True Color and Chromaticity of the Martian Surface and Sky from Mars Exploration Rover Pancam Observations

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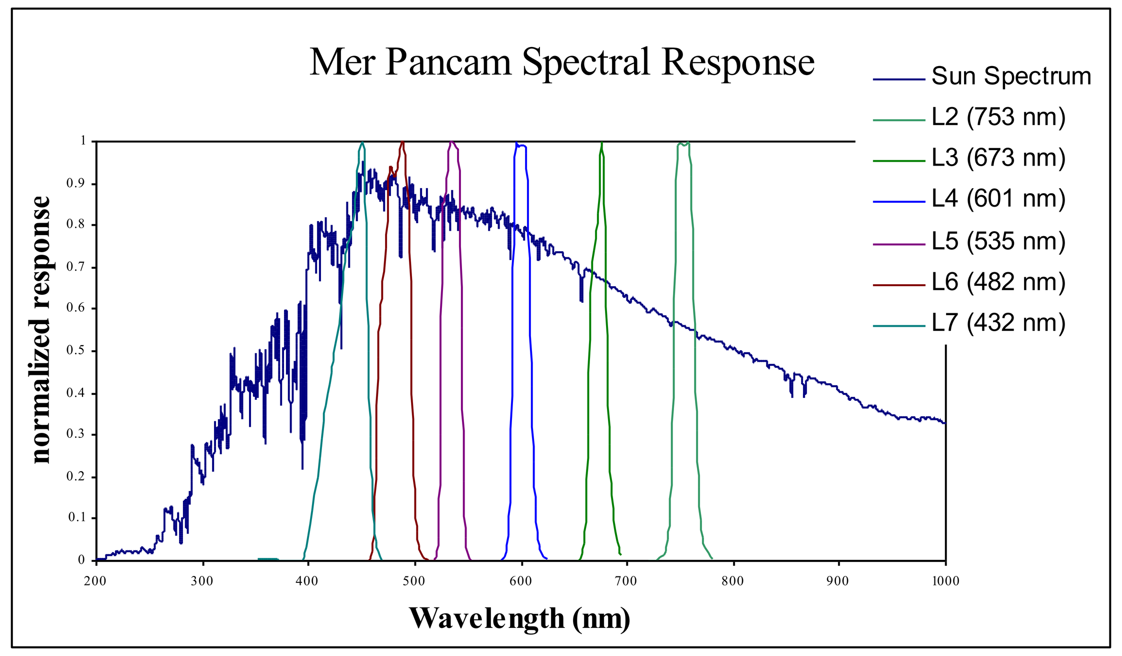
Abstract

We calculate the quantitative color of Mars using calibrated data from the Panoramic Cameras (Pancams) on the Mars Exploration Rovers Spirit and Opportunity. Measured color values of the rover landing sites are found to match the color properties of the Mars Pathfinder and Viking Lander sites. We also use these values to quantify systematic changes in color over time and to increase our perceptual understanding of conditions on the Martian surface. Using the color designation method defined by the ISCC-NBS, the Martian sky is found to be "light to moderate yellowish brown," while average rocks and soil vary between "dark grayish yellowish brown" to "moderate brown". Study of changes in the colors of the rover calibration targets show that the chromaticities are trending towards the "dark yellowish brown" portion of the color space, indicating that the calibration targets are being covered by martian dust as the mission progresses. A similar study of sky chromaticities throughout the missions shows trends in the color of the sky towards "very light yellowish brown."

Radiance to sRGB Conversion Process

The process of creating true color images involves converting calibrated Spectral Power Distribution (SPD) information to the XYZ color space and then to the sRGB color space. The XYZ color space is modeled closely after a human's perception of colors. The space can accurately describe the vast majority of the colors that can be registered by the human eye. Color representations within this space are strictly linear - a pair of colors separated by some arbitrary distance will appear to be twice as different to the same eye as another pair separated by only half the distance within the color space. The XYZ space tristimulus values represent the relative proportions of the three color primaries (Red, Green and Blue) necessary to produce the color being measured. Chromaticity values (x, y, and z) are the X, Y, and Z tristimulus values normalized by their common sum, and are often reported to aid in comparison of values from different locations and recorded by different instruments (Carter et al., 2004).

The XYZ tristimulus values are equal to the integrals of the products of an emissive source's spectral power distribution and the standard color matching functions over the range of the human visible spectrum. Since the available data recorded by the Pancams includes information about only six discrete wavelengths in the range of the human visible spectrum, information about the rest of the spectrum is manufactured with the aid of piecewise third order polynomial interpolation.



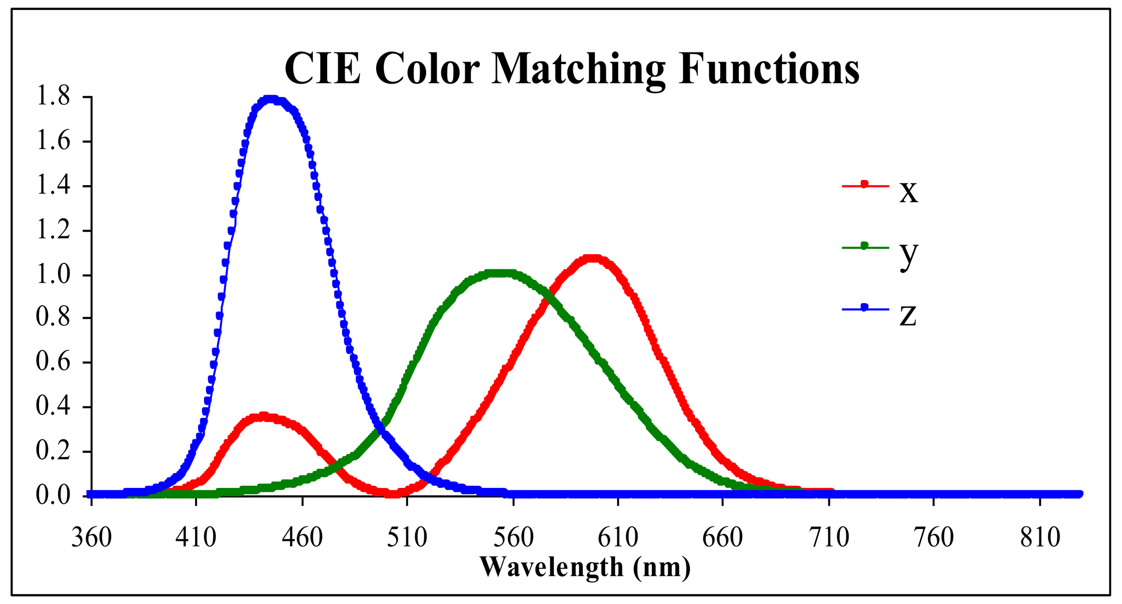
The conversion to the XYZ color space is achieved by applying a two point Newton-Cotes formula to the three integrals:

$$X = \frac{1}{N}\sum_{i=\lambda_1}^{\lambda_2} \bar{x}_i P_i$$

$$Y = \frac{1}{N}\sum_{i=\lambda_1}^{\lambda_2} \bar{y}_i P_i$$

$$Z = \frac{1}{N}\sum_{i=\lambda_1}^{\lambda_2} \bar{z}_i P_i$$

where P_i are the interpolated radiance values and x_i, y_i, and z_i are the standard color matching functions defined by the International Commission on Illumination (CIE) in increments of one nanometer (Carter et al., 2004) and N is a common scaling factor.



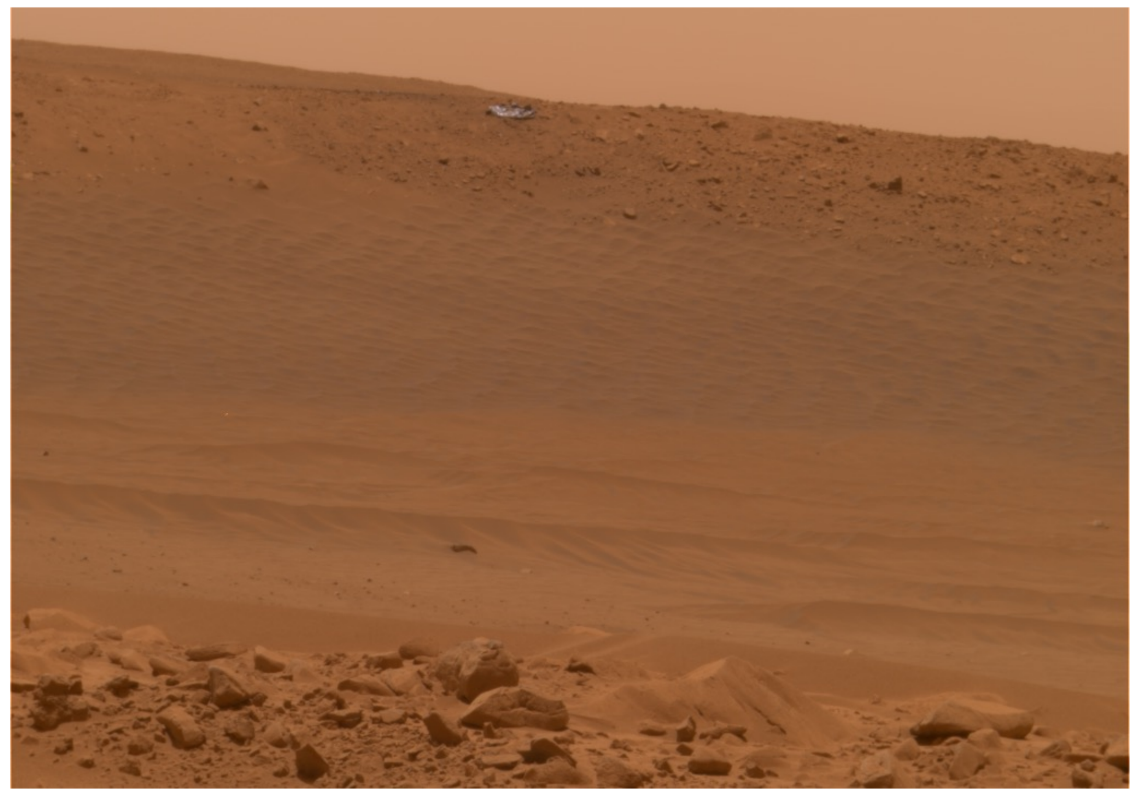
The sRGB space can be defined in terms of standard CIE colorimetric values, which themselves can be calculated from a defined reference viewing environment and knowledge of the spectral sensitivities of the capture device used. Chromaticities for the red, green, and blue ITU-R BT.709 colorimetry standard reference primaries, and the Standard Illuminant D65 are used to calculate a transformation matrix between XYZ and sRGB tristimulus values:

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 3.2410 & -1.5374 & -0.4986 \\ -0.9692 & 1.8760 & 0.0416 \\ 0.0556 & -0.2040 & 1.0570 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

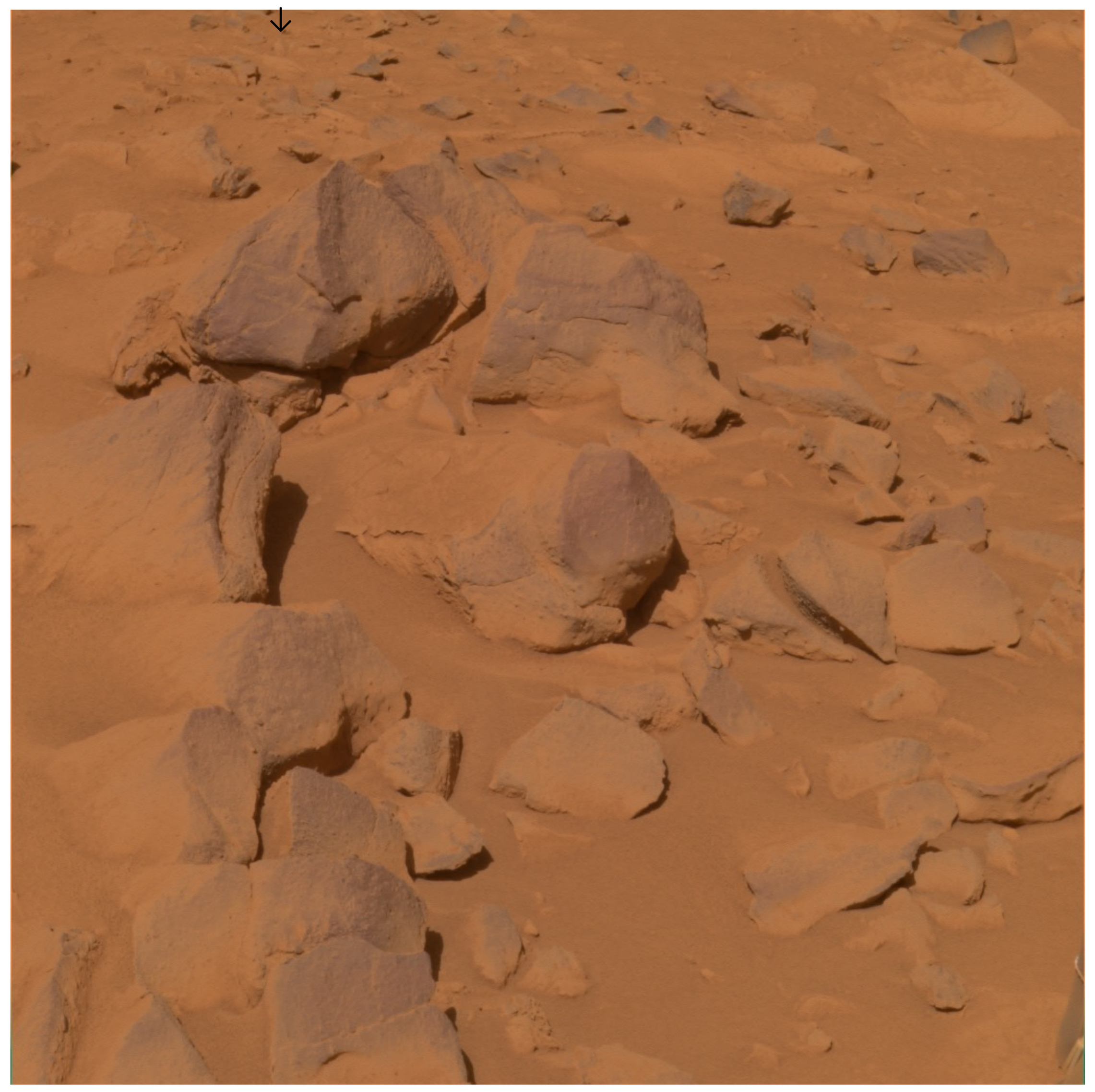
The sRGB tristimulus values are fit to a 2.2 gamma curve which corresponds to the standard used in most CRT monitors:

$$\left.\begin{aligned} R',G',B' &= 12.92 * R,G,B \\ R',G',B' &= 1.055 * R,G,B^{1/2.4} - 0.055 \end{aligned}\right\} \begin{aligned} &R,G,B \le 0.00304 \\ &R,G,B > 0.00304 \end{aligned}$$

These nonlinear sRGB values are then scaled to a common maximum and minimum in the range of 0 to 255 (24 bit encoding accepted by most graphics packages and displays). (Stokes et al., 1996)

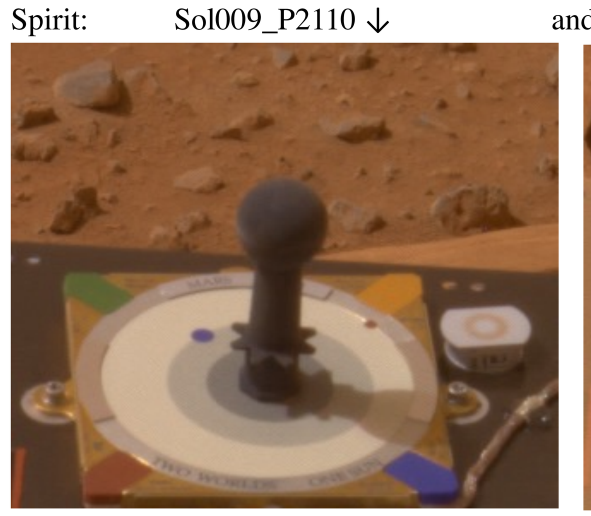


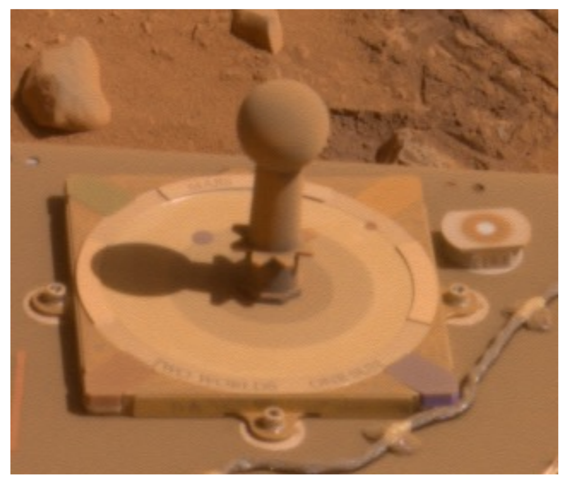
Spirit: Sol080_P2584 ↑ and Sol220_P2565 ↓

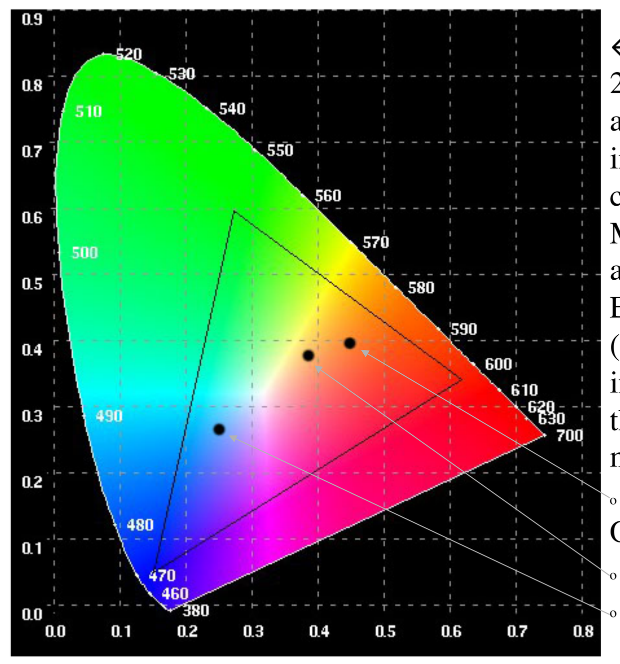


Opportunity: Sol024_P2382 ↑ and Sol038_P2538 ↓

Spirit: Sol009_P2110 ↓ and Sol325_P2111 ↓



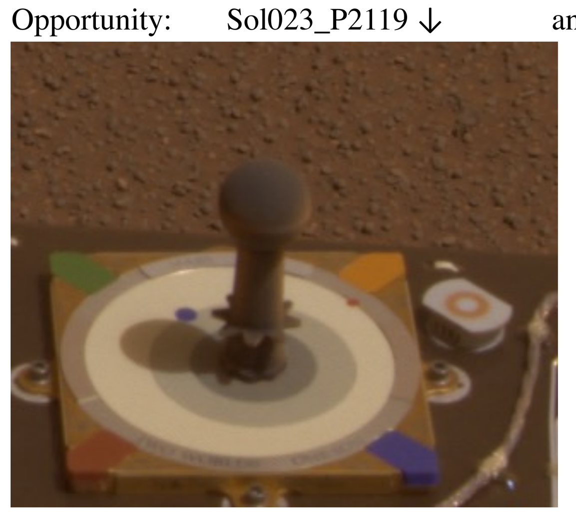


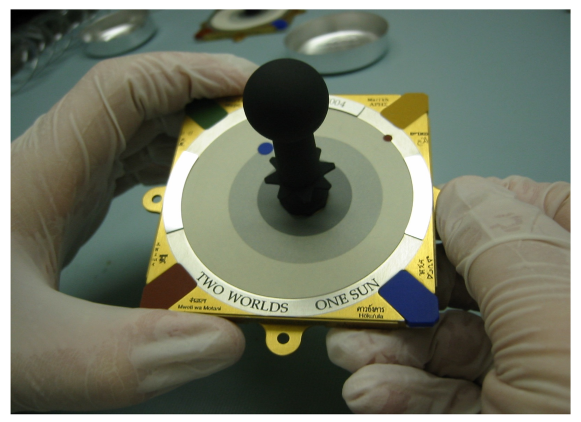


← This CIE color chart (Carter et al., 2004) shows how colors map onto their associated chromaticity values. It is interesting to note that the approximate chromaticity values describing the Martian sky (light yellowish brown) are almost directly opposite those of the Earth sky with respect to the white point (where color temperature goes to infinity). The black triangle represents the average color display capabilities of most RGB monitors.

- Martian surface around Spirit and Opportunity
- Martian Sky
- Earth Sky (Bright, no overcast)

Opportunity: Sol023_P2119 ↓ and Sol302_P2119 ↓





← Calibration Target as photographed on Earth. The four calibration target images shown above and to the left are among the earliest and latest available for both rovers. As time passes, the calibration targets are being coated with dust.

References:

Stokes et al. A Standard Default Color Space for the Internet – sRGB, Microsoft and Hewellt-Packard Joint Report, Version 1.10 1996

Bell et al. Mars Exploration Rover Athena Panoramic Camera Investigation, Journal of Geophysical Research, Vol. 108, No. E12, p. 8063, 2003

Maki et al. The Color of Mars: Spectrophotometric Measurements at the Pathfinder Landing Site, Journal of Geophysical Research, Vol. 104, No. E4, pp. 8781-8794, 1999

Carter et al. Colorimetry, 3rd Edition, International Commission On Illumination, Publication CIE 15:2004, 2004.

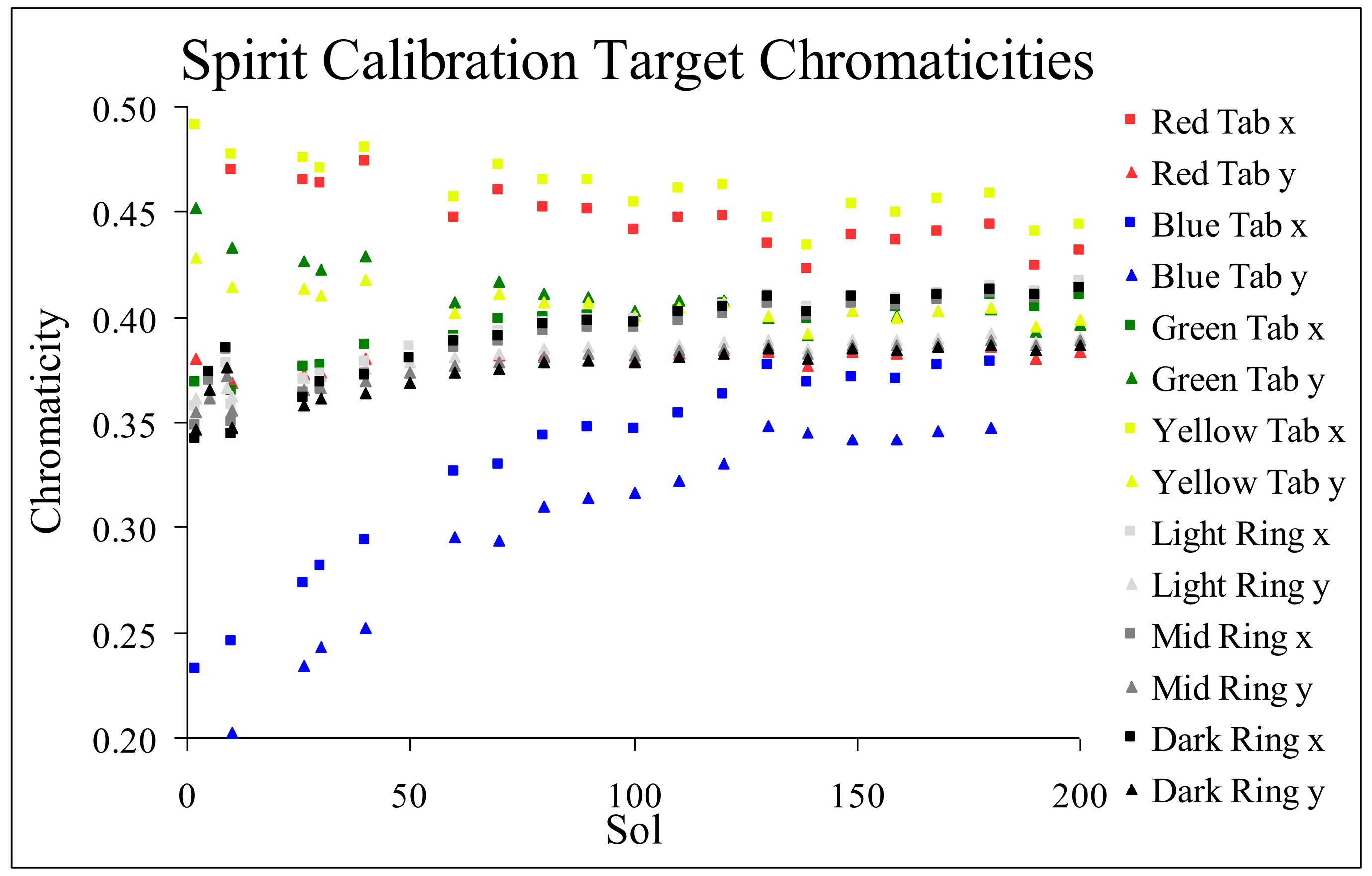
Lemmon, M. T. et al. Atmospheric Imaging Results from the Mars Exploration Rovers: Spirit and Opportunity, Science, Vol. 306, pp. 1753-1756, 2004

Results

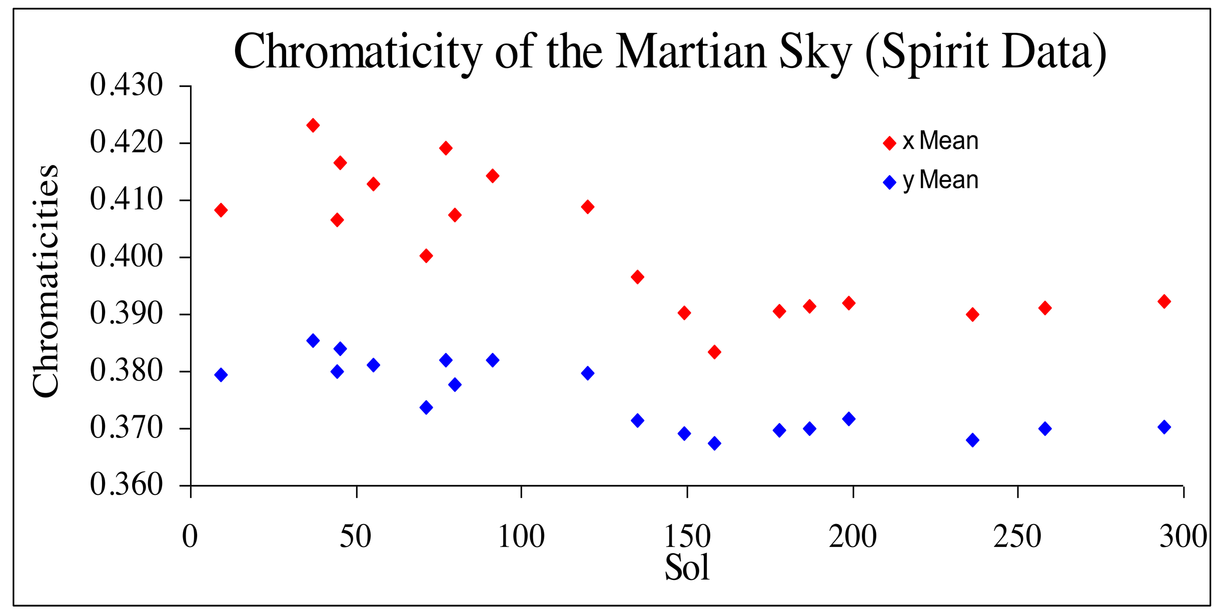
Comparison of Measured Chromaticity Values with Previous Mission Findings

(Pathfinder and Viking values from Maki et. al, 1999)

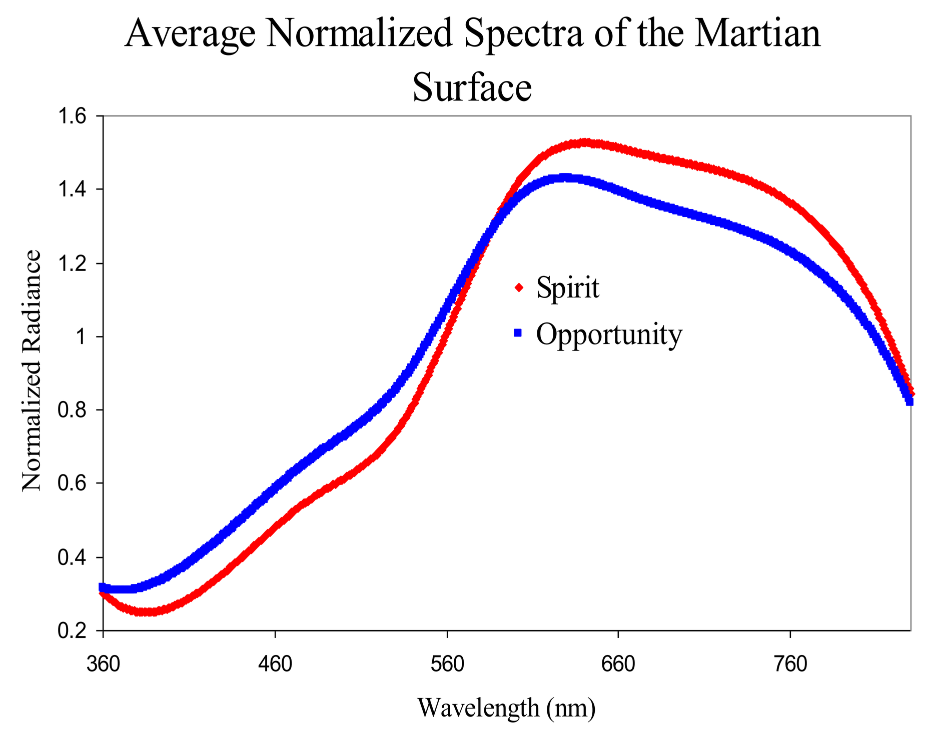
	Sky		Rock		Soil	
	x	y	x	y	x	y
Pathfinder	0.39-0.41	0.37-0.38	0.38-0.41	0.35-0.39	0.43-0.45	0.38-0.41
Viking 1	0.4	0.38	xxx	xxx	0.43-0.46	0.39-0.40
Viking 2	0.4	0.38	xxx	xxx	0.43-0.44	0.39
Spirit	0.39-0.42	0.37-0.38	0.40-0.43	0.38-0.40	0.44-0.46	0.38-0.39
Opportunity	0.38-0.40	0.37	0.39-0.42	0.37-0.39	0.42-0.45	0.38-0.40



In the XYZ color space, an increase in the x chromaticity indicates a color shift to the red, a decrease of x and y is a shift towards the blue, an increase in the y with a decrease in x is a shift towards green, and an increase in both the x and y chromaticities indicates that the image is getting darker (in the red/brown direction). From this, we can see that the calibration target color tabs and grayscale regions are all shifting towards the "dark yellowish-brown" portion of the color space over time, as they get coated with the Martian dust.



The chromaticities of the Martian sky have also changed throughout the span of the mission, although they appear to have stabilized around values of (0.39, 0.37) during the last hundred sols, which corresponds to a color descriptor of "very light yellowish-brown", in the color designation method defined by the ISCC-NBS. The chromaticity changes roughly follow the decreasing atmospheric opacity (Lemmon et al., 2004), though no exact correlation has yet been found.



Using a large number of six band images, it is possible to create an average, normalized spectrum for the Martian surface around each of the rovers. The two spectra shown to the left match the spectra of over 88% of all ground pixels in their associated images to within 2.5% absolute deviation. The spectra were created by averaging splined values from multiple filter sets, each of which was normalized by its common mean radiance value, after outlying values (>3σ had been removed). Using these spectra, it is possible to create near true-color images from data sets with fewer available bands which are more accurate than simply splining the smaller data set. Similarly, two average, normalized spectra are used for processing sky pixels from incomplete filter set images.

Future Work

Future work in this area will involve improved modeling of the Martian surface and sky in order to produce more exact true color images from sparse MER data sets and possibly from data from other camera systems currently imaging Mars. Additionally, an accurate correlation between the atmospheric opacity and sky chromaticity would allow us to draw better conclusions as to the exact color of the Martian atmosphere without suspended dust, and how a human being would perceive the Martian surface.