

# Color Calibration of Spirit and Opportunity Rover Images

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## ABSTRACT

The controversy about color Mars lander image calibration, begun in 1976 during the Viking mission, continues with the 2004 Spirit and Opportunity missions. Officially released color images at web site "Photojournal.JPL.NASA.Gov" continue to show wide variation. Two sets of filters are used by NASA to produce color images from Spirit. One conventional set of red, green and blue filters has been used for images of the calibration chart alone and small pieces of the soil. Another set of infra-red, green and blue filters is used for larger panoramic images. While most objects in the Martian scene are not affected by this change, the appearance of the color calibration chart changes drastically. An extreme example of this can be found in the comparison of the blue color panel using the two different sets of filters. When the blue panel is seen in the panorama images, it appears to be bright red. Small blue wire ties on the rover also appear to be bright red in the panoramas. NASA claims that the blue color panel is unusually reflective in the near infra-red. This makes inspection of the color balance more difficult and many problems exist in published "true color" images. This paper will round up this and other issues involving Spirit color image calibration.

**Key Words:** Mars Lander Imagery, Color Image Calibration, Mars Surface Illumination, Spirit Color Chart, Spirit Rover, Life on Mars, Martian Atmospheric Dust, Near Infra-red

## 1. INTRODUCTION

As of 2004, five scientific spacecraft have successfully landed on the surface of Mars. Each of these spacecraft have carried, among other instruments, at least one color imaging system; however, the color calibration of images returned from Mars has been a source of continuing difficulty since the first pictures from the Viking 1 lander in 1976. All five lander imaging systems were calibrated on Earth prior to launch. Additionally, four of these five landers had onboard calibration in the form of color calibration charts which were held out in the ambient Mars illumination. Calibrations of these color imaging systems made on Earth have proved unreliable due to the long time elapsing between instrument calibration and its actual use on the surface of Mars. Color calibration charts held in Martian ambient light have not completely solved the problem because the coloration of the ambient illumination is still unknown. Current scientific opinion holds that large amounts of red dust in the Martian atmosphere renders both the direct lighting and the scattered skylighting to be heavily colored toward the red. This means that color calibration charts, whether in direct sunlight or in shadow, appear redder on the surface of Mars than they would under ordinary lighting conditions on Earth<sup>1</sup>. As a result of this uncertainty in Martian illumination, the final published images from the Martian surface show a great variation in color calibration. Published images show sky colorations from gray to pink to orange. Landscape colorations have similar variations<sup>2</sup>.

The situation with color calibration of Martian images has not improved with the advent of the 2004 Mars explorations rovers named Spirit and Opportunity<sup>3</sup>. This fact was emphasized by the release of the first large panoramic color picture from the Spirit Rover taken on Sol 5. This panorama covered a large extent of the Mars landscape at very high resolution and was constructed from a mosaic of many smaller images. The Spirit and Opportunity Rovers used a new pan cam charge coupled device imaging system that had very high pixel resolution<sup>4</sup>. The color calibration chart was visible in this mosaic and due to the high resolution of the imaging system. It can be seen in a blowup very clearly. Figure 1 shows this large mosaic panorama with the color calibration chart in the middle near the bottom of the scene. Figure 1 also shows an enlargement of the area immediately around the color chart. The details in this enlargement demonstrate the enormous resolution of the Pancam.

Figure 1 additionally shows an image taken of the color calibration chart taken explicitly for the purpose of calibrating the camera. The comparison between these two images of the color calibration chart is very striking. The blue

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calibration panel on the lower right side of the chart appears to be bright red in the released panoramic image. The yellow and green calibration images both appear to be sand colored, with only the red color chart appearing to have correct color. A wire cable harness that appears to be blue in the calibration image is also red in the published panoramic image. At first glance, the appearance of the color calibration chart in the released panoramic image does not tend to indicate that the colors have been correctly balanced. In fact, a look at the raw digital pixel values for the blue chip shows that the blue digital value is the lowest of all three colors. The values for red, green, and blue are (189, 33, 33). At first glance, this resembles a color inversion. The appearance of this color calibration chart certainly cannot be explained by any possible illumination of the Martian scene.

It is imperative to try to understand the difference between the calibration image taken on Spirit Sol 2 and the panoramic image taken on Sol 5. Figure 2 shows the measured color panel reflectivity taken by Spirit on Sol 2<sup>5</sup>. All four color chips were imaged by the left and right panoramic cameras using six filters in each of the cameras. The left camera had a number of filters in the visible and infrared regions. The right camera had only infrared filters. The left and right camera had two matching infrared filters that could be used for stereo photography. All Spirit and Opportunity color images are from the left panoramic camera. These filters are very narrow in wavelength, usually 20 or 30 nm wide, spaced approximately 50-100 nm apart. This is much finer spectral resolution than is normally used in color photography and much finer wavelength resolution than the human eye is capable of.

The plot on the left side of Figure 2 shows the measured reflectivities on the surface of Mars at each of the filter wavelengths as compared with the measured reflectivity on Earth, recognizing the fact that the absolute reflectivity of the color panels on Mars is not certain due to the uncertainty of the illumination of the Martian panels. However, leaving room for that uncertainty, the reflectivities measured on Mars and on Earth are in good agreement. The reflectivity of the blue color panel is very large, between 425 and 475 nm. However, the blue panel is much more reflective in the near infrared transitioning to high reflectivity at 700 nm, which is exactly at the limit of human vision. Much of the mystery of the panoramic image can be explained by the fact that the calibration image uses filter L4 while the panoramic image uses filter L2 for its red channel. The reflectance of the blue color panel is very low at 600 nm where the bandpass at filter L4; however, it is extremely high at 750 nm, which is the bandpass of filter L2. Most ordinary pigments seen in nature do not change reflectivity as rapidly and drastically as the material used on the blue color panel.

The image on the upper right of Figure 2 shows the released composite image of the color chart using filters 4, 5, and 6. However, if that same composite is made using the data from the L2 filter instead of the L4 filter, the image that results is shown on the lower right of Figure 2. Visually, this color chart has some of the general characteristics of the one shown in the Sol 5 panoramic image; however, replacement of the red channel with near infrared does not account for the very low value of blue seen in the panoramic image. Blue levels in the calibration image should have the appropriate value of blue no matter which red channel is used. The filter difference between the calibration image and the panoramic image is merely the choice for the red channel. Filters for the blue and green channel are identical; therefore it is difficult to understand the lack of blue in the blue colored panel of the panoramic image. This low value of blue cannot of yet be explained.

Some of the difficulty has to do with the Pancam system and its choice of filters. Figure 3 shows two images of the calibration target taken on Earth compared with the standard calibration image taken by Spirit on Mars. The image in Figure 3 on the left shows the calibration target as viewed by an ordinary digital camera on Earth. The center image in Figure 3 shows the same calibration taken by the Pan camera on Earth using filters 4, 5, and 6. The Pancam does an acceptable job on the red, blue, and green panels; however, the yellow panel appears orange in the Pancam image. This may be a result of the unusual pigments used on the calibration target and the narrowness of the Pancam filters. The image in Figure 3 on the far right shows the calibration target taken by the Pancam on Mars. The Pancam image on Earth and the Pancam image on Mars appear quite similar. This is not the result one would expect if the illumination on Mars was substantially redder than that on Earth.

The grays on the Martian color chart appear to be color balanced in the same way as the grays in the calibration on Earth; thus NASA has achieved an image of the Martian color calibration chart that appears similar to the calibration chart viewed on Earth under Earth's illumination. In addition to color calibration shown here for these three filters, L4, L5, and L6, the graphs in Figure 2 show that experimental data taken on Mars match known reflectivities from the chart

on Earth for all filter bands<sup>6</sup>. The accuracy of this plot is remarkable since the illumination spectrum on Mars at all 14 filter bands is still very uncertain. The chart in Figure 2, however, indicates that a detailed model must exist for converting images taken under Martian illumination into images as they would appear under Earth-like illumination. The chart in Figure 2 therefore implies that a detailed model of illumination on Mars exists. Since similar looking color charts have been produced for filters 4, 5, and 6, a critical question becomes one of comparing the color chart in the panorama to the color chart shown in the calibration image.

## 2. CALIBRATION USED ON PANORAMIC IMAGE

Figure 4 shows the key comparison. On the left side of Figure 4 is the color chart from the sequence of calibration images 2P129025698ESF0327P2839LXM1, where X = 2, 5, or 6. This image is the color composite resulting when filter L2 is used for red, L5 is used for green and L6 is used for blue. This is the same image as shown on the far right of Figure 3 except filter L4 for red has been placed by L2. When evaluating any pixel, the blue and green numbers remain the same, but the red pixel values are different; in particular the eye is drawn toward the blue color panel. The blue color panel has 165 counts in blue as before; however, it now has 255 counts in the red channel because of its unusual reflectivity in the L2 filter band.

The right side of Figure 4 shows the color chart used in the mosaic panorama. The blue color panel looks extremely red. This, of course, is because of the large value in the red channel, which has already been explained. However, the blue color panel has only 33 counts of blue. This is five times less blue than in the image produced for calibration purposes.

The inferred blue illumination of the blue panel is five times lower than on Earth. The inferred blue illumination of the gray panels is approximately the same as Earth's. The color chart seen in the mosaic panorama is different from the one produced by the calibration study in a way that implies extreme Martian illumination and one that is not consistent from panel to panel.

The left side of Figure 5 shows the raw pixel comparison between color chart elements used in the calibration study and color chart elements used in the mosaic panorama. Red dots represent red pixel values from the gray panels, green dots represent green pixel values from the gray panels, and blue dots represent blue pixel values from the gray panels. Straight line fits are shown connecting the red, green, and blue pixel values from the gray panels. The elements from the red, yellow, green, and blue panels are also shown by the letters R, Y, G, and B. Red letters for the red filter values, green letters for the green filters values, and blue letters for the blue filter values.

The most startling feature on this graph is the absence of blue in the blue color panel. The cause for the low blue values of seems to be distributed amongst a number of factors.

The gray panels show the camera to be linear, but show that there is a great offset between the calibration image and the mosaic panorama image. All the mosaic panorama values are darker than the ones used in the calibration image. This offset, while great for the red channel, is even a greater value for the green, and largest of all for the blue. An offset in intensity is not what would be expected by a change in illumination. A change in illumination is a multiplicative constant, changing only the slope of the gray pixel values, not the intercept. The slope for red, green, and blue appear to be identical, indicating that the illumination derived from the gray panels in the mosaic panorama is the same as the illumination used on Earth. The large and different offsets are not explainable as an illumination effect. But even though a large offset is used for the blue values of the gray panels, an even larger offset is seen for the blue color panel itself.

Even when these gray panel results are used as a calibration the low blue intensities can't be explained. This is shown on the right-hand side of Figure 5, where all the pixel values in the mosaic panorama have been converted by the curve fit to the gray panels into the illumination of the Mars calibration image. Even taking the very unusual results of the gray panel into account, the reflectivity of the blue panel shown as a blue B falls far below the values shown in the calibrated Martian image. The discrepancy in the intensity of the blue panel is thus distributed amongst several causes, each unexplainable and having a cumulative effect of eliminating blue features in the mosaic panorama.

When the mosaic panorama was constructed using filters L2, L5, and L6, a color calibration chart with large amounts of red on the blue panel was a guaranteed outcome. This large amount of red masks the fact that the blue in the mosaic panorama is almost completely missing. This fact would have been much more apparent if filters L4, L5, and L6 had been used, since the blue panel has almost no reflectivity in the L4 red band. This redness is just an unusual quirk of the narrow filter bands used and the unusual pigment placed on the blue panel.

Nature is less precise. The broadband response of red, green, and blue cones in the human eye is sufficient to extract most of the color information from a landscape scene. This fact is very apparent in Figure 6, a landscape scene taken by the Opportunity Rover using most of the available filters.

A color composite made with filters L4, L5, and L6 looks almost identical to the color composite made with filters L2, L5, and L6. For the purposes of viewing a landscape, the L2 and L4 filters are almost identical. The human eye finds very few differences between the image on the left and the one on the right. If anything, the contrast of greenish rocks and objects, especially near the bottom of the image, appears to be enhanced when using filter L2 for red instead of L4. Thus, it is doubtful if the original mosaic panorama would look very much different if it were taken with filters L4, L5, and L6. The one exception to this would be the color chart itself. The blue color panel in this case would not be red, but would appear almost black. Without the red of the L2 filter landing on the blue color panel, there would be almost no reflectivity from that blue color panel in the mosaic panorama.

The substitution of the L2 filter for the L4 has virtually no impact on the landscape scenery, but does cover up the fact that data in the blue channel, L6, has been mishandled. Panoramic production pictures that show the color calibration chart taken in filters L2, L5, and L6 should show color calibration panels similar to those on the left-hand side of Figure 4. When this occurs, views of the Martian landscape will be portrayed in a manner similar to the same scenery being illuminated under Earth illumination conditions.

Perhaps this is the best goal for the production of color imagery from Mars. Rather than search endlessly for the unknown illumination of the surface, the color calibration charts should be used to render the Martian scenery as it would appear on Earth. Martian objects would be more easily understood if they were illuminated by lighting conditions with which we are all familiar.

In any case, the corrections for the Martian illumination are suspect. In any published final image, it is essential that the assumed illumination model be the same for the colored panels as it is for the gray. These panels are only centimeters apart and they are surely bathed in identical illumination.

### 3. SUMMARY

Images of the color calibration chart taken on Mars for the express purpose of verifying calibration seem to be in reasonable agreement with calibration images taken on Earth under Earth-like illumination conditions. However, calibration charts shown inadvertently on production panoramic images are not compatible with those images made for the express purpose of calibration. This incompatibility is in two areas. First, the gray panel pixel values, while having the same slope in both images, have substantially different offsets. A hypothesis of variable illumination is only expected to change the slope. The offset at the darkest pixel values should always be zero. Black pixels, which are at the intercept, should not be affected by illumination. The observed offsets are preferential to the red and minimize blue. However, in addition to these unusual linear changes, there is also observed a non-linear suppression of blue reflectivity in the L6 channel on the blue color panel. The L6 channel in the mosaic panorama shows virtually no response on the blue color panel.

Color calibration charts in production MER images should either match the charts generated during calibration or should differ from them by a single uniform illumination model, expressed as overall multipliers for the red, green and blue channels.

Otherwise, production Martian images should either be made using the color chart to match Earth illumination, or should be made by trusting the luminosity calibrations made on Earth before launch.



Figure 4. Color Chart Processed for the Panorama and Processed for Calibration Check

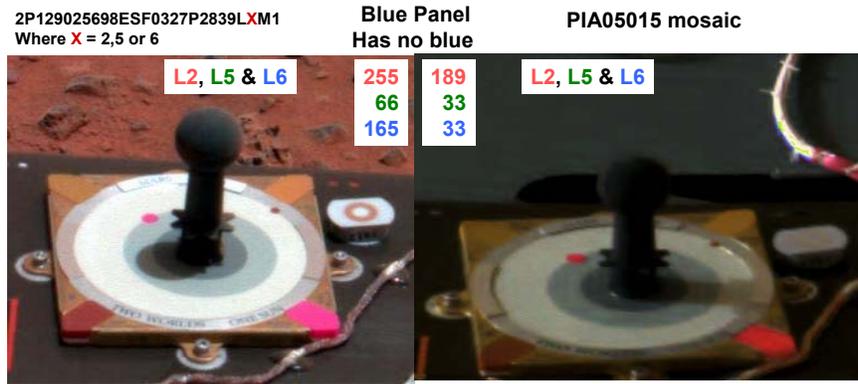


Figure 5. Pixel Value Comparisons of Processed Color Charts

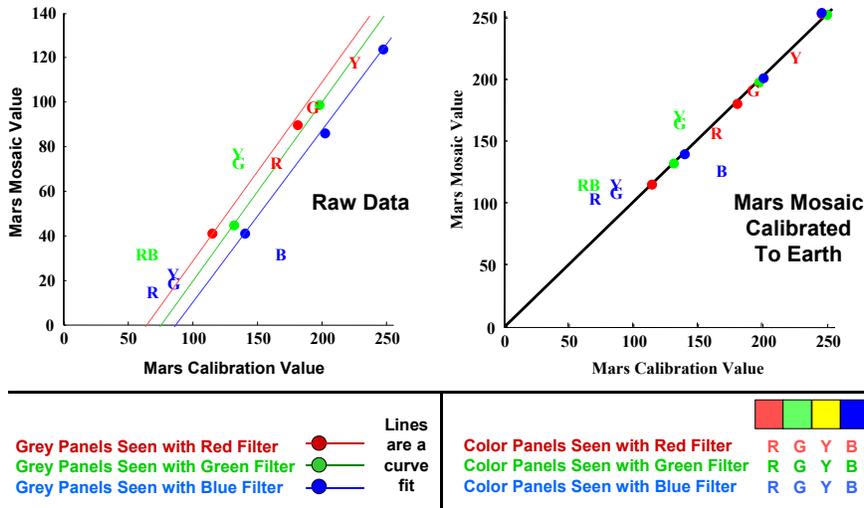


Figure 6. Martian Landscape Using Filters L4, L5 & L6 Compared to Filters L2, L5 & L6



## ACKNOWLEDGEMENTS

The author would gratefully like to acknowledge the contribution of Susan Smith for finding the discrepancy in the color calibration chart in the first Spirit panorama. The author must thank Kathy Brailer who completely choreographed the production of this paper over the internet. Lastly the author must recognize his father, Dr. Gilbert Levin who has been my life long inspiration for the study of Mars.

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