Solving the color calibration problem of Martian lander images

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ABSTRACT

The color of published Viking and Pathfinder images varies greatly in hue, saturation and chromaticity. True color is important for interpretation of physical, chemical, geological and, possibly, biological information about Mars.

The weak link in the imaging process for both missions was the reliance on imaging color charts reflecting Martian ambient light. While the reflectivity of the charts is well known, the spectrum of their illumination on Mars is not. "Calibrated" images are usually reddish, attributed to atmospheric dust, but hues range widely because of the great uncertainty in the illumination spectrum. Solar black body radiation, the same on Mars as on Earth, is minimally modified by the atmosphere of either planet. For red dust to change the spectrum significantly, reflected light must exceed the transmitted light. Were this the case, shadows would be virtually eliminated. Viking images show prominent shadows. Also, Pathfinder's solar cells, activated by blue light, would have failed under the predominately red spectrum generally attributed to Mars.

Accordingly, no consensus has emerged on the colors of the soil, rocks and sky of Mars. This paper proposes two techniques to eliminate color uncertainty from future images, and also to allow recalibration of past images: 1. Calibration of cameras at night through minimal atmospheric paths using light sources brought from Earth, which, used during the day, would permit calculation of red, green and blue intensities independent of scene illumination; 2. Use of hyperspectral imaging to measure the complete spectrum of each pixel.

This paper includes a calibration of a NASA Viking lander image based on its color chart as it appears on Earth. The more realistic Martian colors become far more interesting, showing blue skies, brownish soil and rocks, both with yellow, olive, and greenish areas.

Keywords: Mars color, Mars lander imaging, color image calibration, Raleigh scattering, Mars atmospheric dust, Mars environment

1. INTRODUCTION AND BACKGROUND

Three spacecrafts have successfully landed on the surface of Mars. There were two Viking landers in 1976 and the Pathfinder lander in 1997. These landers retrieved a great deal of valuable information about the Martian surface, including a large number of color images. In the 27 years since the Viking spacecraft landed and the 5 years since Pathfinder landed, there has been no consensus on the calibration of these color images. The coloration of the Martian sky and landscape has been the subject of numerous scientific papers.

The first color image (12A006/001) of the surface of Mars was taken July 21, 1976, at the Viking 1 site, one day after the landing. Immediately displayed on color monitors at JPL, as seen in Figure 1a, the landscape awed observers with its resemblance to that of Arizona. Typical desert colorations of soil and rock, ranging from umber sand to yellowish-brown and olive-colored rocks stood out clearly under a blue sky. Two hours later, however, the official image was changed to the monotone of orange-red (NASA P-17164), Figure 1b, that, with few exceptions, has prevailed in NASA-published images of Mars ever since, as presented by Mutch *et al.*[1]. However, a spectral analysis of color images of the Viking 1 site reported[2] a broader palate. The paper made the first, and perhaps only, reported use of JPL's Image Processing Laboratory to analyze digitally the red, green and blue color channels of the images taken by the Viking 1 lander camera. In addition to studying the color images, their RGB components were transformed into saturation, hue and intensity components to enhance subtle deviations. When these components were equally amplified to produce an equal average sensitivity over the spectral bandpass, the resulting "radiometric" (closest possible approach in appearance to a human observer) images very closely resembled the first color image (12A006/001). Among the range of colors, the paper reported that some of the rocks exhibited greenish patterns that apparently changed between images taken 301 sols apart. Radiometric images of lichen-bearing terrestrial rocks taken and processed through the same system as were the Viking images showed a close resemblance of the lichen colonies to the greenish patches on the Mars rocks. Inclusion in the analysis of three near-IR channels available on the Martian images enhanced the greenness of the patches that were, to the sensitivity of the method, virtually indistinguishable from the lichen colonies on the terrestrial rocks.

Although the authors of that paper drew no conclusion about the biological implication of their findings, the mere comparison of the Mars images with lichen produced a major controversy with the orange-red Mars majority. The paper was heavily criticized by NASA officials who, upon viewing the images, contended they saw no evidence of the features claimed[3]. Even when the greenish colored areas were confirmed in subsequent reports[4],[5], those authors took special care to avoid any possible biological implication.

Levin *et al.*[6] had pointed out that the different sun angles under which the images were obtained might account for some of the apparent differences between the two. After publication of the paper, its authors requested NASA to obtain images of the same area at each Martian-year anniversary, when the same sun angle would prevail. This was done, although power limitations forced a narrowing of the field taken. However, before Viking 1 died, four such images, "repros," were obtained, spanning some 3 Martian years. The images are published here, as Figure 2, for the first time. Comparisons among them show apparent changes in features over time, not only in the near field, where differences on the rocks were first detected, but, perhaps, even more surprisingly, in the distant field.

Mars[7], intended to be, and generally accepted as the definitive compendium on Mars, in all of its 1,455 pages plus 18 color plates, makes no mention or reference to this issue. However a telling statement on this important matter is made on the cover of the book. The cover features a mosaic constructed, as explained in "About the cover," from color images taken by the Viking 2 lander. The resulting panoramic image presents a surprising, nearly universally bland yellowish-ochre landscape and matching sky. However, resisting this strenuous color-suppressing treatment, greenish patches cannot be prevented from peaking through on many of the rocks. This paper picks up the issue and proposes two methods to obtain accurate color images of the surface and sky of Mars in future missions, and demonstrates a method for more accurate recalibration of existing images.

Figure 3 shows a grouping of four Viking lander images and four Pathfinder images from official NASA websites[8]. As seen, the colors of the soil and sky vary greatly among the images. The first Viking image has a sky that shows blue, the second image has an orange sky, the third a pink sky, and the fourth a very red sky. The colorations of the ground vary similarly. The sky in the Pathfinder images varies between white in the first image, gray in the second image, brownish orange in the third, and orange in the fourth image.

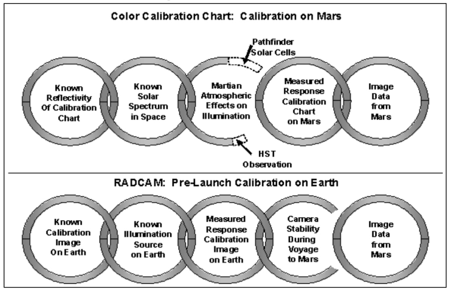
The first Pathfinder image shows reddish soil with some blue/green patches. The second image shows the Sojourner rover with its solar cells appearing grayish rather than its actual blue color. The solar cells on the lander also appear devoid of blue in the third image. The Viking lander camera used a scanning mirror, a photodiode, and three colored filters to generate red, green, and blue images, which were then merged to form the color image. The Pathfinder lander had a charge-coupled device, which took data simultaneously in red, green, and blue. Both landers had onboard color calibration charts, which were illuminated by the ambient light on Mars.

2. EXISTING CALIBRATION METHODS

Viking and Pathfinder had two methods of calibration. The first calibration scheme involved the use of the color charts that were visible in some of the Martian images. The second method was called RADCAM, and it was based on calibration of the flight camera on Earth. These cameras took images under controlled lighting conditions and modified them until they matched the scene itself. The calibration algorithm was kept in computer data files, which were, and still are, available to calibrate raw Martian images.

A description of these calibration procedures is shown in Figure 4. As shown in the figure, both of these chains of calibration are broken at one point. The color calibration chart method has a gaping hole on the middle link where the atmospheric effects on the illumination of the color chart are very much in doubt, and are the subject of a great deal of research. The RADCAM chain fails because the stability of these solid state devices during the trip to Mars is not known; therefore, the performance of the camera on the Martian surface is not necessarily the same as it was on Earth.

Figure 4. Chains of Calibration



The color chart calibration chain (Figure 4) shows that the reflectivity of the color calibration chart is very well known. Were this chart in space, it would be illuminated with a spectrum from the Sun that is very well known. Unfortunately, by the time this solar illumination passes through the Martian atmosphere, it is modified in ways that are not currently understood. Many scientific studies postulate a large amount of red dust in the atmosphere, modifying both the direct and scattered light from the Sun. This broken link renders the rest of the calibration data difficult to use.

On the surface of Mars, excellent raw data were taken from the color calibration chart and from the surface itself. Unfortunately, it is not known what the color chart should look like in the illumination from the Sun as it reaches the Martian surface. If the appearance of the color chart on Mars were known, then the chain would be complete and we would be able to calibrate the other pixels in the Martian image from the surface based on the calibration of the color chart. The unknown appearance of this color chart on the surface of Mars prevents a definitive coloration of the Martian environment. This is principally responsible for the proliferation of different color calibrations and different colorations of the surface of Mars as seen in Figure 3.

The RADCAM calibration chain (Figure 4) appears to have been dismissed by image analysts. This may be because of the uncertainty in the stability of the camera and its solid state components during the voyage to Mars. However, this seems to be a very reasonable calibration chain. In applying it, a calibration source on Earth is illuminated with a light source whose spectrum is measured. A comparison of the calibrated output with the calibrated target under the available calibrated illumination source provides a mathematical formula by which raw data from the camera can be converted into the desired image. This calibration, of course, can be tested while the camera is on Earth by re-imaging the calibrated target or any other known image. This was done in the case of Viking and Pathfinder. These calibration algorithms have been stored and remain available today.

The critical question is the usability of these calibration algorithms on these cameras after they have made their voyage to Mars. If the camera were stable, all questions of atmospheric effects and illumination would be eliminated since the algorithms have been tested on Earth to convert raw data into calibrated images. The calibrated images produced would then be correct, regardless of the coloration of Martian objects or the illumination. The absence of such images in publications indicates that image analysts doubt that the camera's response measured before launch was still accurate after these cameras reached the Martian surface.

3. INFORMATION FROM PATHFINDER SOLAR CELL

In Figure 4, the color calibration chart chain, broken by the unknown atmospheric effect on illumination, is shown as partly rebuilt based on evidence from Pathfinder solar cells and observations from the Hubble Space Telescope. These dotted links represent lines of research that might some day reconnect the color calibration chain and solve these coloration issues. A great deal of research on solar cells for space applications has been performed at NASA's John Glenn Research Center in Cleveland[9]. One of the differences between the Viking and the Pathfinder missions concerns the power source for each lander. The Viking lander was powered by a radio thermal generator (RTG), which extracts electrical power from radioactive plutonium. However, partly because of safety concerns, the Pathfinder lander was designed to be powered by solar cells converting light from the Sun and sky into electrical power. The power production of these solar cells was relayed to Earth by telemetry as part of monitoring the health of Pathfinder. This telemetry showed that the Pathfinder solar cells produced the amount of power for which they had been designed[10].

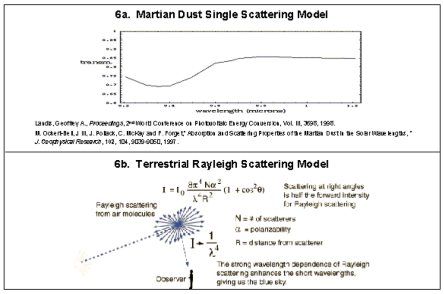
It is well know that the efficiency of solar cells critically depends on the spectrum of the light with which they are illuminated. Solar cells are solid state devices. Photons entering the solid state material collide with electrons in the conduction band and promote them to the valance band in which they become mobile and move toward the collectors. The efficiency of this process depends on the likelihood that an electron will absorb enough energy from a photon to be promoted across the band gap to the valance band. This probability is zero if the photon energy is less than the band gap energy. This probability of electron promotion increases rapidly with increasing photon energy. Red photons have a very low efficiency in photovoltaic cells. The overall efficiency of the photo cell is dependent on the fraction of the incident green and blue light.

The inefficiency of red photons in photovoltaic cells is mirrored by the inefficiency of red photons in exposing ordinary black and white film. For this reason, all darkrooms are illuminated by red lights to prevent fogging of film. Color calibration charts in the Viking and Pathfinder lander images are heavily red with little, if any, green and blue components. Were the colors reported by these images correct, the illumination would result in inadequate power production by the solar cells for their assigned tasks. This constraint is illustrated in Figure 5.

The illumination postulated for the color chart cannot be so tilted toward the red that it would be unable to produce the power that was observed in the Pathfinder lander. Figure 6a shows a model for atmospheric transmission as seen from the surface of Mars[11]. This hypothesized model shows an atmospherics transmission of only 70% at a wavelength of 4,000 angstroms, which is the blue end of the visible spectrum. In the model, at 5,000 angstroms, which is green, the transmission is only 75%. This means that a quarter or more of the blue and green photons are hypothesized to be unavailable to the Pathfinder solar cells, which should have a marked effect on their power production as compared with the same solar cells in space. This transmission model is based on single scattering of light by red dust particles in the Martian atmosphere. In reality, however, dust storms were observed only two times during Viking lander 1's three Martian years of observation[12]. During the 2245 sols observed, less than 10% exceeded normal[13] atmospheric opacity.

The effect of this hypothesized red dust is to absorb blue and green and to scatter the red resulting in the predominance of red as is often shown in published lander images. This means that, while the transmitted red is being reduced by scattering in the sky, the blue and green are being reduced even more strongly by absorption. The illumination of the color chart is then hypothesized to be red, both from the direct sunlight, as shown in the figure and by scattered sunlight in the rest of the sky. This greatly contrasts with the situation on Earth, as with any atmosphere of uncolored gases, in which the color of the sky is dominated by Rayleigh scattering[14] and must be blue.

Figure 6. Atmospheric Scattering

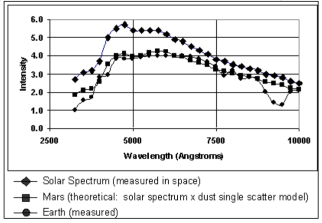


Atmospheric molecules, much smaller than a wavelength of light, fall into the Rayleigh scattering regime shown in Figure 6b. Carbon dioxide molecules, like oxygen and nitrogen molecules, are much smaller than a wavelength of light. Even though the density of the Martian atmosphere is only 1% that of Earth, this is somewhat compensated by the fact that the atmosphere on Mars extends to much higher altitudes due to the lower gravitation of Mars. The physics of Rayleigh scattering shows that the intensity of the scattering is proportional to $(1/\lambda)^4$. This causes the scattering to be dominated by short wavelengths, which are blue, and thus causes the sky, as seen from the surface of a planet, to appear blue. This sky coloring should exist on Mars barring significant interference by dust particles.

Even though the theoretical models for scattering and transmission of light are hypothesized in many of the published images to be very dissimilar on Earth and Mars, the results for direct sunlight are amazingly similar. Figure 7 shows a comparison between the spectrum of sunlight as measured in space and on Earth, and the spectrum of sunlight theoretically predicted to occur on the surface of Mars. The top curve with the diamond markers is the spectrum of sunlight measured in space[15]. The lower curve with the solid circles is the spectrum of direct sunlight measured on Earth when the Sun is directly overhead[16],[17]. The curve with the square markers is the product of the solar spectrum in space with the Martian dust single scattering model shown in Figure 6a. This transmission model was calculated for the Sun being directly overhead.

The Rayleigh scattering of the blue light on Earth is shown in the figure to be similar in magnitude to the hypothesized absorption of blue by red dust in the atmosphere on Mars. Over the visible wavelengths, 4,000 to 7,000 angstroms, the experimentally measured spectrum on Earth and the theoretically hypothesized spectrum on Mars match to within about 5%. This should mean that the color calibration charts received direct sunlight on Mars quite similar to that experienced on Earth. In most pictures of the Martian surface (except during rare dust storms), the direct light seems to be much

Figure 7. Direct Solar Illumination on Earth and Mars (Sun Directly Overhead)



stronger than the scattered light from the sky, as can be seen from the darkness of the shadows of the rocks and of the lander spacecraft. Sand in the shadows of these rocks appears much darker than the sand immediately adjacent to it, indicating that scattered light from the sky is not very strong.

The Martian dust single scattering model does not appear adequate to explain the high red-to-blue ratio of the calibration charts in most published images. However, the similarity of these transmitted spectra could explain why the solar cells have performed so well, but their performance is incompatible with the redness of the “calibrated” Martian images.

4. INFORMATION FROM THE HUBBLE SPACE TELESCOPE

There exists one other important piece of data concerning the scattered light in the Martian sky. Every 2 years, at Mars and Earth conjunction, images of the planet are taken by the Hubble Space Telescope as shown in Figure 8. The resolution of the Hubble Space Telescope in sufficient to allow imaging of the planet’s limb as seen in Figure 8. The Hubble Space Telescope has onboard spectrometers which are used to study the Doppler red shift of distant stars. These spectrometers can be used to calibrate the light reaching the imaging camera on the HST. The spectrometers are capable of looking at the same stars as the imaging camera and therefore provide an excellent calibration. A study of these images was made by Philip James[18], who found that scattering of the Martian atmosphere as seen from Earth is predominantly blue. This adds another constraint on the broken calibration link in Figure 4. If the results of the Hubble Space Telescope are correct, the Martian sky cannot be as red as shown in many published images, and the illumination from the sky cannot be contributing to the red dominance of the color calibration charts.

Both the Hubble images and the performance of the Pathfinder solar cells argue for a much greener and bluer environment than is currently shown in lander images. However, neither of these measurements is sufficiently definitive to repair this broken link and allow the production of a reliable calibration. This uncertainty cannot be resolved until a Martian lander measures the spectrum of solar illumination. The most important question with respect to the color of Mars might be: What does an image of the Martian surface look like if it were illuminated by the same light that we are familiar with on Earth?

A rock formation seen in Earth daylight may not look familiar to us in a very red illuminating light. In order for geologists to recognize the minerals that they are familiar with on Earth, it might be more appropriate to perform a color calibration that renders the geological formations as if they had been in the same illumination that geologists are accustomed to seeing on Earth. In this case, the color calibration chart should be set to appear similar to its appearance in a sunlit area of Earth. This may not produce geological images as they would appear to an astronaut on Mars, but it will render those geological formations in the same coloration that geologists on Earth are accustomed to observing, permitting direct comparison of the samples. To this end, a simple illustration is performed on Figure 9 on a published image of the Martian surface from Viking.

5. SIMPLE EARTHLIKE CALIBRATION

The center nine panel square in Figure 9 depicts the color chart aboard the Viking 1 lander. Two of these charts were aboard the lander, as seen in Figure 9. The right side of the figure shows the NASA-published image of the Viking 1 lander scene. The authors attempted to make a linear conversion to simultaneously transform the red, green, blue, black and white panels into their Earth-measured counterparts. However, an inconsistency in the color chart as presented in the NASA image made this impossible. Analysis showed that the “blue” panel actually contains almost equal parts of blue and red, while the white and gray panels are neutral. It is difficult to understand the large presence of red in the blue panel under any but the most extreme red illumination. Unknown illumination provides only three free parameters in the RGB space, the relative scaling of the three colors. Comparison of two color charts provides 15 constraints (three each from the red, green, blue, black and white panels). A change in illumination should require only three free parameters (the illumination intensities) to transform the image to satisfy the 15 constraints. The calibration scheme used here can compensate for any change in illumination, and for other changes. However, application of the method to the NASA image was found to be impossible. This means that the official image must have been produced from the raw data by a non-linear (potentially non-physical) calibration method that cannot be corrected by linear transformation, indicating a degree of subjectivity in the method employed by NASA.

Although the non-linearity of the NASA image makes it impossible to transform it accurately, the method was applied, thinking it might provide the closest possible approach to a correct re-calibration of the NASA image. In July 2003, the authors photographed the color chart on the Viking lander on display at the Smithsonian Institution Air and Space Museum, in Washington, D.C. Since fabrication, the Viking lander has rarely been exposed to the outdoor sunlight or any other ultraviolet source that might accelerate any color change. A Nikon Digital Coolpix 885 camera was used, with the flash set for auto white balance. A strip of the color chart in the digital image is shown as the first color bar on the extreme left of Figure 9. This Earth-like color bar was transformed into the numerator matrix shown in the center of the figure.

The same operation was performed on the identical color chart of the NASA-published lander image shown on the right side of the figure, yielding the RGB color bar on the right side of the figure. This Martian color bar was transformed into the denominator matrix shown in the center of the figure.   The ratio of these matrices (Earth / Mars) produces a transfer matrix. The transfer matrix transforms the colors of the Martian color chart into those of the Earth color chart. The results of this transformation are seen in the color bar second from the left of the figure. The comparison of the color bar derived from the Earth digital photograph to that from the Mars NASA-recalibrated color bar shows a close match, demonstrating that the transformation did approach the Earth scene.

All the pixels of the NASA-published original image on the right side of Figure 9 were similarly transformed into the image with Earth-like illumination as seen on the left. The sky now appears blue, where it has been a dark pink before. The U.S. flag becomes more familiar. The soil appears browner and the rocks in the scene show more contrast to the soil, more nearly resembling Figure 1a, the color image as first reported from Viking 1. The controversial olive-green areas reported by Levin *et al.* [19] re-appear.

The calibration provided by this scheme may, in fact, be more nearly correct than the ones used to create the published images. There is currently insufficient information to make a judgment. Nevertheless, it can be argued that this calibration procedure produces an image close to what the Martian surface would look like under an illumination similar to that on Earth. Images calibrated in this way might be more useful products for geologists and scientists than are the images as currently published. Calibrating the color charts as if they were shown in Earth sunlight produces a picture that shows the soil and rock formations on Mars in a light that is more familiar to scientists on Earth. One goal might be to identify possible Martian igneous and metamorphic rock by comparing the images of these rocks to their Earth counterparts when similarly illuminated.

6. ROBUST CALIBRATION METHODS

The true color of Mars could become known on future missions if the lander cameras were calibrated on Mars using light sources brought from the Earth. Figure 10 illustrates three ways to do this. In this figure, a Martian camera is viewing a color calibration chart at night under illumination by the black body spectrum from an incandescent light bulb brought from Earth. Since this chart is very close to the camera, and the light bulb is close to the chart, the effects of the atmosphere are negligible. (If there were any concern about the atmosphere, the light bulb, color chart, and camera could all be connected by clear plastic of known properties rather than to allow any of the light to transit the Martian atmosphere.) The second panel in the figure shows a method in which the Martian lander camera observes red, green, and blue LED’s that have been calibrated on Earth.

The third panel depicts a calibration procedure based on a tunable dye laser also brought from Earth. If these calibrations were performed at night, they would be based purely on light of known spectral content. It would be reasonable to expect that the calibration algorithm derived at night would still be valid during the next Martian day. If the stability of this calibration were a concern, the camera could be designed to face inward toward the spacecraft during the daytime to look at a dark enclosed area with calibrated light sources of known spectral properties. At the desired time, the camera could immediately be turned around, look at the ambient scene, and take images using the same calibration parameters. Once the lander cameras are calibrated using light with known spectral properties, the rendition of these images on Earth would no longer be open to question. These calibration procedures could eliminate the broken link in the chain shown in Figure 4.

7. HYPER-SPECTRAL IMAGING

The coloration of Martian lander images has been so uncertain for such a length of time that it is perhaps desirable to use a higher level of technology to ensure that the issue is resolved. In the time since the Viking lander, a new technology has been developed called hyper-spectral imaging which is able to provide a complete spectrum on every pixel in a lander image. Hyper-spectral technology provides the equivalent of running each image pixel through a spectrometer. This concept is illustrated on the upper left panel of Figure11, in which a complete color spectrum is shown behind each pixel, turning the 2 dimensional image into a 3 dimensional cube of data.

A hyper-spectral imager provides a spectrum measured in hundreds of wavelengths as compared to the broad red, green, and blue wavelengths captured in a traditional color image. This more detailed spectrum of each pixel is more easily calibrated and provides scientific information beyond that available in color imaging. The upper right portion of Figure 11 shows the results of a multi-spectral imager that was onboard the Pathfinder lander[20]. These graphs show the spectra for several different pixels of an image of a rock named Barnacle Bill. The spectrum recorded by Pathfinder covers the wavelengths from 4,400 angstroms to 10,000 angstroms, all of the visible spectrum except the extreme blue end, and continues well into the infrared spectrum. Since infrared light begins around 7,000 angstroms, only half of the data taken by the Pathfinder imager is in the visible.

The multi-spectral imager on Pathfinder measured the spectra in only 11 wavelengths. Thus, there are only about 5 spectral measurements of visible light. This certainly represents an improvement over red, green, and blue color imaging which, together with the infrared wavelengths, provides a spectrum scientifically valuable for geologists. This portion of the figure shows the spectral differences among areas around Barnacle Bill, portions of Barnacle Bill that are thought to be oxidized volcanic cinders, portions of the solid rock face, background soil, and unoxidized volcanic rock.

Today’s hyper-spectral imaging technology is greatly improved over the multi-spectral imaging of Pathfinder. In many hyper-spectral instruments, the visible region of the spectrum is divided into more than a hundred spectral bands[21]. With hyper-spectral imaging, it is possible to imagine recording scientific data that could answer many fundamental questions about Mars. One very important and obvious result would be the analysis of pixels that are part of an image of the Sun received on Mars. At the bottom left of Figure 11 is a cartoon of a spectrum of the Sun obtained by a hyper-spectral imager. The blue points represent data received, while the red curve represents a theoretical model, such as a 6800° K black body spectrum. The spectrum of direct sunlight incident to Mars could be accurately measured by this instrument and would solve, once and for all, the question of direct illumination, and would greatly help to define the appropriate scattering model for the Martian atmosphere.

The hyper-spectral imager could also produce the spectra from pixels in the sky at differing angles from the Sun. These spectra of scattered light could be compared directly against the theoretical model of Rayleigh scattering, which predominates on Earth, and to the dust single scattering model[22]. At the bottom center of Figure 11 is a cartoon of a hypothetical spectrum from a pixel in the sky that could be received from a hyper-spectral imager. The blue points represent received data, while the red curve represents one of these theoretical models. The observation of this sky spectrum from many different pixels in the sky could be used to define the interaction between sunlight and the Martian atmosphere, adding a great deal of information about the Martian atmosphere.

Finally, the cartoon at the bottom right of Figure 11 shows how spectra could be generated by pixels from different rocks in the lander’s environment. Coordinated with the Sun and sky spectra, these detailed spectra would have a great deal of geological value. Since the illumination from the Sun and sky would be known, the hyper-spectral imager could measure the absolute reflectivity of geological formations in the scene.

Hyper-spectral imaging could also go a long way toward improving the reproduction of colors in the Martian scene. Once the hyper-spectral data were received on Earth, a device could be constructed to recreate exactly the observed spectra in an image. Therefore, rather than looking at an image in which the broad red, green, and blue bands have been approximately reconstructed, humans could look at a scene in which the exact spectrum of each pixel was faithfully reproduced on Earth. Humans would then be able to estimate the coloration of the scene by allowing their eyes to view the exact visible spectrum that was recorded on Mars. The most important possible find could be spectra that might be of biological significance, perhaps an indication of photosynthetic microorganisms.

An example of the advanced state of hyper-spatial imaging is the Hyperion hyper-spectral imager, which is currently operating on the Earth-observing spacecraft EO-1, orbiting the Earth at an altitude of 700 kilometers[23]. The Hyperion imager weighs 49 kilograms and uses an average of 51 watts of power. This spectrometer has 220 bands of which 30 are in the visible. It has been calibrated to an absolute radiometric accuracy of 6%. A sizeable fraction of the 49 kilograms is needed for a telescope which achieves 30 meters resolution on the Earth’s surface from a distance of 705 kilometers. This telescope would be unnecessary on a lander mission. A hyper-spectral imager could settle the calibration issues, which have plagued Martian lander images for 27 years.

8. SUMMARY

No consensus has evolved concerning the color calibration of Martian lander images. There is a wide variation in the calibration of published images seen in newspapers, scientific articles, and on the Internet. Important basic questions have remained unresolved. The color and scattering physics of the sky is still at issue. There is a wide range of uncertainty about the coloration of light illuminating the Martian surface. There is wide uncertainty about the coloration of the soil and rocks. Because of these unknowns, there is a great uncertainty about the reflectivity of objects on the ground and how those geological objects would appear if they were illuminated by a known light source.

In an effort to resolve these issues, two broad categories of solutions are recommended. The first is the calibration of color cameras completely based on light sources that are brought from Earth, making no use of ambient light on Mars. These calibrations could occur either at night or during the day in a dark enclosure. This procedure would seal the break in the chain of calibration caused by the unknown illumination at the Martian surface. Once this calibration was achieved, it could then be used on raw data taken from the surrounding environment. Calibrated images produced by this technique would show the actual coloration of the Martian surface in the true Martian ambient lighting.

A more technically advanced and more expensive method of determining the absolute coloration of the Martian surface would be to use a hyper-spectral imager instead of a conventional red, green, and blue color camera. A hyper-spectral imager provides the complete spectrum of each pixel leaving no question as to that pixel’s color content. These measured spectra could then be faithfully reproduced on Earth. This would allow the viewer to see a precisely recreated spectrum from each pixel in an image.

Using these advanced technologies should close the broken links in the chain of calibration. Images could then be produced that would be of greater value to geologists, chemists, and biologists studying Mars. These calibrations could also be used to understand the reflectivity of the Martian scene and to produce another set of images that show how the scene would look if illuminated by light on Earth. The full potential of Martian lander imaging could then be realized. In the meantime, the existing images of the Martian surface may be recalibrated to Earth conditions, as shown in Figure 9, to provide what is very likely a closer approach to reality than presently available.

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Figure 1. Viking 1 Lander: First Color Photo 12A006

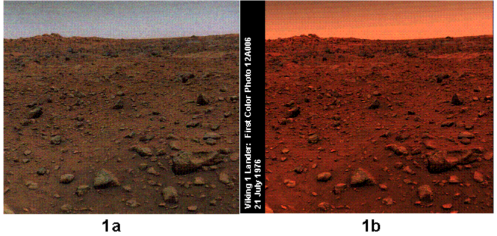
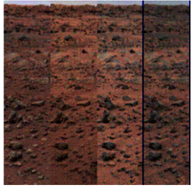
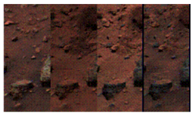


Figure 2. “Repros” of Viking Lander 1 Images Spanning 3 Martian Years
(**Note**: Hole in foreground of last 3 images resulted from a sample taken after Sol 34)





Sol	0034	0652	1387	2053
Sun Angle (Az/Elev)	275.8/084.1	297.6/084.3	252.9/086.6	257.1/086.7
ID	P-12B027	E-12I022	C-12J079	C-12J169

Figure 3. Lander Imagery from Current NASA Web Sites

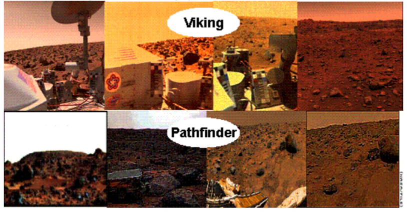


Figure 5. Conflicting Hypotheses

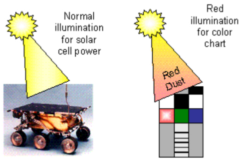


Figure 8. Mars Imaged by HST During Opposition

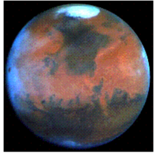


Figure 10. Methods for Nighttime Calibration at Night Using Known Light Sources

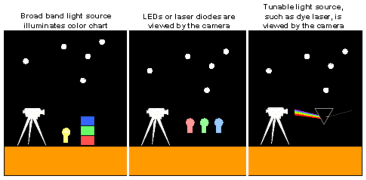


Figure 9. Calibration Scheme

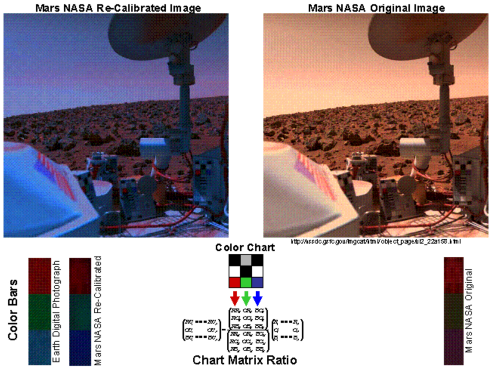
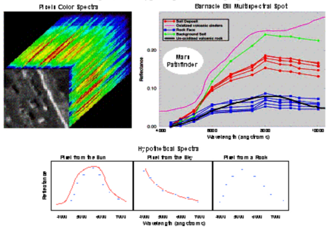


Figure 11. Hyper-Spectral Imaging



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