Determination of Martian Surface Reflectivity From 0.4 to 1.1 Micron Using a Vidicon Spectrometer

by

Douglas John Mink

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science at the Massachusetts Institute of Technology May, 1974

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ABSTRACT

A new astronomical instrument, the vidicon spectrometer, is being developed at the M.I.T. Planetary Astronomy Laboratory. Based on the silicon diode vidicon system currently in use there, a low dispersion prism is added between the vidicon image tube and the telescope, allowing digital vidicon photographs to be taken of spectra. These spectra are stored on magnetic tape and computer processed to create intensity vs. wavelength curves for stars and planets. The high spatial resolution of the vidicon image tube, combined with a higher spectral resolution than photometer filters currently in use at M.I.T. give this instrument potential in the study of planetary surface composition from spectral reflectivity. Procedures for reducing the vidicon images to spectra have been tested on a set of spectra of two stars and the planet Mars. It is concluded that the vidicon response is not linear enough with variations in exposure time at low levels of incoming light for consistent star spectra, although it works well with Mars due to the planet's larger intensity where the vidicon tube has its poorest response. The spectrometer slit is so narrow (one second of arc for this data) that wavelength-dependent variations in refraction of light from a point source by the atmosphere cause star spectra of variable quality. Because of the low quality of the star spectra, direct spectral reflectivity measurements (which are obtained using Mars to star ratios) proved to be impossible. Although further tests of the spectral and intensity response of the silicon diode vidicon should be carried out in the laboratory before good results can be guaranteed, the present Mars spectra may probably be used in conjunction with photometer-derived reflectivity data to expand coverage of the surface of Mars.

Thesis Advisor: Thomas B. McCord

Title: Associate Professor of Planetary Physics
Acknowledgements

Numerous people were involved in the design and construction of the vidicon spectrometer, although I have only met a few. Professor Thomas B. McCord, Mr. Jeffrey Bosel, and Ms. Carle Pieters have been informative about the design of the hardware, as well as the conditions under which they obtained the Mauna Kea data. Dr. Robert Huguenin lent his insight into the problems of Martian surface composition, as well as criticizing an early draft of this thesis. Steve Kent, who is also working with the spectrometer, provided criticism and astronomical knowledge. My spouse, Catherine, has greatly aided me financially and morally, while David McDonald greatly expedited the production of this thesis, with the aid of several computers.
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1. Introduction

Although Mariner 9 has returned a vast quantity of information about the planet Mars, little was learned about surface composition. From such experiments as the infrared spectrometer, particle size and silica composition were estimated, but these determinations had error bars so great as to be nearly useless in reaching conclusions about the composition of the surface materials of Mars. Until the Viking Lander in 1976, there is no way to physically look at a Martian rock with instruments.

Probably the most useful technique for remotely sensing surface composition is reflectance spectroscopy. Dollfus (1961), studying the polarization of light reflected by Mars, concluded that limonite, a hydrated iron oxide, was probably a major constituent. Hovis (1965) observed absorption bands in the near-infrared reflectivity of limonite and suggested that they would be a diagnostic test for limonite on Mars. Sagan et al (1965) compared absorption bands they observed in laboratory specimens of limonite to Dollfus' Martian albedo curves and concluded that a surface with at least some limonite was not inconsistent with the data. Adams (1968) observed absorption bands between 0.5 and 2.5 microns in many iron-bearing minerals, the positions of which varied significantly from mineral to mineral. These bands are caused by electron transitions in iron ions and by vibrational bands in hydroxyl ions and water molecules. Adams suggests that
the absorption feature observed in Tull's (1966) geometric albedo curve is not inconsistent with a hydrated basalt composition. The feature observed at one micron in their spectra is not due to iron in iron oxides, but to iron ions in silicates. Adams and McCord (1969), using geometric albedoes obtained during the 1967 opposition discovered that curves for the bright areas had different shapes than those from the dark areas of the Martian surface. They concluded that the surface was composed of a combination of oxidized basalt and hydrated iron oxides. The bright and dark areas were modelled as being composed of the same material in different degrees of oxidation.

McCord and Westphal (1971, see also McCord, Elias, and Westphal, 1971) observed Mars during the 1969 opposition and noted that the iron ion absorptions were in different places, indicating compositional differences. Seven areas were observed, four dark and three bright, each being about five Martian longitudinal degrees in diameter. From this data, much compositional analysis has been done (see Figure 1 for examples of mineral reflectivities compared to Mars); however, from such a small sample, generalizations about the rest of the surface cannot be made. Despite over twenty additional spots obtained during the 1973 opposition, such interesting features as the Coprates canyon and the Hellas basin remain uncovered; what is needed is whole disk coverage at high spectral and spatial resolution. A new technique, vidicon spectroscopy, has been developed to obtain the
Figure 1.
Comparison of Mars dark area reflectivity to reflectivity of sheet silicates. Note resemblance to the clay minerals, kaolinite and montmorillonite.
(Courtesy Dr. Robert Huguenin)
desired high resolution full-disk coverage. This thesis describes that technique.
II. The Vidicon Spectrometer

The silicon diode array vidicon was originally developed for television and picturephone use, but because of its large dynamic range, high quantum efficiency, and linear response, it is being used by a growing number of astronomers as a digital replacement for photographic plates. The only advantage a photographic plate has over a vidicon is spatial resolution; however, that is not a limiting factor as atmospheric conditions are the resolution-limiting factor in astronomy. McCord and Westphal (1972), Kunin (1972), and McCord and Bosel (1973) have reported on the development of a vidicon system for single-frame astronomical photography at the Planetary Astronomy Laboratory of the Massachusetts Institute of Technology (MITPAL). This system is based on an RCA silicon vidicon tube with a peak quantum efficiency of 85% at 0.5 microns, sloping off to about 6% at 1.1 microns (see Figure 2). Using filters this system has been developed as a two-dimensional imaging photometer, using filter sets similar to those used with photometers for spectral reflectivity work at MIT. As reported by McCord and Bosel, a vidicon spectrometer which would give the spatial resolution of the vidicon combined with a greater spectral resolution than such a vidicon photometer is under development.

The vidicon spectrometer is basically an optical system which is attached to the front end of the vidicon system on the telescope. Schematically it consists of a low-dispersion prism...
Figure 2. Quantum efficiency of the RCA vidicon. This is the percentage of incoming photons which the diode array and affect it as opposed to being reflected or passing through without being absorbed. This graph was made by averaging the published curve over 250 angstrom segments.
through which light from a slit situated at the focus of the telescope is passed. The dispersed image of the slit is then refocused onto the surface of the vidicon diode array. In practice this is done through a system of mirrors (see Figure 3 for details) to avoid the infrared absorption of lenses.

The vidicon tube consists of a 1024 by 1024 array of reverse-biased diodes. A photon impinging on the vidicon target results in a decrease in charge in the diode it reaches. The image is read out by scanning the diode array with an electron beam which recharges the diodes as it hits them, producing a current proportional to the amount of charge lost. By knowing where the beam is at any given time, the intensity at each location in the diode array can be known. These intensity elements are then passed on to be recorded and displayed (for further details on the electronics of a silicon vidicon see Crowell and Labuda (1963)). The vidicon is read out as 250 rows of 256 image elements, each of which corresponds physically to four diodes. In such a lower resolution scan, less accurate positioning is required of the electron beam. No data is lost, and the vidicon's resolution is still better than the atmosphere allows. The intensity image is amplified, recorded on magnetic tape, and displayed on a slow scan TV monitor. This image is then available for further computer processing. The spectrometer system is diagrammed in Figure 4.

A portion of a vidicon spectrometer image is presented in Figure 5. The elements along the column correspond to spatial
Figure 3. Optics of the MITPAL vidicon spectrometer.
The telescope is to the right.
Figure 4. The MITPAL vidicon system with the spectrometer attached.
elements along the slit. Wavelength is along the abscissa. The magnitude of each element is proportional to the current from the vidicon diode array at the time a corresponding diode was read by the scanning electron beam. The image is now ready to be turned into a spectrum.
Figure 5. A portion of a vidicon spectrometer image of Mars. It runs from about 0.9° in the leftmost column to 0.9° in the rightmost.
III. Image Processing

The first processing that must be done to the image is to convert the column coordinate into wavelength. This is done through the use of a calibration function:

\[ S = S_0 + \frac{C}{(\lambda - \lambda_0)} \quad \lambda = \lambda_0 + \frac{C}{(S + S_0)} \]

where \( S_0, \lambda_0, \) and \( C \) are three constants determined from three column number-wavelength correspondences as follows:

\[ C = \frac{(\lambda_1 - \lambda_2) (S_1 + S_0)(S_2 + S_0)}{(S_2 - S_1)} \]
\[ S_0 = -S_1 + \frac{(\lambda_2 - \lambda_0) (S_2 - S_1)(S_3 - S_1)}{(\lambda_1 - \lambda_2)(S_3 - S_2) - (\lambda_2 - \lambda_0)(S_2 - S_1)} \]
\[ \lambda_0 = \lambda_1 - \frac{C}{(S_1 + S_0)} \]

These correspondences are obtained by observing the spectrometer image of a calibration lamp with known sharp emission lines (as shown in Figure 6). From this calibration, which is redone periodically as data is taken, the wavelength-column relationship is known (see Figure 7 for an example). The resolution also varies as a function of wavelength, as would be expected (see Figure 8 for a sample dispersion function plotted from the first derivative of the calibration function).

Now enough is known to process a spectral image. A program
Figure 6. A spectrum of the calibration source, indicating vidicon intensity of each vidicon element along one row. Assigned wavelengths are indicated.
Table 7. Wavelength as a function of vidicon column for a typical calibration function. The three column (Sn)-wavelength (Ln) pairs used to determine the function are given at the top. Column number is at the left, wavelength at right.
Figure 8. Spectrometer dispersion function. Spectral resolution per image element as a function of wavelength.
has been written which runs as a subroutine under the Planetary Astronomy Laboratory's image processing system (DIPSYS) which has been set up to provide a metastructure under which vidicon images may be easily processed. A simplified diagram of this program appears in Figure 9. The spectral image is read off the run tape by DIPSYS and stored on a disk where it is available to the spectral processing routine, which has three basic tasks. The first and easiest is to punch out the intensities along one row of the image onto computer cards for input into a plotting routine (this was how Figure 6 was produced). Second, it can subtract the average background from the image, column by column, where the rows over which the background is to be averaged are read from the input instruction cards. Last, and most important, the program can produce a new image in which all of the elements have the same spectral resolution. For spectral reflectivity work, where the range of interest is 0.4 to 1.2 microns, a resolution of 250 angstroms, the best resolution at 1.2 microns, was chosen.

Figures 10 and 11 show the effects of this processing on an image of the standard star Xi 2 Ceti. Portions of these images are then integrated spatially along the slit. Due to atmospheric and telescope optical effects, a star image is not a point; it is smeared out spatially into a Gaussian distribution of intensity which is at its maximum where the point source would be. To use the full energy output of the star at a given wavelength, the image must be integrated across all rows where the image intensity is
Figure 9.
Structure and interaction of the vidicon spectrometer image processing programs.
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Figure 11. A portion of the processed image of ξ² Ceti from 0.35µ to 0.70µ. Each image element represents intensity per ten angstroms averaged over a 280 angstrom resolution element. The background was first subtracted out of the vidicon image.
above the background. After this integration, the spectrum vector is punched out onto cards for plotting and further processing. A more advanced version of this processor will incorporate the plotting, ratioing, and other functions into one DIPSYS subsystem, where only disk files will be used.

The final procedure needed for good spectral reflectivity data of the surface of a planet is to know from what part of the surface the spectrum originates. A photograph is taken through the eyepiece, looking at the slit in a mirror tilted 45 degrees to the optical axis of the telescope (the first surface in Figure 3). A similar logging arrangement is used for photometer data. A plotting program has been written to create Calcomp plots of the coordinate grid of Mars (or any other planet) projected onto a disk using the physical ephemeris of the planet from The American Ephemeris and Nautical Almanac and the time of observation in Universal Time. Figure 12 is a block diagram of the program, while Figure 13 is a typical, although smaller than normal, output. To position the spectrometer slit on the disk of the planet, the negative of the photograph of the telescope image is projected onto the grid, and the slit marked by hand. At this point the original vidicon images have been reduced to constant resolution spectra of stars and known positions on Mars; and reduction to spectral reflectivity data, as well as testing, can begin.
PHYSICAL EPHEMERIS (1 MONTH)

CREATE TABLE OF SUB-EARTH POINT COORDINATES AND APPARENT DIAMETER

ADD HOURLY CHANGE OF PARAMETERS TO TABLE

RUN CARD: day of month UT start of run UT end of run caption

CALCULATE POSITION OF SUB-EARTH POINT

CALCULATE NUMBER OF MAPS TO BE DONE (one per five minutes)

DRAW LINES OF LATITUDE in spherical coordinates, hold $\phi$ constant and rotate in $\theta$. transform so that sub-earth point is at $\phi=90^0, \theta=0^0$ and project to plane.

DRAW LINES OF LONGITUDE in spherical coordinates, hold $\theta$ constant and rotate in $\phi$. transform as with latitude lines.

WRITE CAPTION object, time, sub-earth point, apparent diameter in arc-seconds.

LOG MAP and INCREMENT TIME

GET NEW RUN CARD and CHECK FOR LAST INPUT

Figure 12.
Flowchart of grid plotting program.
Figure 13. A typical grid plot produced by the program in Figure 12, the third produced for vidicon spectrometer Mars run C.
IV. Analysis of Data

The first major attempt to use the vidicon spectrometer to take spectra for reflectivity work occurred during the opposition of Mars during October, 1973. On two consecutive nights the Mauna Kea eighty-inch reflector was trained on the planet Mars, and about 75 spectra were taken, as well as an equal number of spectra of the standard stars Alpha Lyra and Xi 2 Ceti. Xi 2 Ceti was chosen because it was near Mars in the sky, while Alpha Lyra has a spectrum which is well known and is used to calculate planet/sun ratios to get reflectivity. Figure 14 demonstrates the reduction methods used to get spectral reflectivities from raw intensity spectra. To avoid airmass reductions, spectra of Alpha Lyra and Xi 2 Ceti were taken when the two stars were at the same airmass, 1.38. Since star/star ratios exhibit little variation with low airmass changes, the ratio of the two stars obtained from these spectra can also be used to reduce reflectivities at other airmasses. Before any data was reduced to reflectivities, extensive testing was done to see whether the data would be usable. This portion of the thesis will describe that work, using the best results obtained to date.

Figure 15 shows a high resolution spectrum of Alpha Lyra which has been averaged over 250 angstrom segments to simulate the spectrometer output. Figure 16 is an Alpha Lyra spectrum from the vidicon spectrometer from which the vidicon response has been
AIR MASS CORRECTED SPECTRA

MARS

STAR 1
($\xi^2$Ceti)

STAR 2
($\alpha$Lyra)

$\frac{\text{MARS}}{\xi^2\text{Ceti}}$

$\frac{\text{MARS}}{\alpha\text{Lyra}}$

$\frac{\alpha\text{Lyra}}{\text{SUN}}$

Figure 14. Production of spectral reflectivity from raw spectra. Air mass correction not needed if objects to be ratioed are at the same air mass.
Figure 15. Spectrum of α Lyra, averaged over 250 angstrom resolution elements, from a 50 angstrom resolution spectrum provided by Steve Kent.
Figure 16. $\alpha$Lyra spectrum from vidicon spectrometer with vidicon response (Figure 2) divided out.
removed. Note that the peak is shifted to a slightly longer wavelength and that the shape is generally broader to about 0.7 microns. To test the repeatability of the data, pairs of spectra of the same star were ratioed to each other. Results of one such pair are shown in Figure 17 (all ratios plotted are normalized to 1.0 at 0.575 microns). Figure 17a is the ratio of two Alpha Lyra spectra with similar airmasses (1.40/1.38), but different exposure times (5sec/1sec). If the response of the system were perfectly linear, that is, if intensity recorded from a given source is a linear function of the integration (exposure) time, the curve would be flat. It is obvious that it is not; however, the relatively flat region corresponds with the peak intensities of the spectra, so it may be that low level signals are nonlinear representations of the intensity received from the star. To test this idea, a 'pedestal' was set up under the spectrum. All intensities below a certain value would be ignored, and possibly, the nonlinear features of the curve would go away. Figures 17b and 17c show the results of installing pedestals of 300 and 400, respectively (the maximum intensity registerable is 400). A pedestal of 300 seems to help from 0.5 to 0.8 microns, but a larger pedestal doesn't help at all. Figure 18 shows a similar ratio for two Xi 2 Ceti spectra with slightly different airmasses (1.67/1.32) and different exposure times (20sec/15sec). Once again the curve is relatively flat over the peak in incoming energy, this time from almost 0.4 to 0.8 microns. (Figure 19 is a
Figure 17a. Ratio of two αLyra spectra, all elements above background included.
Figure 17b. Ratio of same two α-Lyra spectra, this time including no elements less than 300.
Figure 17c. Ratio of same two α Lyra spectra, this time including no elements less than 400.
Figure 18. Ratio of two $\xi^2$ Ceti spectra, including all image elements above background.
typical Xi 2 Ceti spectrum). This time, however, there is a smooth upturn which has some undetermined significance. Thus, star ratios seem to be usable, at best, from 0.4 to 0.8 microns.

Now that there is some idea as to the reliability range of the spectrometer, indefinite though it may be, the Mars spectra can be observed. Figure 20 is a typical Mars spectrum, summed over five vidicon elements down the slit. Note that the peak is in the red, rather than the blue like the two stars' spectra. This is because the stars are both of spectral type A0, while the sun, which is providing the light which is reflected from Mars is a cooler, redder type G. Figure 21 shows a saturated spectrum of Mars. The peak intensity of 4095 is surpassed from 0.5 to 1.0 microns, although around 1.1 microns, the signal is unsaturated. Originally it was thought that the unsaturated portions of a saturated spectrum could be used to extend the range of an unsaturated spectrum which had a very low signal beyond 1.1 microns. The data show, unluckily, that there is little or no overlap between the good signal from one and the good signal from the other type of spectrum. Once again, an attempt was made to do away with low, nonlinear signals with a pedestal. Figures 22a,b, and c show the progressive changes as pedestals of 300 and 400 are subtracted from the original spectrum. Ratios of Mars images seem to be more consistent than those of star images. Figures 23a,b, and c and 24a,b, and c are the results of ratioing different images of Mars to each other. The three images used
Figure 19. A typical $\xi$ Ceti spectrum. Note that the peak is at a longer wavelength and the shape is broader than $\alpha$ Lyra.
Figure 20. A typical Mars spectrum
Figure 21. An overexposed spectrum of Mars. Arrows indicate intensities reading greater than 4095 in at least one element of the image which went into the resolution element.
SMARSC-1 INTEG.

Figure 22a. Mars spectrum
Figure 22b. Mars spectrum with pedestal of 300.

SMARSC-1 INTEG.
Figure 22c. The same Mars spectrum with a pedestal of 400.
were taken within 15 minutes of each other. The same portion of the image was used in each case. Each is a one minute exposure. Note the flat curve from 0.5 to 1.1 micron, indicating better repeatability than for the stars, possibly due to more signal above a nonlinear level. As the pedestal is increased, some of the apparently good data is lost, but the noise is gone by the time a pedestal of 400 is used (c). The Mars spectra are probably recoverable.
Figure 23a. Ratio of two Mars spectra.
Figure 23b. Ratio of two Mars spectra, each of which has a pedestal of 300.
Figure 23c. Ratio of same two Mars spectra, this time with a pedestal of 400 under each.
Figure 24a. Ratio of two Mars spectra, without pedestals.
Figure 24b. Ratio of two Mars spectra, each of which has a pedestal of 300.
Figure 24c. Ratio of same two Mars spectra, each of which now has a pedestal of 400.
V. Recommendations for Future Use of the Vidicon Spectrometer

Although it appears that it will be impossible to do spectral reflectivity work using the vidicon spectrometer due to an inability to meaningfully ratio stars and planets over a useful range, the instrument has advantages which will make it worthwhile to develop it. The combination of good spectral resolution (250 angstroms or better, compared to 300 angstroms for a filter photometer), with complete spectral coverage and high spatial resolution indicate much promise. It appears that the limiting factor will be the response function of the vidicon tube, with its nonlinearities in wavelength and intensity. Once more lab work is done to quantify knowledge about this problem, the instrument will be ready to gather more data. Another problem which may affect the star spectra is the problem of differential diffraction of the star's light by the earth's atmosphere. Different wavelengths, diffracted at slightly different angles would show up at different positions in the smeared out star spectrum, and if the slit is smaller than the apparent diameter of the star, part of the star's spectrum would be lost, in a wavelength-preferential manner. The solution is to widen the slit; although the spectral resolution at the vidicon would be reduced, the spectrum would be much more reliable. But what about the Mars data from Mauna Kea? With the high spatial resolution and apparent good response of the vidicon, something should be recoverable. The planet in the slit occupies
up to 35 elements in a vidicon column when it is about 23 arc
seconds in diameter, and the slit is two elements wide, so, with
good seeing of 1.5 seconds or less, there are fifteen spectra per
spectrometer image. Luckily, the slit passes over some photometer
spots that were taken within days of the vidicon spectrometer run,
allowing relative reflectivities to be obtained, basically
extending the photometer data for more complete surface coverage.
For example, Figure 25 shows the position of the slit on the
planet's disk during one run. This one slit passes through the
Coprates canyon as well as a large dust storm to the southwest of
Coprates. Using a photometer spot as a standard and modifying
resolution to match the photometer, some interesting data should
be forthcoming.
Figure 25. Position of one set of spectra across the disk of Mars. Latitude and longitude of the sub-earth point, S, given.
REFERENCES


