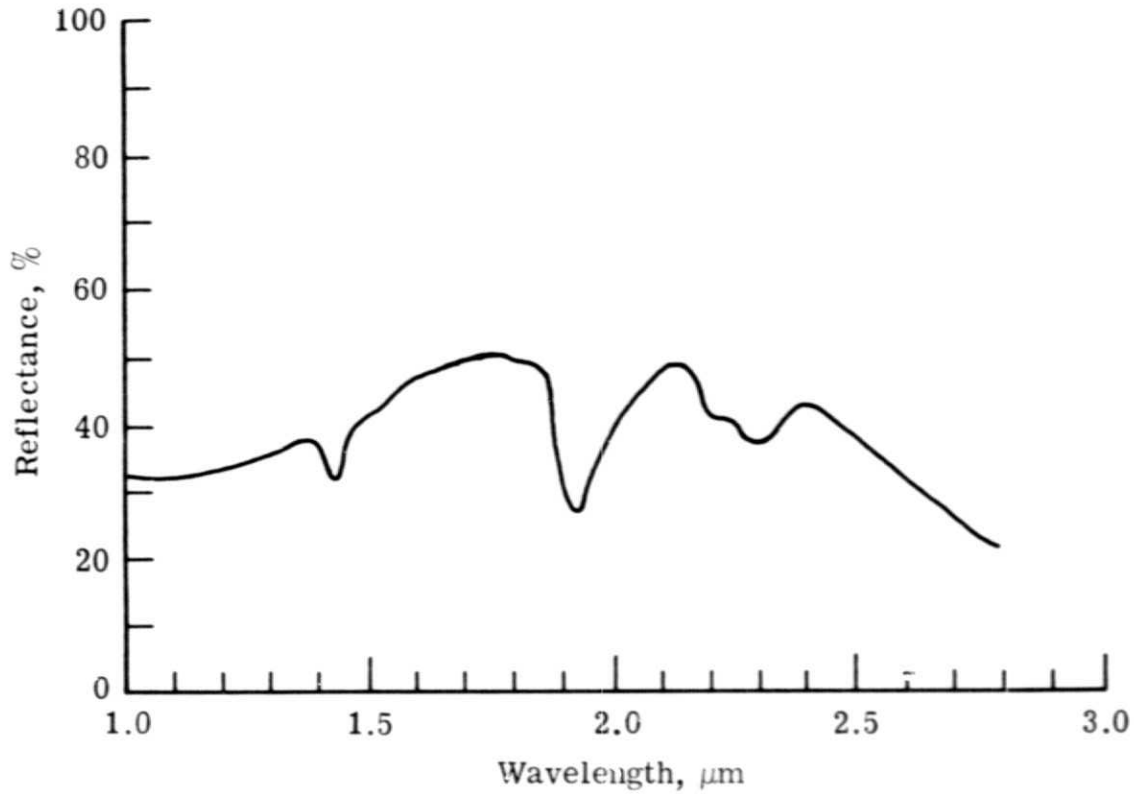


Figure 2.- Spectral reflectance of Montmorillonite.

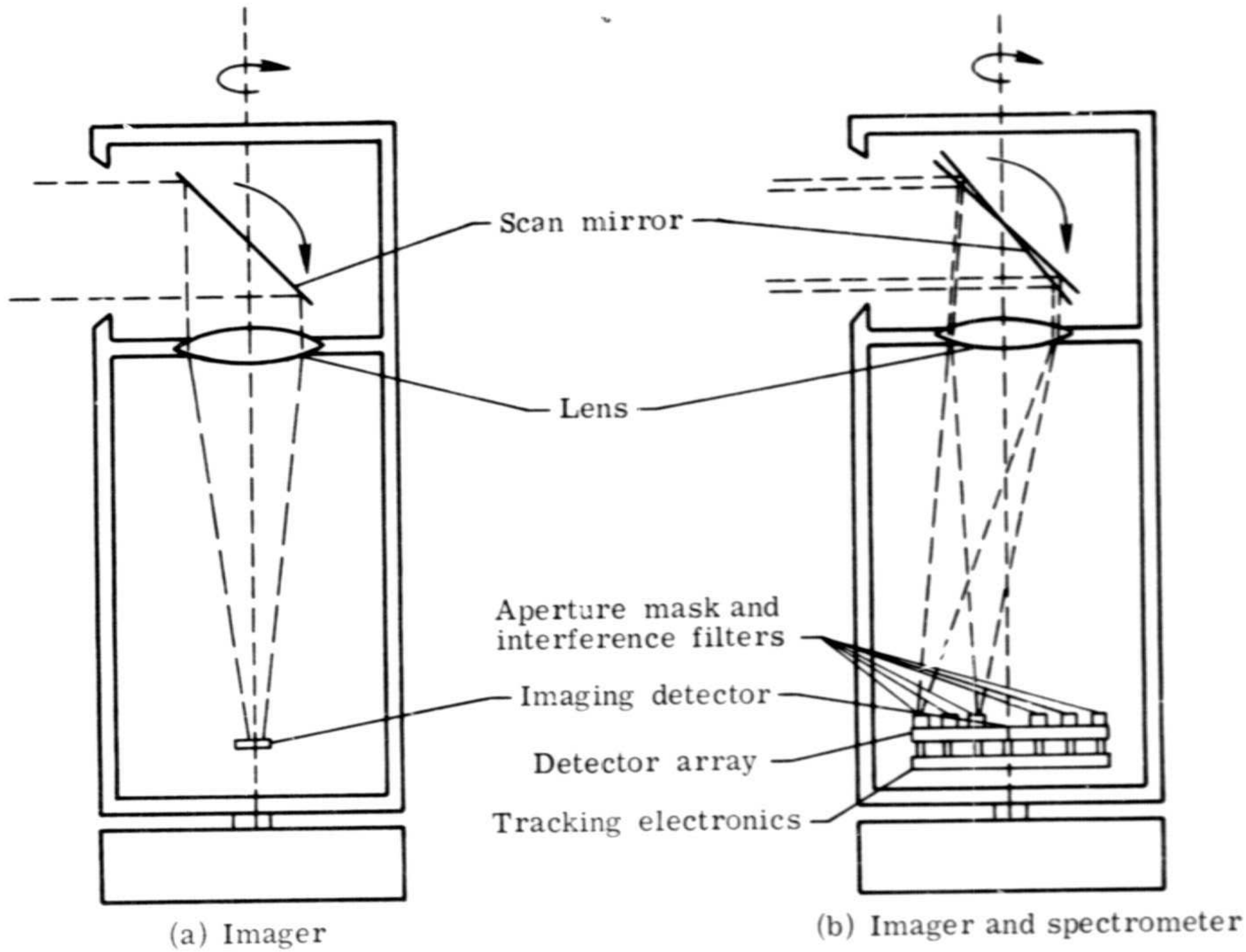


Figure 3.- A basic configuration of the facsimile camera as an imager and a spectrometer.

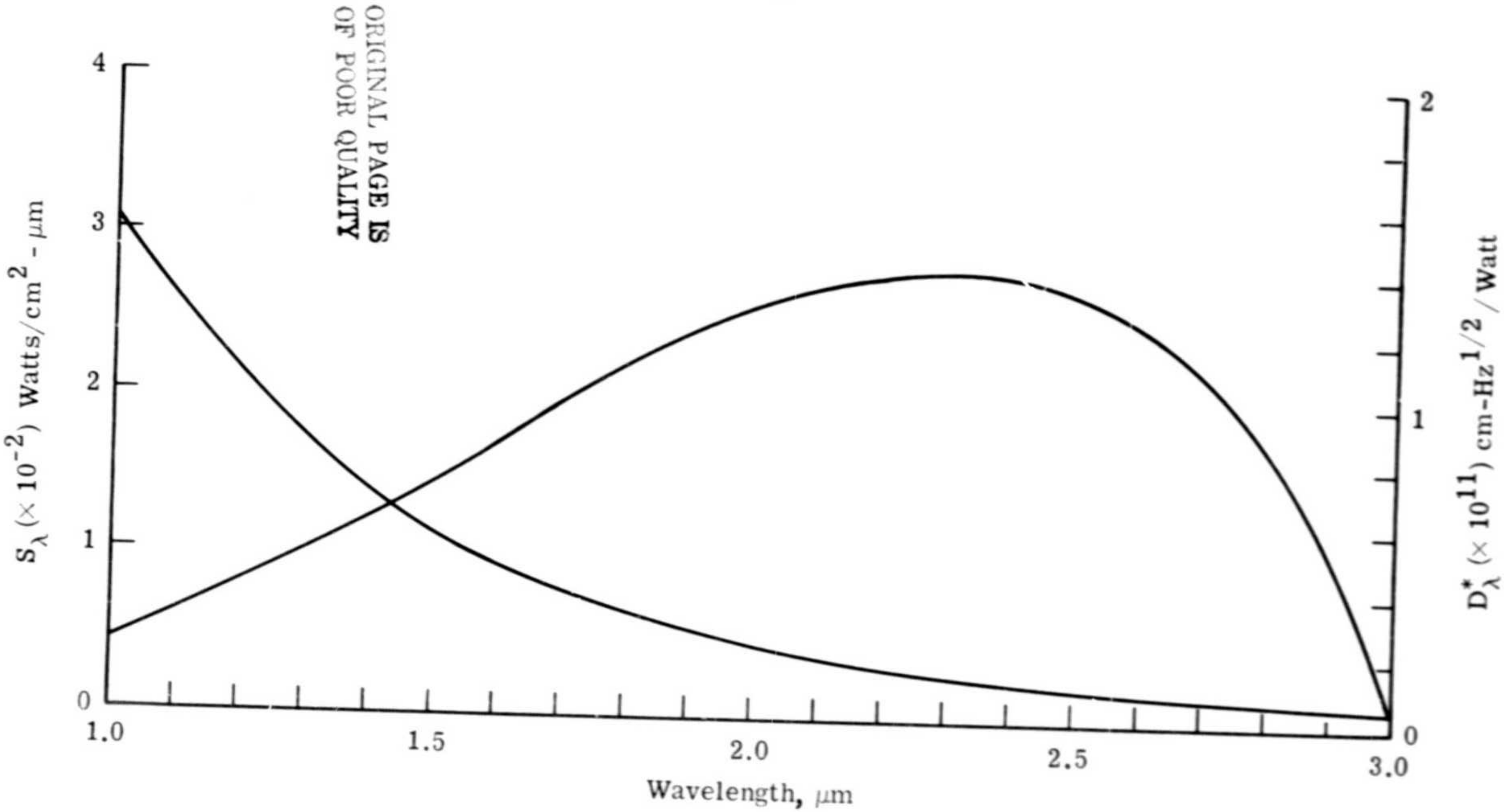


Figure 4.- Solar spectral irradiance on Mars and spectral detectivity of lead sulfide detector.

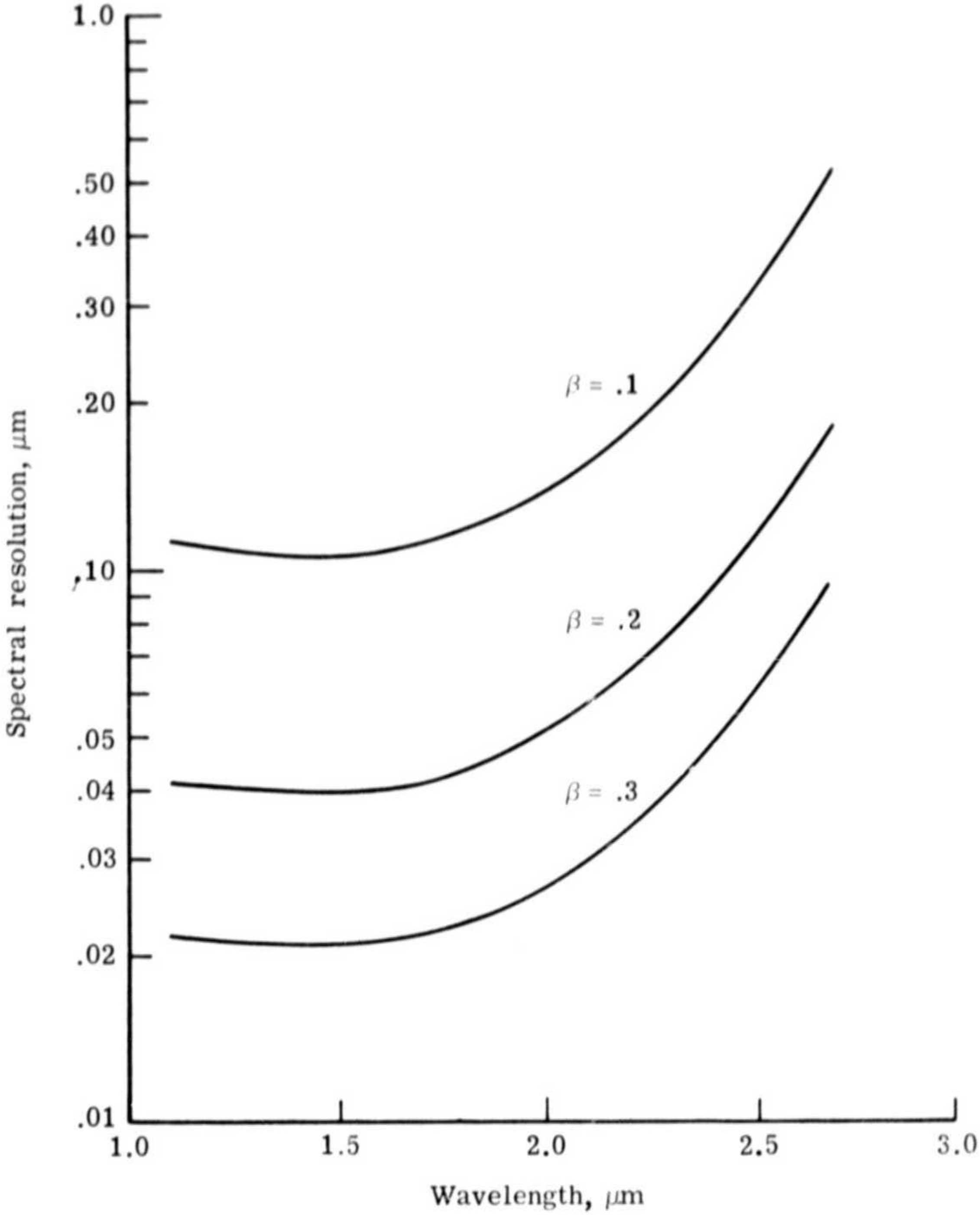
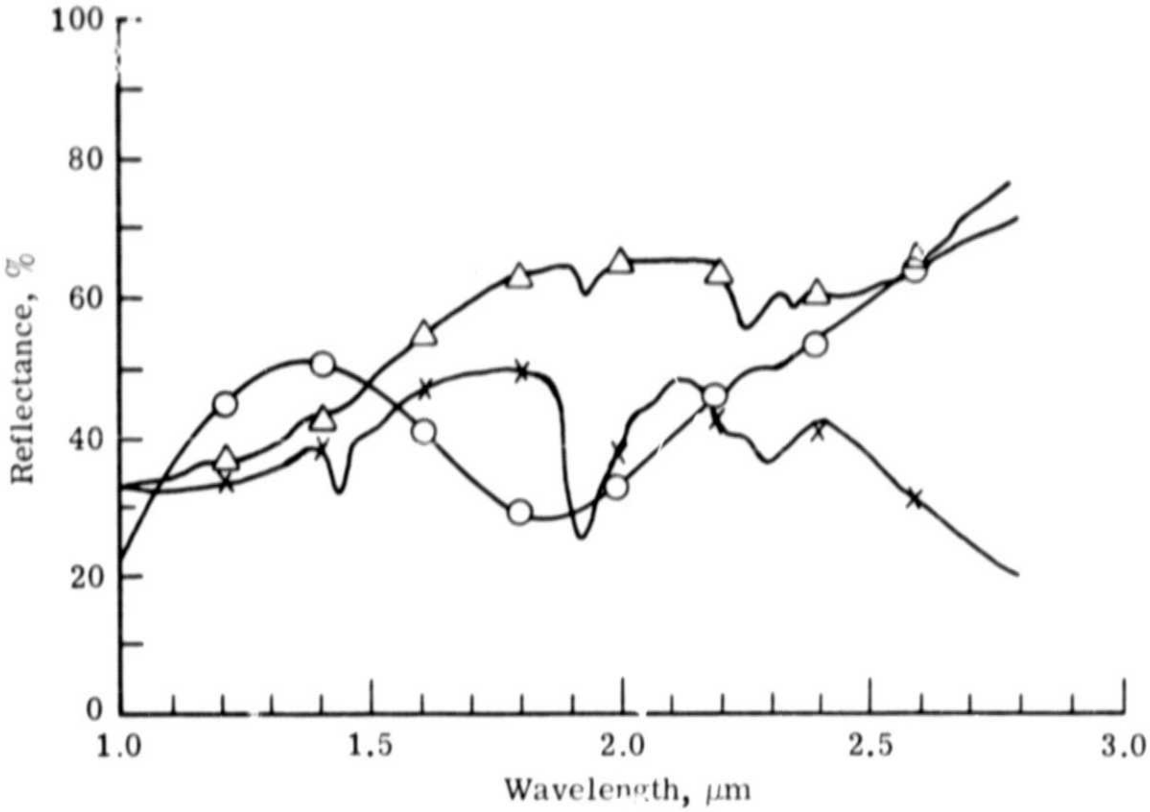
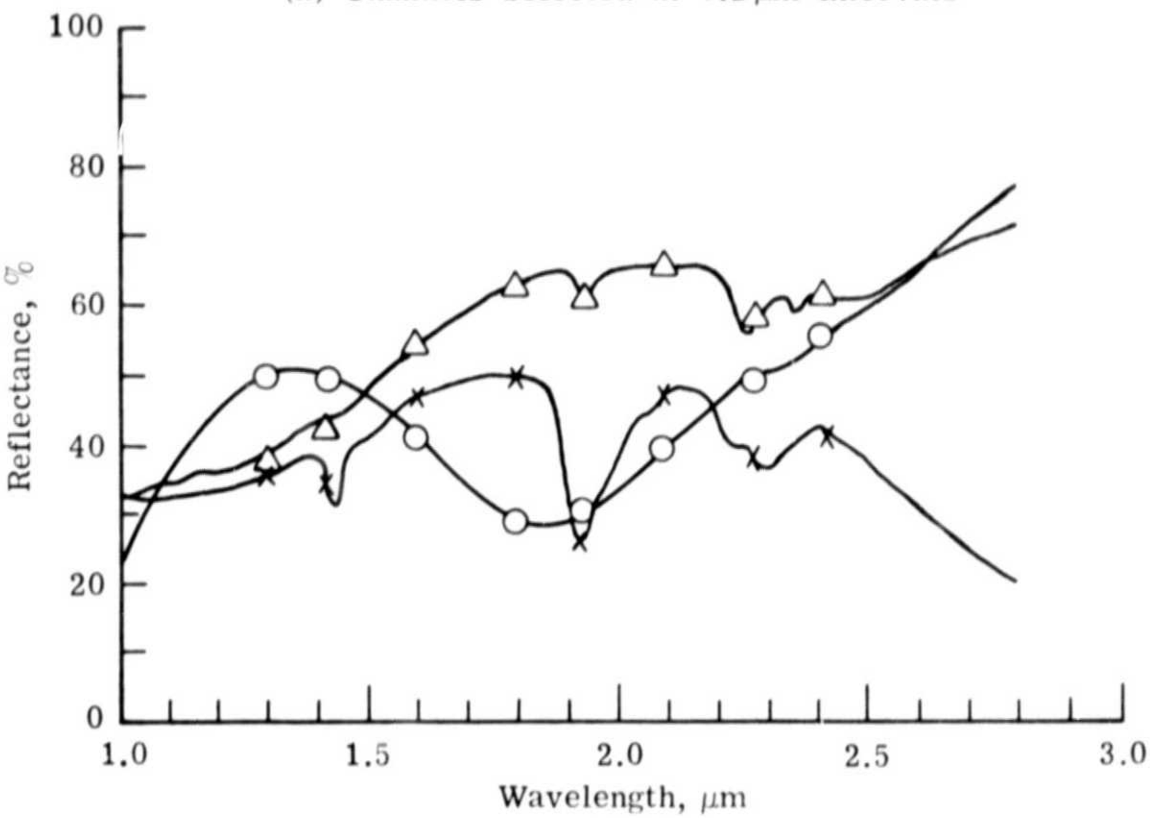


Figure 5.- Spectral resolution (fifty percent transmission points) as a function of wavelength.

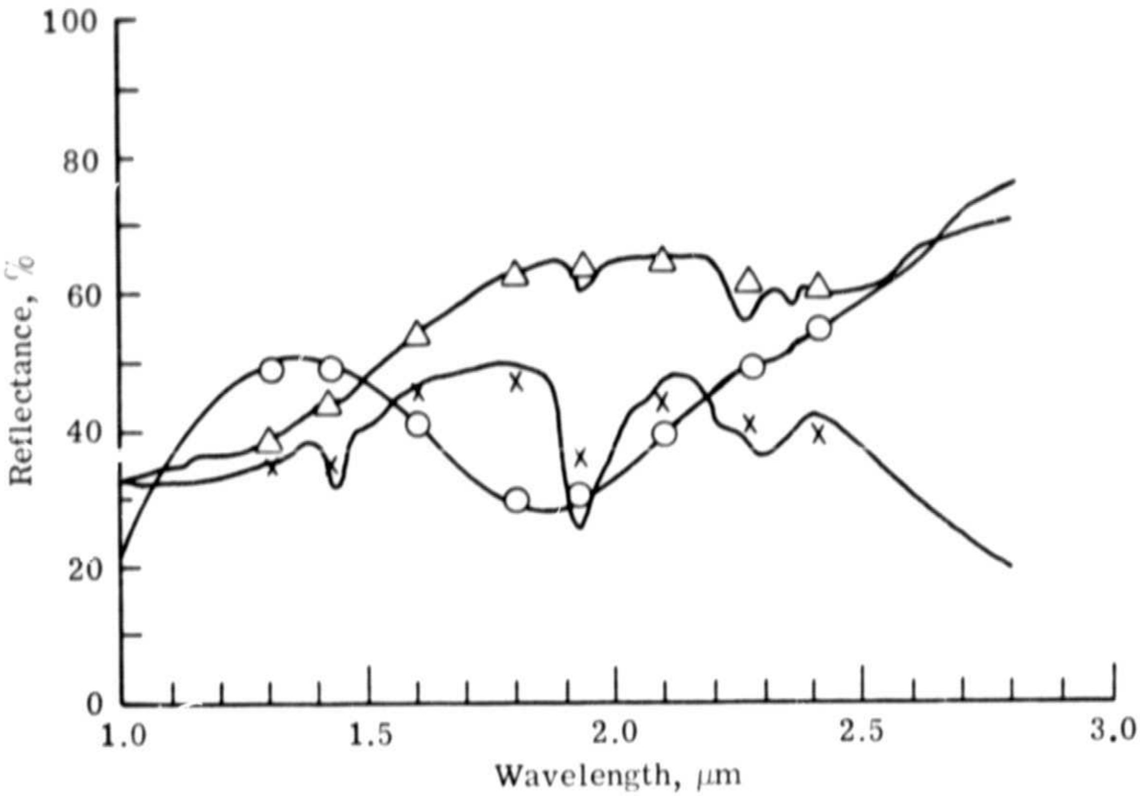


(a) Channels selected at 0.2 μm intervals

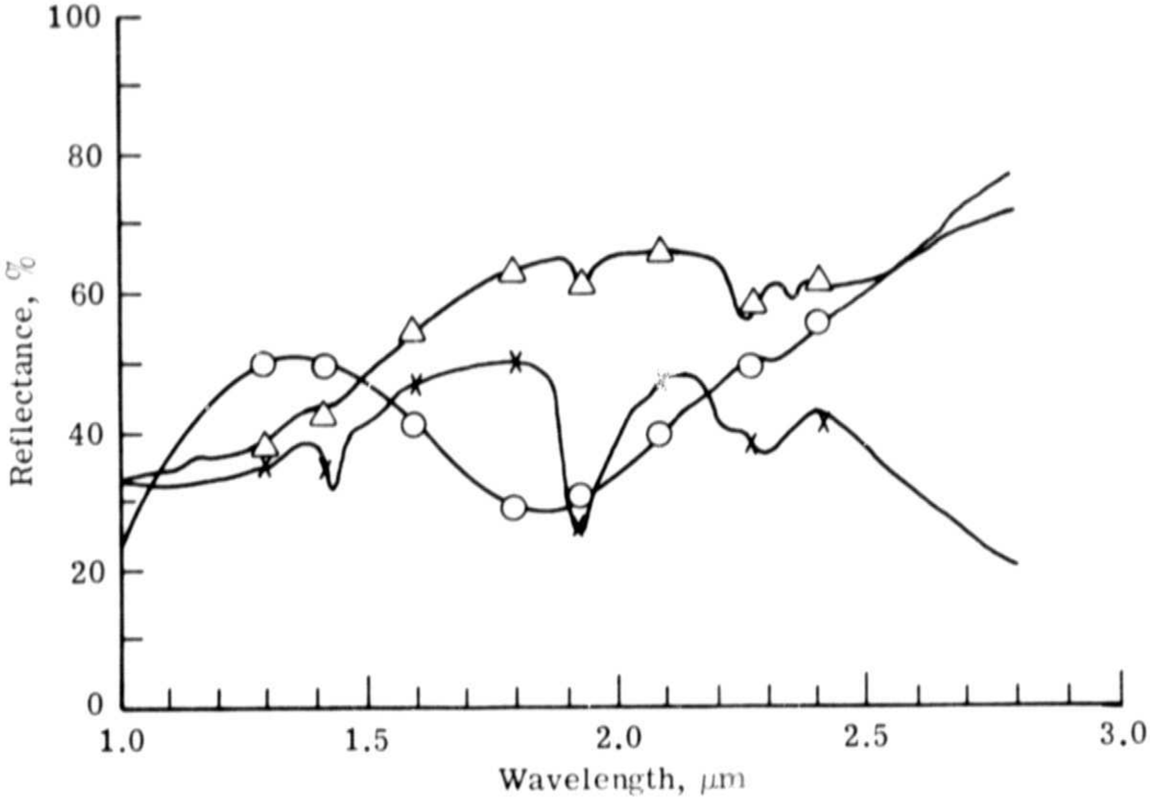


(b) Channels selected for particular surface materials

Figure 6.- Selection of spectral channel positions, β = .3 deg.

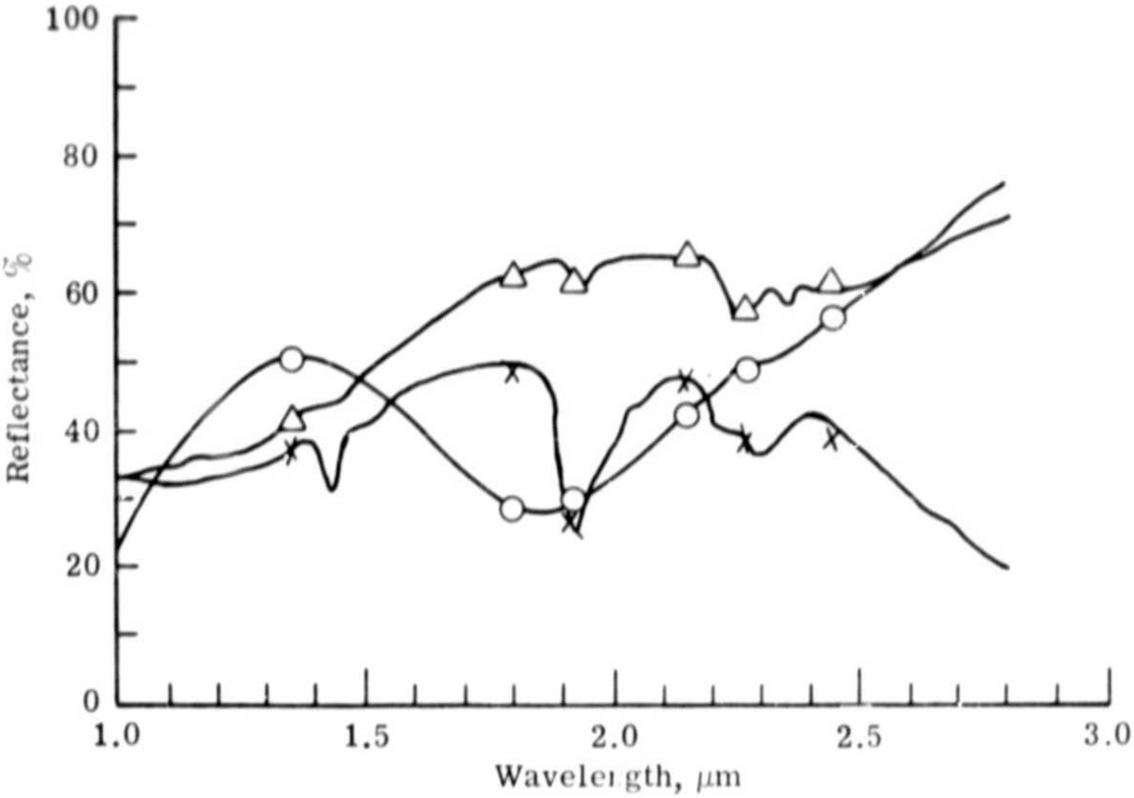


(a) Spatial resolution = 0.1 deg.

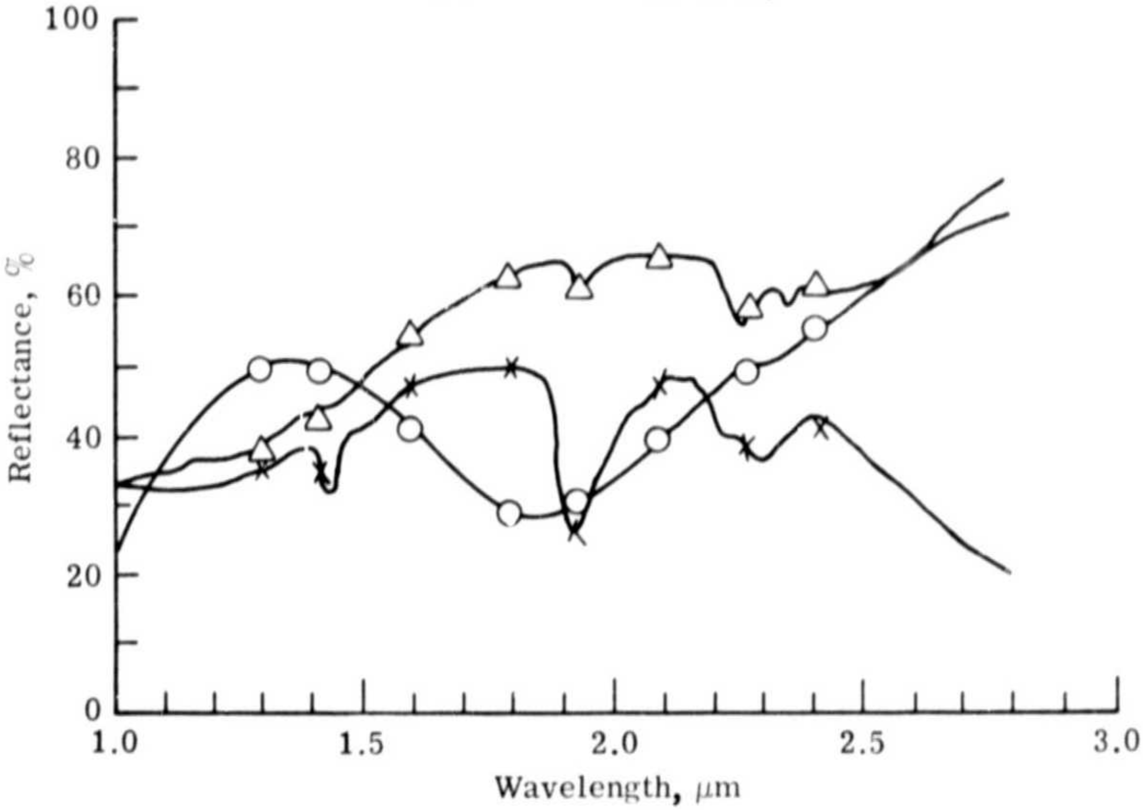


(b) Spatial resolution = 0.3 deg.

Figure 7.- Spatial and spectral resolution trade-off.



(a) Six-channel design



(b) Eight-channel design

Figure 8.- Number of spectral channels, β = 0.3 deg.