Color Calibration of the Martian Images

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ABSTRACT

Correct color calibration of images sent from Mars is essential to their usefulness in providing mineralogical, geochemical, chemical and, possibly, biological information. This paper demonstrates the impact of correct calibration on the Viking Mission images. The color charts imaged by the Viking Landers are compared to the color chart on the duplicate Viking Lander at the Smithsonian. When the R, G and B levels obtained from the gray panels are aligned, good agreement is found with the Martian red color panel. The B and G color panels in the Viking image "raw data" as published, however, appear greatly dissimilar to the actual panels viewed on Earth. An excess of red is found on all of the Martian blue and green panels. Limits on the multiplicative intensity properties are derived showing that only extreme red illumination could change the Martian B and G color charts so dramatically. Such extreme illuminations are shown to be incompatible with the gray panels. It appears that the true raw image data have been modified prior to publication to convert the blue and green pixels to gray, rendering a grossly changed image.

Key Words: Mars Lander Imagery; Color Image Calibration; Mars Surface Illumination; Viking Color Chart; Viking Lander; Life on Mars; Martian Atmospheric Dust; Viking Raw Image Data

1. INTRODUCTION

Since the Viking Lander sent its first color images in August of 1976, there has been a great deal of difficulty producing color images with a consistent color balance. For the first several hours, the images were shown to have a blue sky with some greenish areas on rocks. After that, a major recalibration was performed, which rendered these Viking images in a much redder tone with a red or pink sky, and the green areas replaced with gray. Several hours after that, the images were recalibrated again with the sky moving toward a more neutral pink, the areas on the rocks remaining grayish[1].

A roundup of subsequent published Martian lander images has shown a wide variety of scene colorations[2,3]. Official published images from Viking, Pathfinder, and, more recently, Mars Exploration Rover (MER), continue to show wide variations of color. The builders of the Viking, Spirit, and Opportunity landers provided two methods for calibrating the color response of Martian imaging. The first method was a derivation of color calibration algorithms using the flight cameras while still on Earth before launch. The actual flight cameras were used to take images on Earth, which were then used to develop color calibration algorithms. These algorithms were tested repeatedly and found to produce reliable color imaging while the spacecraft were still on Earth. These calibration algorithms were then stored for use with the digital data transmitted from Mars. This method of calibration relies on the assumption of stability of the camera instrument during the transit from Earth to Mars.

The other method of color calibration depended on the observation of color calibration charts onboard each of the landers as illuminated by ambient Martian sunlight and skylight. While this technique does not require any assumption of stability of the flight camera during its transit, it does require that assumptions be made about the color of the light with which the color charts are illuminated. Both Viking and MER rovers carried these charts. Current scientific opinion[4,5] holds that the color charts and the Martian surface are illuminated in a very red light caused by large amounts of red dust in the atmosphere. The exact effect of this red dust is not currently known and is often cited as one reason why there is so much variation in color.

Prevailing theories suggest that the putative large amount of dust in the Martian sky also causes both transmitted light from the Sun and scattered light in the sky to be red. The result is a set of color imagery in which the landscape and the sky both appear red. This is the opposite of the sunset situation on Earth, in which the scattered light is blue and the

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directly transmitted light is red because the blue light is subject to Raleigh scattering. The theory of red Martian illumination has even been taken into account in the design of solar cells for use on Mars landers[6] with these cells' photosensitivity peaking in the red.

The two Viking calibration schemes left a great deal of uncertainty. The color calibration algorithms tested on Earth were not guaranteed to work on Mars after such a long and difficult transit, and the color chart calibration scheme had uncertainty caused by the unknown effects of dust on the incident illumination. The unknown illumination makes it difficult to calculate the actual colors of Martian landscape and features. However, the lander color chart can be used to answer the scientific question—"How would the surface materials, sand and rocks of Mars, appear if they were illuminated by standard Earth-like conditions?"

Geologists, and possibly biologists, might be able to identify features on Mars with which they were familiar if they could be shown a coloration of the planet in normal Earth-like illumination. The onboard color charts can be used to answer this question. If colors in Martian lander images are calibrated to match the calibration chart on Earth under known illumination, then the scene surrounding that color chart would appear as on Earth under Earth illumination conditions.

The law of reflectivity states that the observed intensity for any object in a scene is the product of the scene's illumination with the reflectivity of that object. The illumination of a scene must affect all pixels equally. Consider each color image as three sets of digital values, one set for red, one for green and one for blue. The illumination of the scene will multiply all the red digital values by one constant, all the green digital values by a second constant and all the blue digital values by a third. The red, green, and blue channels can thus be calibrated independently. The Martian illuminated calibration chart should be able to be completely converted into a terrestrially illuminated one by the multiplication of one constant for all the red values, a second constant for all the green values and a third for all the blue ones.

$$\left(\begin{array}{c}\text{Red Pixel}\\ \text{Intensities}\end{array}\right) = \begin{array}{c}\text{Red}\\ \text{Illumination}\end{array} \times \left(\begin{array}{c}\text{Red Pixel}\\ \text{Reflectivities}\end{array}\right)$$

$$\left(\begin{array}{c}\text{Green Pixel}\\ \text{Intensities}\end{array}\right) = \begin{array}{c}\text{Green}\\ \text{Illumination}\end{array} \times \left(\begin{array}{c}\text{Green Pixel}\\ \text{Reflectivities}\end{array}\right)$$

$$\left(\begin{array}{c}\text{Blue Pixel}\\ \text{Intensities}\end{array}\right) = \begin{array}{c}\text{Blue}\\ \text{Illumination}\end{array} \times \left(\begin{array}{c}\text{Blue Pixel}\\ \text{Reflectivities}\end{array}\right)$$

Equation 1: Illumination is a set of three independent constants

It is a simple matter to compare the red, green, and blue levels of Martian calibration charts with those of the identical charts on the flight spare lander on Earth. This produces a remapped function that brings all pixels from a condition of unknown Martian illumination to known Earth illumination. Experimental data records have been archived from the Viking project from the original 9-track tapes made for the lander imaging team[7]. This set of all Viking Lander images is currently being distributed by Washington University on CD ROM's. For comparison, actual color charts are currently available from spare flight Viking Lander housed at the Smithsonian National Air and Space Museum. This lander was identical to those actually flown to Mars and could have been sent if a malfunction had developed on either of the other two vehicles. Images of these color charts were obtained using a modern color digital Nikon camera under typical white flashbulb illumination.

2. DATA PROCESSING

Images from the flight spare Viking Lander and forty Viking Lander images were studied to provide pixel coordinate locations for the color calibration charts as shown in Figure 1. Individual pixels within each identified color chart were segregated into groups according to their calibration box if each pixel was in the center half of the box in both horizontal and vertical directions. The median value of each pixel box was calculated for red, green, and blue components.

Figure 2 shows this process for Viking image 11B088. The left side of Figure 2 shows the image with two color charts outlined in yellow. The color chart on the left is illuminated in direct sunlight. The color chart on the right is in the shadow and is therefore illuminated by skylight. The gray columns in the center of Figure 2 show the extracted gray panel levels for each of the gray boxes on the three-color charts. The left column shows the raw values from the color chart on Earth. The middle column shows the raw values from the sunlit color chart on Mars. The right column shows the extracted values from the shaded color chart on Mars. The raw extracted pixel values for the red, green, and blue panels are shown in the upper right of Figure 2. The calibrated color panels are shown in the lower right of Figure 2. These are the red, green, and blue values remapped by the transform between the gray panels on Earth and Mars as described in the next section.

3. GRAY PANEL CALIBRATION PROCEDURE

The complete calibration of the red, green, and blue channels can be accomplished by a comparison of the 11 gray panels on the Earth and Martian color charts. Since gray contains equal amounts of red, green, and blue, the gray panels can be used to calibrate all three channels. Figure 3 shows the gray panel calibration for the sunlit chart of image 11B088. The left half of Figure 3 shows the raw data where the X axis indicates the raw pixel value from the color chart on Earth, and the Y axis shows the raw pixel value from the color chart on Mars. Red circles show the gray color value in the red channel for both Earth and Mars. Green circles show the gray color values for the green channel, and blue circles show the gray color values for the blue channel. Straight red, green, and blue lines show a curve fit through these data points. The curve fits from these gray panels completely define the calibration from Martian illumination to terrestrial. The data from the Red, Green and Blue color charts were then studied to see if their transformation from Martian to terrestrial illumination was the same as that of the gray panels.

Red, green, and blue letters designated “R” show the red, green, and blue channels for the red panel on the calibration charts. Red, green, and blue “G’s” show the red, green, and blue color channels for the green panel, and red, green, and blue “B’s” show the red, green, and blue channel values for the blue panel.

The right side of Figure 3 shows the same data calibrated by the results of the gray panel curve fits. On the Y axis, the Martian pixel values, have been remapped to appropriate Earth scaling by use of the red, green, and blue channel curve fits. By design, all the red, green, and blue circles are now on a diagonal line, showing that the curve fits have indeed remapped each raw Martian pixel value to be equal now to each corresponding raw Earth pixel value. All the red, green, and blue circles now lie on this diagonal line.

The physics of the multiplicative nature of the Martian illumination require that the gray panel remap functions permit remapping the Martian color panels to their observed terrestrial values. The experimental results from the Viking images, however, do not obey this law. As seen in Figure 3, the gray panel remap functions leave the green and blue panels with a large excess of red as compared to the Earth-bound color chart. The calibrated blue panel has almost 3 times the amount of red found on the terrestrial chart, while the calibrated green panel has more than 5 times the amount of red found on the terrestrial color chart. No effect of Martian illumination can explain this fact.

Figure 4 shows the calibration of the chart that is in the shade. This calibration plot is almost identical to that of the sunlight chart. This is remarkable considering:

1. The shaded chart probes lower regions of the calibration curve than the sunlit chart.
2. The illumination of the shaded chart (from the sky) is much different in character than illumination of the sunlit chart.

The percentage excess red in both the blue and green color panels in the shade is almost exactly the same as for the sunlit chart. The result of these excesses can be seen on the lower left of Figure 2. The red, green, and blue, from the Earth-based chart are shown in the left column. The calibrated reds, greens, and blues from the two Martian charts are shown in the center and right columns. The reds from Earth and Mars appear to have approximately the same coloration. However, the Martian greens look somewhat olive, and the Martian blues are distinctly purple. Both the greens and the blues of the Martian images show an excess of red. In all Viking imagery, the blue panels look distinctly purple when compared to the color calibration chart as seen on Earth.

Under both illuminations, the appearance of the blue and green color panels, relative to the grays, cannot be explained by an unknown multiplicative illumination. And this problem seems to manifest itself in an identical fashion for both direct sunlit and indirect skylit illuminations. The green and blue panels and the scene may appear to be red because of the illumination; however, the 11 gray panels are unaffected. The gray panels and the gray parts of the spacecraft should be tinted toward the red in the same fashion as the rocks, the sky, and the blue and green panels. However, according to the digital pixel values, the gray panels do not appear to be participating in this red illumination. Another way to measure this effect is to see what illumination is inferred from the gray panels and from the colored panels. Figure 5 shows the multiplicity of illumination that would be required from the pixel values observed in each panel.

When the curves are fit on Figures 3 and 4, the log of the Martian intensity has a linear relation to the Earth's intensity. These slopes are almost equal and can be taken as an indication that the illumination of the gray panels on Mars is virtually the same as that of the white flashbulb illumination on Earth used in this study. The fact that these slopes are almost identical confirms the analysis that the illumination of the gray panels on the Earth and Mars are virtually identical. In any event, the calibration remapping procedure converts the Martian illumination of the gray panels to white (by definition).

When the calibrated red panel is compared to the Earth-bound red panel, the illumination inferred on Mars is slightly shifted toward the blue. The red panel is not quite as red on Mars as is its terrestrial counterpart; however, the inferred illumination is a bluish-hue very close to white. The key finding is that the inferred illumination for the green and blue panels is enormously red.

For the green panel to be as depicted in the Viking images, its illumination would have to be 10 times stronger in the red channel than in the green and blue. The green panel on Earth has a very small response in the red channel. The green panel on Mars shows a substantial fraction of red. The only way this could be caused by the illumination would be if the ratio of red-to-blue incident to this panel were 10 to 1. The situation on the blue panel is very similar. The illumination ratio of red-to-blue is a factor of four. However, the red-to-blue ratio for the red and gray panels is unity. How can these panels, located only centimeters apart, be subjected to such different illuminations?

The results shown above are from the analysis of only one Viking Lander image, 11B088. In order to do a statistically significant survey of all the Viking color imagery under a variety of illumination conditions varying from dawn to noon to dusk, a total of 40 color charts was analyzed, 28 for Lander 1 and 12 for Lander 2. These constitute all the color charts that were either completely in sunshine or completely in shade.

Chart Condition	Images Used
Viking 1 Sunlight	12B069, 11B088, 11G227, 11H050, 11I049*, 11I082, 11I115, 11I148, 12C083*, 12C153*, 12C163*, 12C229, 12D038*, 12D136*, 12F134, 12G081, 12I068, 12I101, 12I134 ,12I167
Viking 1 Shade	12B069, 11B088
Viking 2 Sunlight	22A166, 21E107
Viking 2 Shade	22A158, 21A210*, 21A218, 21B043, 21B104, 21C056*, 21C173*

* Two calibration charts used from this image

Table 1: Viking images used in the color chart analysis

Figure 6 shows the results from 26 Viking Lander 1 color charts, which were illuminated by sunlight. The upper left shows the results of calibration of the gray panels. The results form a tight pattern of equal intensity around the diagonal line. The upper right plot shows the results from the red color panel. The red value for the Martian red color panel is almost perfect compared to its terrestrial counterpart. The green and blue panels are slightly brighter than their terrestrial counterparts. The Martian red panels look slightly more blue and green than their terrestrial counterparts. However, the bottom half of the figure shows the results for the green and blue panels. The green panel has a tremendous excess of red when compared to the terrestrial panel. The amount of red in the green panel is almost 80% of the green in the green panel. The scatter on these results is very small considering that these images represent illumination from the Sun at all different times of the day. The green values for the green panel appear to be weak by about 5%. This deficiency in green may not be significant; however, the excess in red is undeniable.

A similar situation exists on the blue color panel. The amount of red seen is at least 3 times higher than seen on Earth, and is almost as strong as the blue itself. The blue panels also appear to have a slight deficiency in blue and perhaps a more significant deficiency in green. The terrestrial blue panel has a strong green content that is not completely seen in the Martian charts. The red excess, however, is unmistakable, and more striking than its excess in the green panel. The red and gray panels appear consistent with the same illumination, but the blue and green panels appear to be under very strong red illumination. The scatter for all these data is remarkably small considering the number of charts analyzed and the variety of times at which the images were taken.

Figure 7 shows the scatter plot for the results of two Viking 1 calibration charts that were in the shade. The results are remarkably similar to those from the sunlit charts. The excess red for the blue and green panels is almost identical. All the values are very close to the scatter shown for the sunlit charts. This is important because gray calibration curves are formed at much lower intensity for the shaded charts than for the sunlit charts; however, they still seem to produce almost the same calibrated results.

Figures 8 and 9 show the results of the same analysis on Viking Lander 2, which, being at higher latitude, might experience different illumination or more atmospheric effects from lower sun elevations. The results are nearly identical to those from Viking Lander 1. The green and blue panels show large excesses of red and the blue panel shows a significant deficit in green. The results from all 40 color charts are remarkably similar and tend to indicate a potential problem in the red channels of the archived Viking Lander data. The red channels appear to be behaving normally on pixels that are either red or gray, but appear to be showing excess intensity on pixels known to be blue or green. This indicates a possible processing bleed-through problem from the blue and green channels into the red channel. This might have occurred through a bleed-through error of the form of Equation 2, or, more realistically, of the form of Equation 3.

$$\text{Red} \quad = \quad \text{the greater of} \quad \{ \ \text{Red}, \quad 0.8\ \text{Green}, \quad \text{or} \quad 0.9\ \text{Blue} \ \}$$

Equation 2: Possible formula for Blue and Green bleed-through to the Red channel

$$\text{Red} = \ln(e^{\text{Red}} + e^{0.8\ \text{Green}} + e^{0.9\ \text{Blue}})$$

Equation 3: Possible analytic formula for Blue and Green bleed-through to the Red channel

The bleed-through error appears not to be a function of illumination intensity. It appears to be a function of the ratio of red-to-blue-or red-to-green at all intensities. Intensity seems to have added to the red channel wherever the blue or green significantly exceeded the red. In other words, the red channel doesn't appear to be independent, but rather has been modified based on the content of the other two channels.

This appears to be an irreversible transformation, mapping many colors into one. A pixel that appears gray may in fact have been gray, or it may have been blue-green and converted to gray by the addition of excess intensity in the red. The blue color panel appears purple, but presumably so would a purple panel.

4. RECOVERY OF THE RED CHANNEL

If the blue and green channels are approximately correct, it may be possible to reconstruct the red channel by subtracting the blue and green channels from a black and white image taken if taken with a broadband filter. During the Viking mission, basic black and white filters were used with designation BB1 through BB4 for high-resolution black and white imagery. However, these filters were never used at the same resolution as the color red, green, and blue filters, and there are no co-located images in the black and white and colored filters. However, an extremely broadband filter, called the survey (SUR) filter, was used to make images that were co-located with red, green, and blue color images. There were a number of attempts to generate a "seven filter multi-spectral sequence." The seven filters being the traditional red, green, blue, three infrared bands and the very broadband survey filter. Image 11B088 is a part of one of these multi-spectral sequences. The red, green, and blue filters are combined to form image 11B088. The infrared 1, infrared 2, and infrared 3 filters are combined to form image 11B089. The single survey filter is used to form image 11B090.

Image ID	Start Time	Image Description	Filter	Comment
11B088-BLU	1976-08-30 T10:02:23Z	COLOR TRIPLET	BLUE	SEVEN FILTER MULTISPECTRAL SEQUENCE
11B088-GRN	1976-08-30 T10:02:23Z	COLOR TRIPLET	GREEN	SEVEN FILTER MULTISPECTRAL SEQUENCE
11B088-RED	1976-08-30 T10:02:23Z	COLOR TRIPLET	RED	SEVEN FILTER MULTISPECTRAL SEQUENCE
11B089-IR1	1976-08-30 T10:05:53Z	INFRARED TRIPLET	IR1	SEVEN FILTER MULTISPECTRAL SEQUENCE
11B089-IR2	1976-08-30 T10:05:53Z	INFRARED TRIPLET	IR2	SEVEN FILTER MULTISPECTRAL SEQUENCE
11B089-IR3	1976-08-30 T10:05:53Z	INFRARED TRIPLET	IR3	SEVEN FILTER MULTISPECTRAL SEQUENCE
11B090-SUR	1976-08-30 T10:09:23Z	LOW RESOLUTION SINGLET	SURVEY	SEVEN FILTER MULTISPECTRAL SEQUENCE

Table 2: Viking images used in red channel replacement

Figure 10 shows the spectral characteristics of these seven filters[8]. The survey filter has an enormous band covering all of the visible spectrum and extending out to 1100 nanometers in the infrared. The red, green, and blue filters are shown occupying the visible portion of the spectrum, each filter overlapping slightly with its neighbor. It's important to note, however, that there is no overlap at all between the blue and red filters. It is, therefore, very difficult to imagine how the red filter could be responsive to the blue color panel.

Assuming that the survey, blue, green, infrared 1, infrared 2, and infrared 3 channels are usable, it should be possible to construct an approximation to the red channel by subtracting out the blue and green and infrared channels from the survey channel. This would leave a very broad red channel with an infrared response out to 850 nanometers; however, it should be an interesting experiment to see if the reconstructed red channel could be used as a replacement for the existing red channel.

Figure 11 shows an initial attempt at this reconstruction with the infrared not yet subtracted. The left image in Figure 11 shows the original red filter. The next image shows a potential replacement red filter, based on taking the survey filter and subtracting the blue and green as indicated in the formula. The next image is the original color image 11B088 and the right-most image is the same image with the red channel replaced. Obviously, the new red channel is weaker. The sky is now blue, and an interesting change can be seen in the landscape out toward the horizon. While the basic color of the landscape is the same reddish tone, gray areas around rocks are now rendered in green. The coloration of this landscape is typical of that seen in the originally calibrated images A006 for the first few hours after they were received. The coloration of these rocky areas will probably intensify once the infrared is taken out of this replacement red channel. These multi-spectral sequences give a unique opportunity to allow the red channel to be regenerated. Approximately 20 sequences exist from both lander sites.

The red channel is a source of controversy today in the Spirit and Odyssey images. Most of the Spirit and Odyssey color images are displayed in approximate true color by the combination of the infrared green and blue filters. The lack of color images using the red, green, and blue filters has been dismaying in this most recent Mars lander mission. Further study of the Viking red channel could be very fruitful in resolving these long-lasting questions of Martian lander color calibration.

5. SUMMARY

In the last 28 years, large variations in the coloring of published Martian lander images have failed to coalesce into a consensus. The reason given for this wide range of image color calibration is the uncertainty in the color calibration caused by unknown Martian illumination. On some future date, a spacecraft may land on Mars carrying its own calibration light source of known spectral properties. Until this occurs, the illumination of Martian color calibration charts will continue to be an issue. An attempt is made in this paper to analyze the illumination of the Martian color charts for consistency. These Martian color charts show a consistent excess red illumination for the blue and green panels, but not for the red panel or any of the gray panels.

A tenable hypothesis supporting the published calibration charts does not appear to be possible. Instead, a more likely hypothesis is that a problem exists with the red channel. Large values in the blue and green channel appear to be bleeding over into the red channel. Pixels that would have been blue or green appear to have been grayed out by the addition of red. An initial attempt has been made to recover the red channel by subtracting blue and green from a co-registered black and white image. This initial attempt did not take into account the large infrared component of the black and white survey filter on Viking. A more robust attempt, subtracting five channels, could provide improved results. These results may show even more of the green rock colorations seen in the first Viking images. Many powerful mathematical techniques can be used to estimate the relative strength of the infrared blue and green channels contribution to the survey channel. Contribution estimates can be made based on the overlap of measured bandwidths or from mathematical correlation techniques comparing variations in the survey channel with each of the other five channels. A sufficiently rigorous attempt at reconstructing the red channel might go a long towards solving the current color calibration dilemma.

FIGURES

Figure 1. Color Chart - Earth Reference from Flight Spare Viking Lander

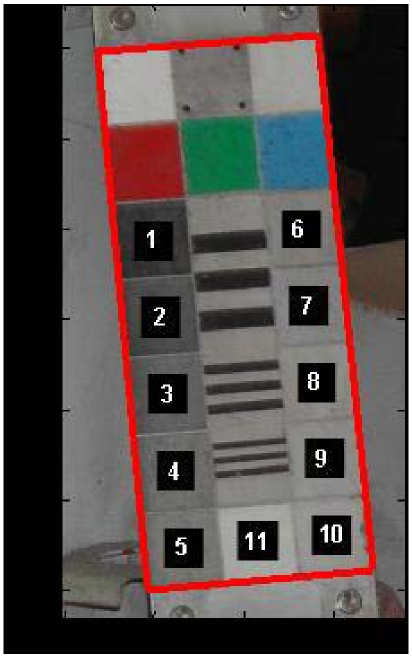


Figure 10. Red Channel can be reconstructed from Survey Channel (SUR) by subtracting B, G, IR1, IR2 & IR3

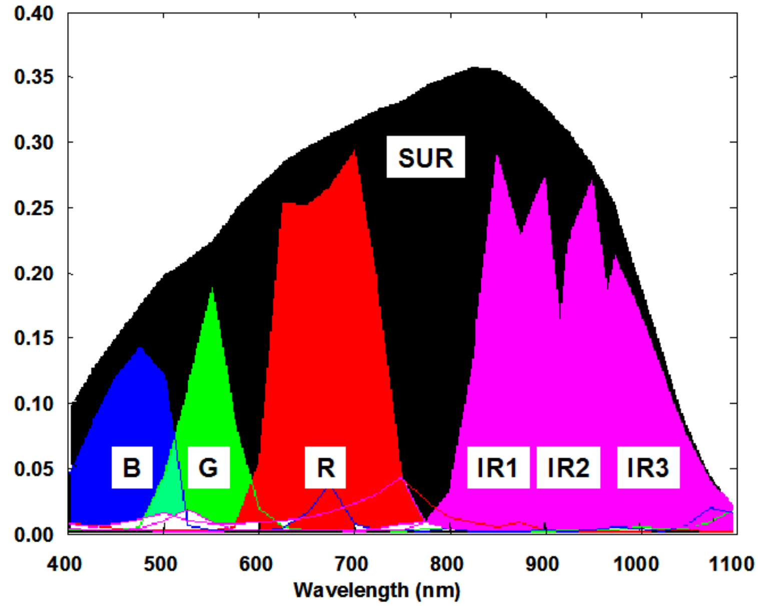


Figure 2. Median Colors Extracted from Image 11B088

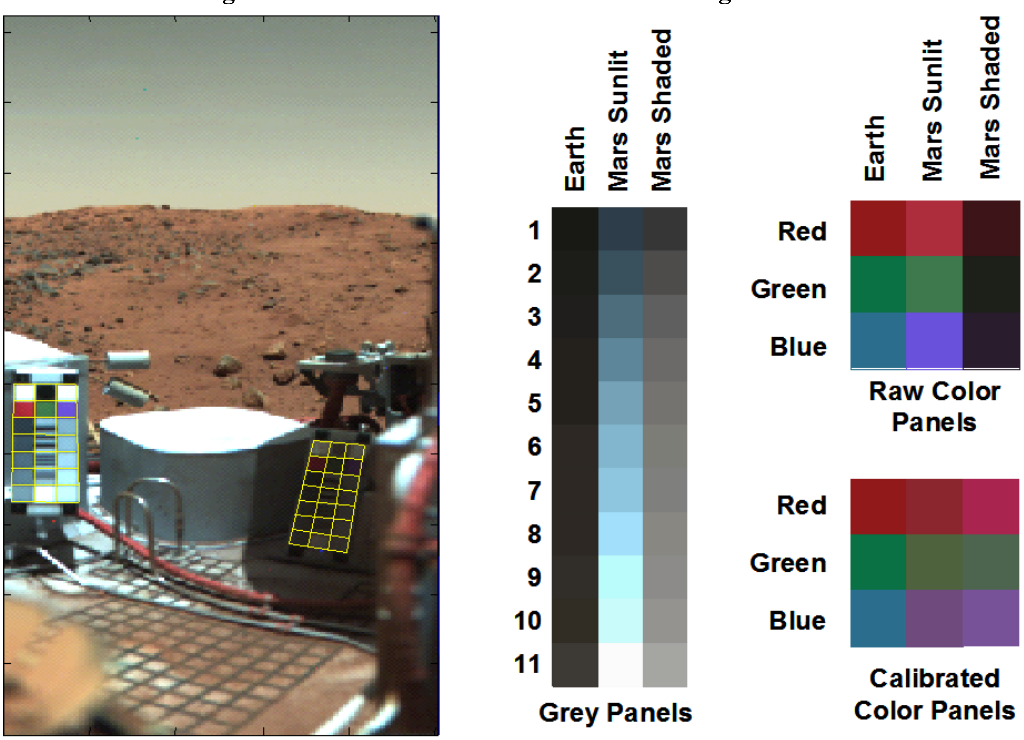


Figure 3. Grey Panel Calibration for Sunlit Chart

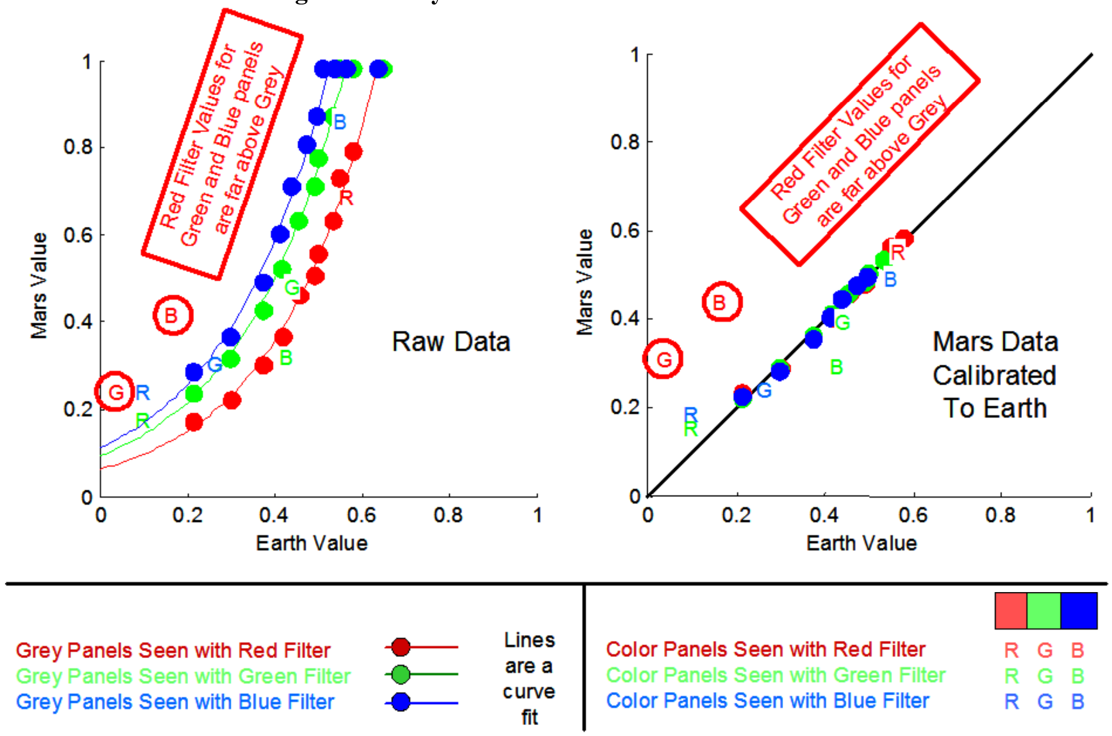


Figure 4. Grey Panel Calibration for Shaded Chart

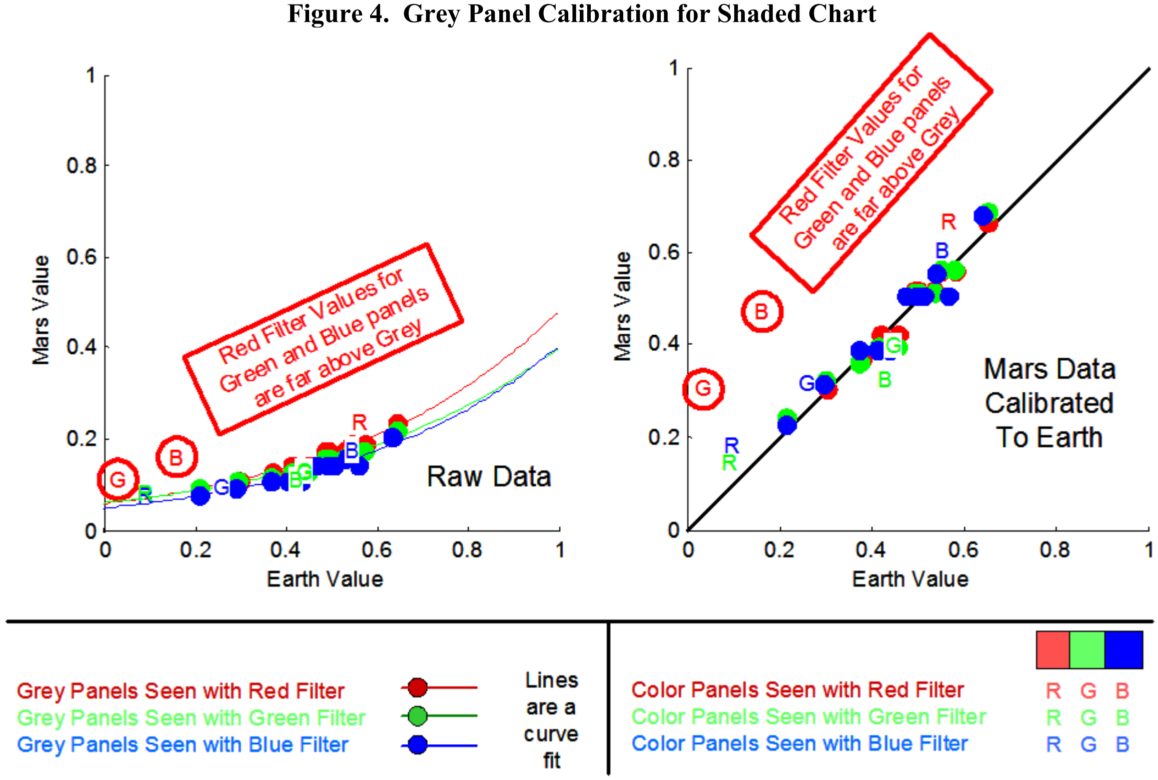


Figure 5. Constraints on Unknown Illumination

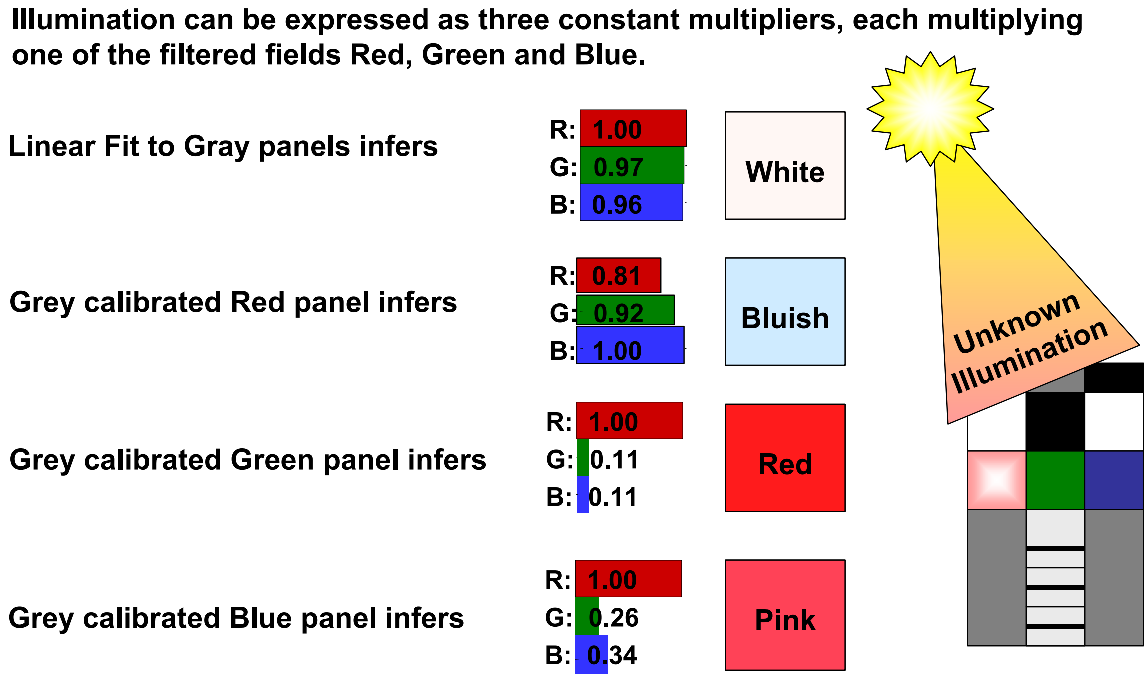


Figure 6. Viking 1 in Sunlight (26 Charts)

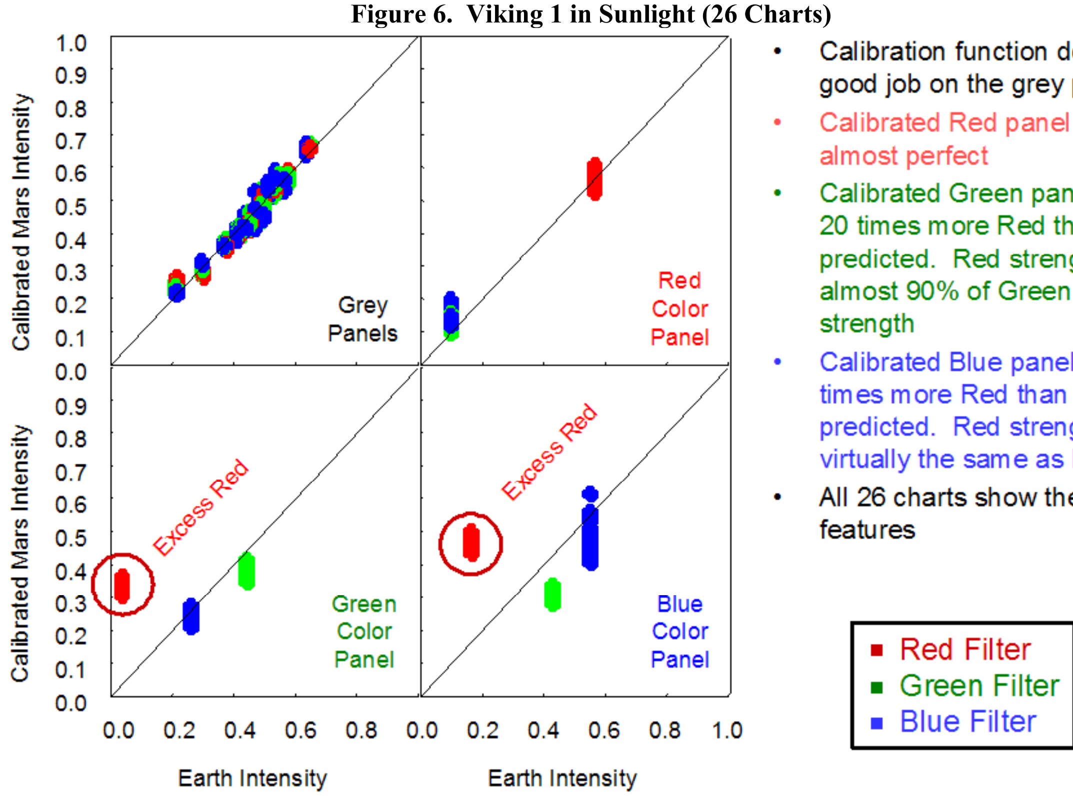
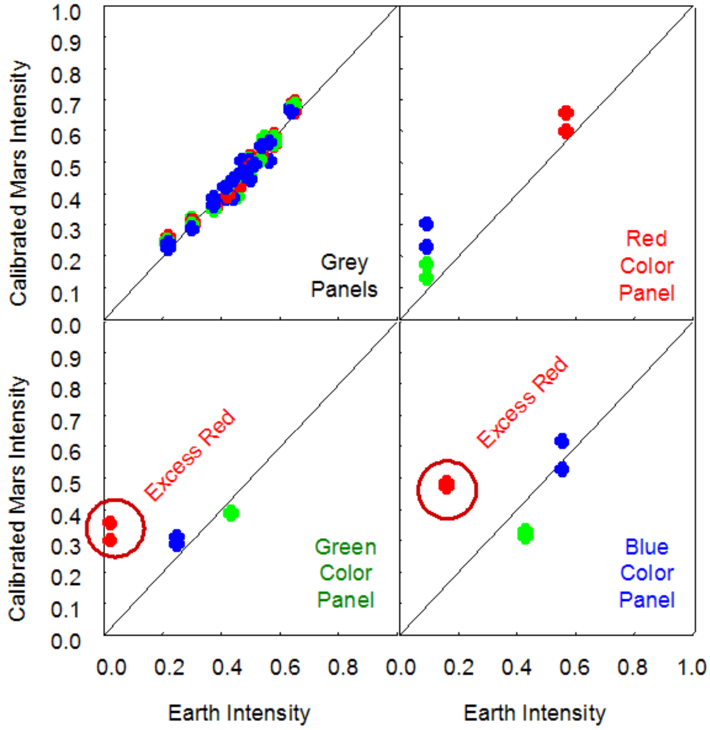
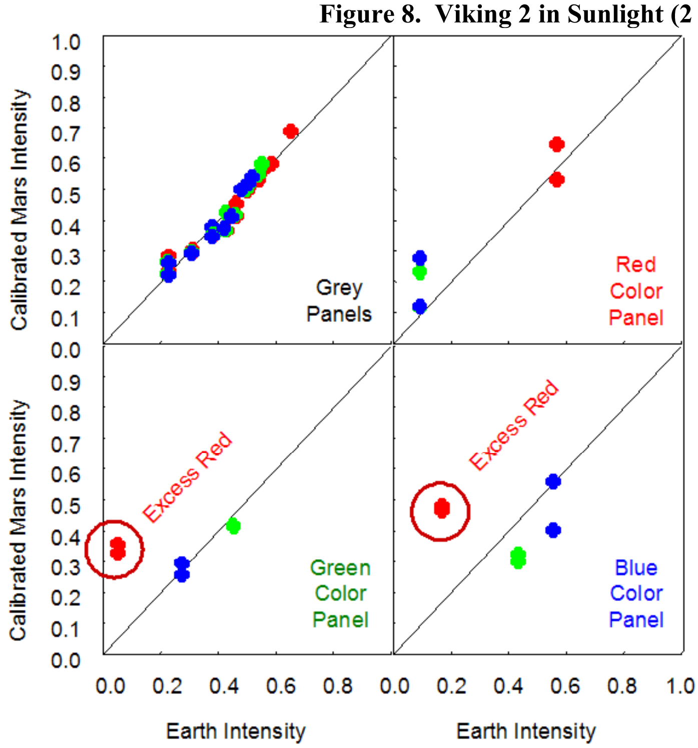


Figure 7. Viking 1 in Shadow (2 Charts)



- Calibration function does a good job on the grey panels
- Calibrated Red panel is almost perfect
- Calibrated Green panel has 20 times more Red than predicted. Red strength is almost 90% of Green strength
- Calibrated Blue panel has 3 times more Red than predicted. Red strength is virtually the same as Blue
- Both charts show these features

Figure 8. Viking 2 in Sunlight (2 Charts)



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- Calibrated Blue panel has 3 times more Red than predicted. Red strength is virtually the same as Blue
- Both charts show these features

Figure 9. Viking 2 Charts in Shadow (10 Charts)

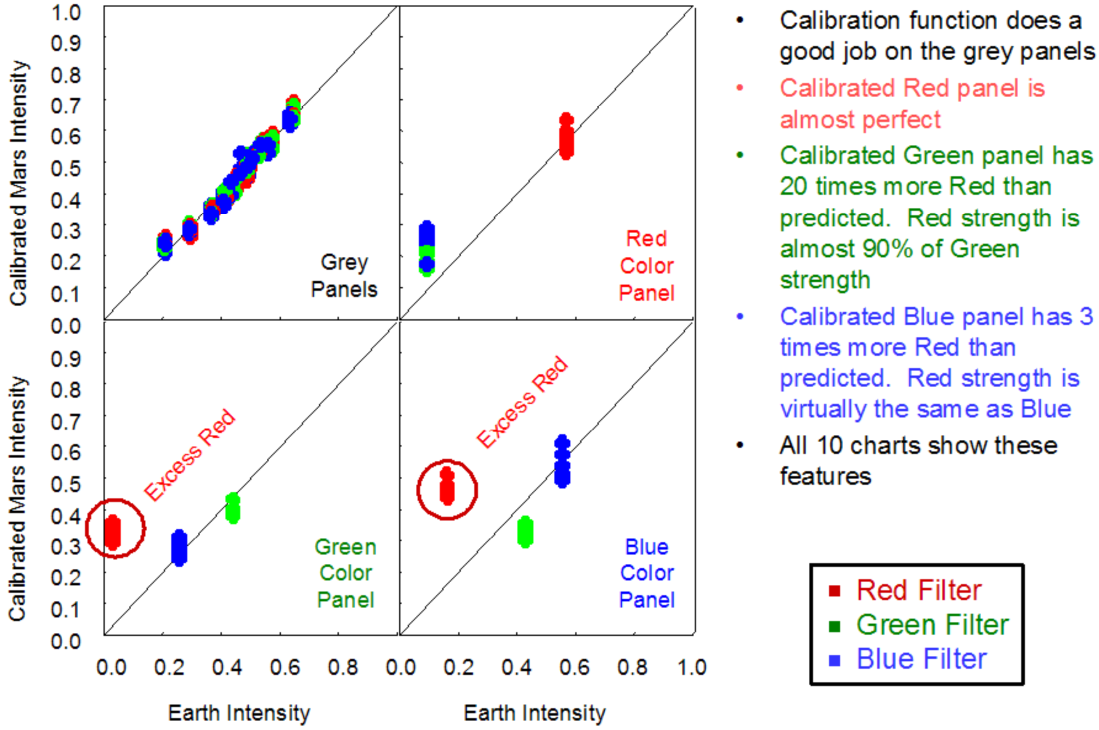
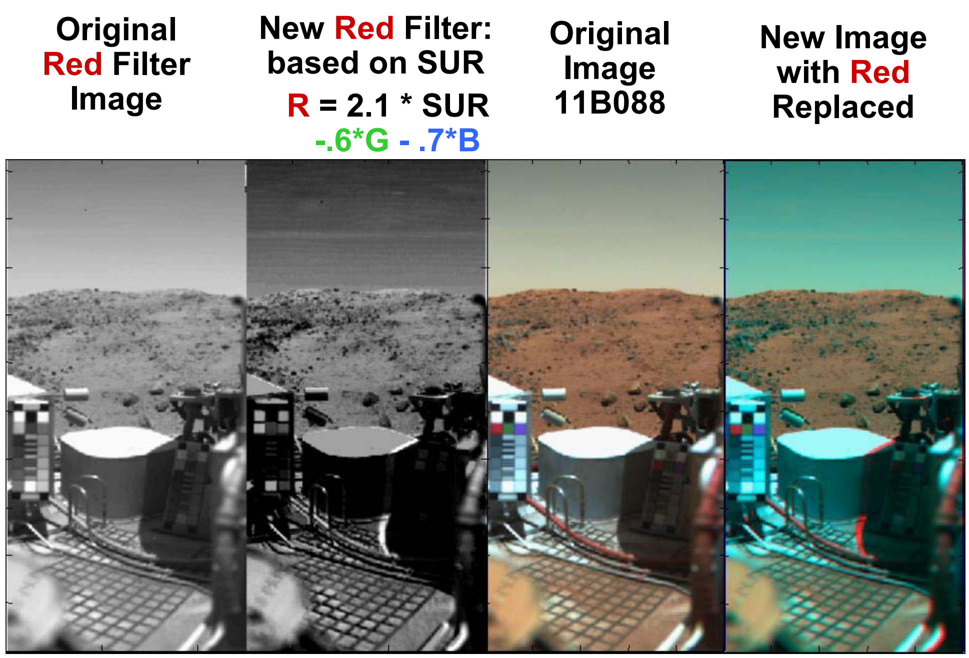


Figure 11. Attempt to Reconstruct Red Filter using SUR



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