CIECAM02 and Real-World Images – *from Mars*

Jim Hewitt, Hewlett-Packard Company, Boise (USA)

Abstract

A human observer has never stood on the surface of Mars, yet color images from Mars have been produced. The twin Mars Exploration Rovers (MERs) have been on the surface of Mars for over two (earth) years and have taken many 1000's of images. The MER Pancam can acquire calibrated multispectral images that can be processed to produce colorimetric "true-color" images of Mars. While these images are primarily intended to allow science – in particular geology – to be done, they can also be used to display the Martian scenes in roughly representative color. The Pancam images can be further processed using color appearance models to produce "true color appearance" images that should display the color appearance to humans. CIECAM02 is applied to the colorimetric true-color images to Martian scenes to simulate the true color appearance.

Background

The twin Mars Exploration Rovers (MER) Spirit and Opportunity have spent over two Earth years exploring the surface of Mars. Both are *well* beyond their 3 month warranty and are still going strong. [1] The rovers have been serving as eyes on Mars, acquiring copious amounts of data to help Earth-bound scientists perform scientific study of Mars.

In addition to other scientific tools, the rovers each have a Panoramic Camera (Pancam) perched atop a mast that allow it to capture images that scientists use to determine the make-up of the materials. Although the images are acquired primarily to aid the mission scientists to decide what rocks and soil to investigate further and then to help investigate them [2,3], the cameras do capture enough data to allow representative color images of the scenes to be rendered [4,5].

Since landing on Mars, Pancams on the two rovers have acquired more than 100,000 images [4]. The difficulty lies in processing these multi-spectral images to generate *true* true-color images that are representative of what a human being on Mars would actually observe [6]. Colorimetric renditions of the images have been produced that don't take the illuminant into account. Color appearance models – such as CIECAM02 – can produce images that a human observer would experience on Mars.

MER Pancam Design [2,5]

Each rover actually has a pair of Pancams - a left and a right imager, which can also be used for stereoscopic imaging. The Pancam is a multispectral imager consisting of a 1024x2048 CCD split into equally sized imaging area and frame transfer buffer. The resulting images are at most 1-megapixel images but can be stitched together to create a larger panoramic image.

Each Pancam has an 8-position filter wheel to image in the 400nm-1100nm wavelength range, including some solar filters and an empty filter. The left Pancam includes the filters mainly in the visible range. The filters in the Pancam filter wheel are narrowband interference filters, most with a 20 nm bandpass. The 'peaky' filter transmittances have minimal overlap and allow up to 6 bands in the visible region in the left camera. Figure 1 shows the effective system-level response of the Pancam imager with the human visual system color matching functions overlaid (in color) for reference.

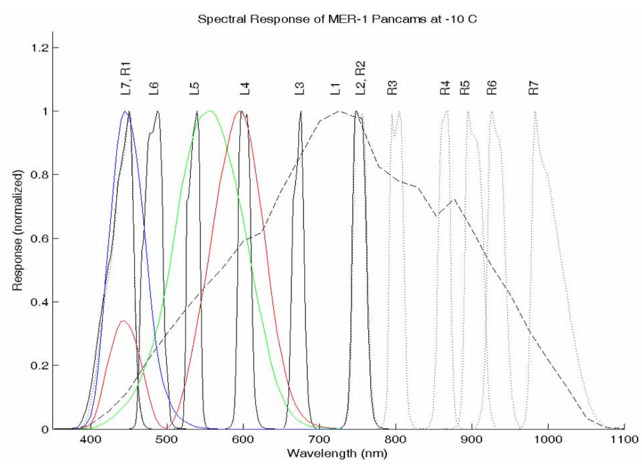
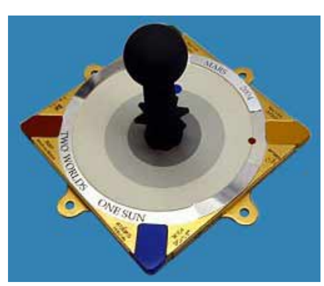


***Figure 1**: Pancam Filters Transmittances and Color-matching Functions[2].*

Pancam Calibration

To support the calibration of color images from the Pancams, each rover includes a calibration target. The target is located on the rover so that it will be illuminated by sunlight during Martian mid-day. The target contains various grayscale rings in addition to several colored patches whose spectral power distribution is well known, and two mirrored sections to allow the sky to be sampled. The calibration target also includes a gnomon, which serves to cast a shadow on the gray rings to allow measurements of the diffuse element of the Martian illuminant to be characterized. (See Figure 2 below.)



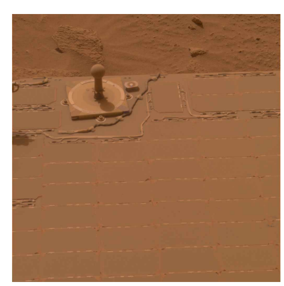


***Figure 2**: Calibration Target on Earth (left) [2,4] and on Mars coated with dust (right). [4,6,7]*

Each pair of Pancams was fully characterized on Earth before the launch of the rovers [2].

The calibrated radiance images/data are available for all of the MER Pancam images from both rovers at the NASA Planetary Image Atlas [8] web site. The image files acquired through the various filters can be converted to gif files by using the PDS Image Viewer software available at the Planetary Data System (PDS) home [9]. For processing into color images, the files can be downloaded in the PDS file format which contains all the necessary information to properly interpret the image files. The Planetary Image Atlas site allows the images to be located by date, rover, and other parameters, but the downloaded file names must be carefully interpreted and the image data must be carefully processed according to the PDS documentation using the calibration data files [7].

Colorimetric Processing of Pancam Images

The advantage of the calibrated absolute radiometric images from the Pancams is that they provide enough data to generate colorimetric estimates of the color of the scenes. An estimate of the spectral power distribution of each pixel of a scene can be obtained from the multi-spectral images. This approach is much better than the easier method of using just three of the images obtained through approximately red, green, and blue filters, or - even worse - using a blue filter, green filter, and an infrared filter to generate approximate color images.

It has been shown that the most accurate color reproduction is spectral. The Pancam colorimetric approach is spectral [2,4,7].

Colorimetric Approach for True-Color Pancam Images

When the Pancam images are calibrated to radiometric units, they are reasonably accurate descriptions of the spectral power distributions (SPD) of the scene. From the SPD of the scene and the human color matching functions, the XYZ tristimulus values can be obtained if the scene has been captured with all 6 of the visible light filters and the exposure conditions match. From the tristimulus values, conversion to any color space can be made. For display on Internet browsers, the tristimulus values can be converted to sRGB using the standard transformations. This standard colorimetric approach for specifying the color as detected by the Pancam imaging hardware has been used by Bell et al. [4,7]

Because the spectra were obtained though 6 very narrow filters, Bell uses a cubic spline to up-sample the images to estimate an SPD that matches the spacing of the color matching functions used. Bell then uses a trapezoid rule to perform the numerical integration to arrive at the XYZ values. Lastly, the XYZ values are converted to sRGB by use of a suitable matrix and a gamma adjustment to match the gamma of 2.2 for sRGB displays. The resulting images are called 'true-color' images and are posted on the Pancam True Color web site [6]. Given the SPD of the scene that is available, these represent the best-effort colorimetric color representation of the Martian images.

For the remainder of this paper this shall be referred to as the Colorimetric True Color approach, or just the colorimetric approach.

Limitations to Accurate Color Reproduction

There are many weak links in the process of reproducing true color, including observer metamerism, the actual viewing conditions, and calibration of monitor used for display. However, even assuming the best conditions, the resulting images from the colorimetric approach are still only approximate colorimetric matches.

Neither the scene nor the illuminant SPD is accurately known, or rather, is only accurately known at 6 points in the visible range. Reasonable colorimetric results can be obtained with sampling on the order of 10nm, or even 20nm [10], but not the average 60nm spacing achieved by the Pancams. From a sampling theory point of view, the spectrum should be sampled at a rate over twice the highest frequency of the spectral frequency domain. Normally an under-sampled spectrum will not allow the true character of the spectrum to be reconstructed.

Even so, the standard practice specified by ASTM E 308 [11] defines the process and provides tables of weights for using spectra sampled at different spectral spacing. Although it provides no such tables for 60nm spacing, certainly the spec implies that a simple interpolation may produce reasonable results if appropriate weights are used.

It is also difficult to get a good measurement of the SPD of the Martian illuminant. Although the rovers included a calibration target/Sundial to make it possible to calibrate the cameras and to have access to information that would allow the spectral content of the illuminant for each image to be measured, in practice the task is not so easy. Since landing, the calibration targets have become coated with dust [1, 4] and the actual layer of dust has been variable as it is sometimes cleaned off by wind or dust devils on Mars. However, efforts are underway to model the Martian illuminant. [12, 13]

Color Appearance Modeling

The conversion to XYZ is strictly colorimetric, and does not take into account any *color appearance* phenomena. Indeed, in colorimetry the viewing conditions are defined and one attempts to determine whether two different stimuli will match each other. Tristimulus colorimetry can only indicate if two stimuli match (to an average observer) - not actually *predict the appearance* of the stimulus. Thus, the colorimetric approach should really be thought of as a Near True-Color approach.

On the other hand, color appearance modeling attempts to predict the appearance correlates for a given stimulus under different viewing conditions. Thus, we wish to predict the appearance of a scene on Mars to a human observer under Martian viewing conditions and we need to display that representation under different viewing conditions such that the color appearance is as close as possible to the real scene. Colorimetry will calculate what the stimulus is while color appearance modeling will predict the actual color appearance of that stimulus to human beings.

Discounting the Illuminant

The effect of discounting the illuminant has by far largest impact on color appearance, especially considering the different illuminant on Mars. This effect, which was originally described by von Kries, is often referred to as Chromatic Adaptation and leads to what is called Color Constancy. Even though the colorimetry might be very different under different illuminants, the human observer *perceives* the same color. One common example is a piece of white paper: it will be perceived as white under a wide range of illuminants once chromatic adaptation is complete.

The illuminant is expected to play a large role in the color appearance of the Martian scenes due to the color of the Martian illuminant. The Martian sky is a butterscotch [14] color, or even redder [12, 13] when larger amounts of red dust is suspended in it due to frequent dust storms. The effect of this reddish illuminant can be seen in the reddish cast in most of the Colorimetric true-color images. While there is no doubt that the scene is actually *measured* as being red by the Pancams, a color appearance model approach should at least discount the illuminant somewhat to take into account the ability of the human visual system to become adapted to the non-Earth-standard illuminant.

CIECAM Processing of Pancam Images

The best effort approach to achieving the best possible true-color images involves two additional steps beyond the colorimetric approach. First, using the illuminant (reference viewing) conditions when the Pancams captured the images, one converts the XYZ images into the CAM color appearance space. Then the image would be converted out of the CAM space to sRGB according to the defined viewing conditions for sRGB. The CAM approach for generating true color-appearance images is shown in Figure 4 and is highlighted by the CAM block.

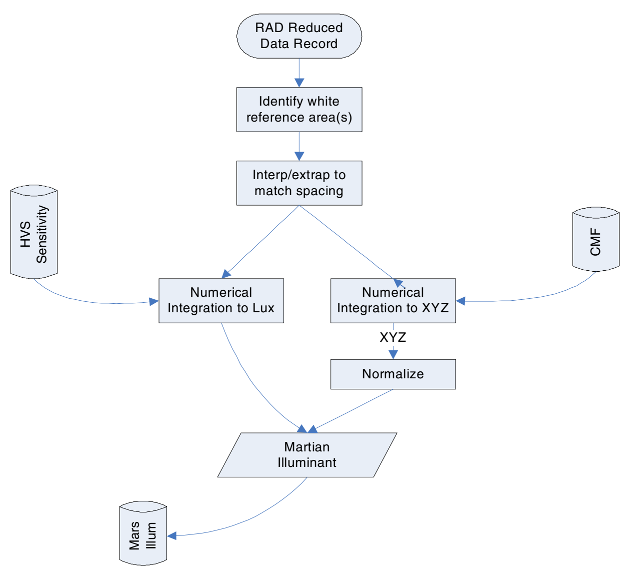


Figure 3: *Schematic Diagram of Mars Illuminant Database*

Mars Illuminant Database

The scene illuminant can be derived or extracted from the actual scene images. Ideally, the first step would be to collect into a database the SPD and luminance of the prevailing Martian illuminant for many images indexed by rover location and date/time (see Figure 3). This would allow the reference viewing conditions to be associated with any image, based on measurements near-in-time or, perhaps, from a model of the Martian standard illuminant. However, the derivation of a complete, accurate Martian illuminant database is well beyond the scope of this project.

Illuminant information was only derived for the CAM-processed images. For this project, crude estimates of the prevailing illuminant were obtained from the images by using the XYZ values of specular reflections off of metallic items in the field of view (after making sure the those portions of the image were not overexposed). The illuminant values obtained for a number of images in this manner seemed to be reasonably close to those inferred from the calibration targets.

True Color Appearance Approach

The true color-appearance image process was implemented in Matlab due to the ease of rapid-prototyping and to the ready availability of an implementation of the CIECAM02 conversion as a Matlab function.

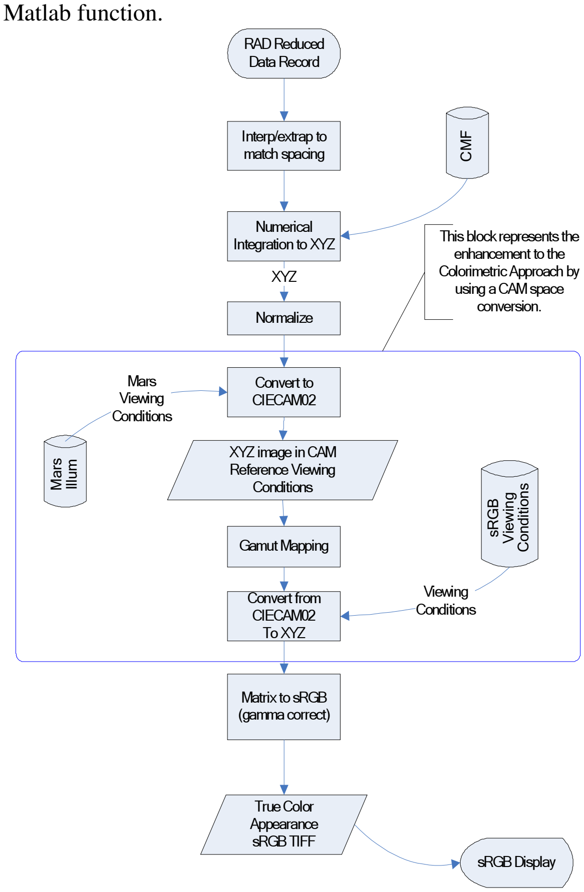


Figure 4: *Schematic Diagram of "True Color Appearance" Approach*

This implementation enhances the Colorimetric True Color approach by adding a step to convert into the color appearance model space. This step can be programmatically included for a color appearance image rendering or omitted for a colorimetric image rendering. The process converts the raw PDS image data to XYZ format, then optionally applies the CAM model to generate a modified XYZ image based on the color appearance model, and then finally converts the XYZ image to sRGB for display and print-out.

Performance optimizations, intended to not adversely affect the quality of the final images, were used to reduce the computation time. Firstly, a simple gamut-mapping strategy was used. The clipping approach has generally been found to be somewhat lacking for perceptual rendering [15] but clipping to the sRGB gamut surface was used because it is very quick. Secondly, each image was interpolated using a cubic spline to 18 points to allow the 20nm spacing weights to be used for the color-matching function in the tristimulus calculation. The code also optionally allows the 6 bands to be used directly by subsampling the 20nm weights to match the spectral bands of the Pancam imagers. This optimization could introduce small discrepancies but they can minimized if appropriate weights are used. [11] Thirdly, each image was handled as an indexed-color image to eliminate redundant color space conversion calculations. Since CIECAM does not consider the context of each individual pixel, the process took the shortcut of converting each unique 24-bit color in the image only once. In this last case, the results would be identical, but the performance gain was significant.

Lastly, in the calculation for the illuminance of the scene, some assumptions were made. In the conversion from XYZ to sRGB, the RGB values were normalized to the range from [0,255], which lost the absolute illuminance information. In principle this level can be calculated from the image data using calibration data. In practice, this is more difficult and Bell is working on making the calibration data available to make it possible [6]. In the absence of real illuminance data, the illuminance was assumed to be on the order of what one would expect from Solar illuminance values on Earth scaled for the approximate heliocentric distance to the Martian orbit. This works out to a range of 0.53 to 0.36, or roughly 1/2 to 1/3 of the value on Earth. From Hunt's table of typical (Earth) illuminance levels [15], a value of 25000 lux for a hazy Sun was scaled to 10000 lux. A range of values was tried and did not seem to produce dramatically different results.

Applicability of CIECAM02

CIECAM02 was chosen for the color appearance model. Actually, CIECAM97s [16, 17] was also used initially and only small differences were noted in the resulting images. The Matlab implementation available for both models used essentially the same input parameters.

One of the first questions that must be answered before using CIECAM02 is whether it is truly needed or is applicable. Clearly the viewing conditions (D65) are not the same as the scene-capturing conditions. The illuminant is not monochromatic so some level of chromatic adaptation is expected. There is a desire to display the *appearance* of the actual scenes as the human observer would perceive them if at the scene.

Thus, CIECAM02 is applicable for rendering these scenes. All that remains is to properly choose the values for the parameters for the model.

Rationale for Selection of Values of Parameters

As for the other parameters that specify the viewing conditions [16], the Martian illuminant was obtained as described above. The adapting field was taken to be 20% of that. A value of 1 was chosen for the sp value and both complete and partial adaptation were tried. The images in the Results section below were generated with complete adaptation. Although the chromaticity of the Martian illuminant is different from that on earth, the range of illuminants found were not radically different. In fact, the chromaticity values found are clustered very near to the illuminants used to derive the CAT02 chromatic adaptation matrix. As discussed above, the luminance levels were assumed to be fairly high. Thus, with a not-too-dissimilar illuminant at high luminance levels, adaptation was estimated to be complete.

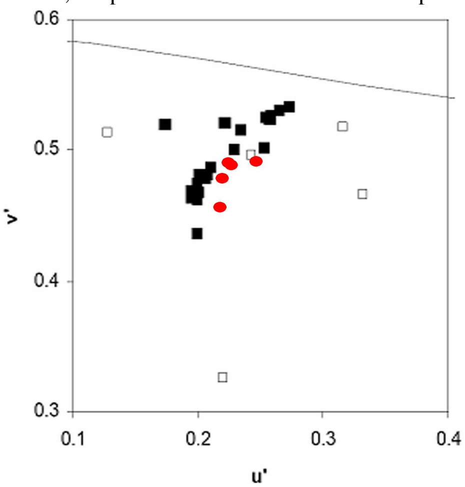


Figure 5: *Martian Illuminant Chromaticities (red ovals) compared to CAT02 Training Chromaticities [16]*

Results

A very small subset of the available Pancam true-color images was selected for processing (13 in total). The criteria for selection were simple: "interesting" scenes that either included the calibration target or specular reflections for estimating the illuminant, or that were taken near-in-time to images that included calibration material. These were processed first as colorimetric images and compared with the corresponding sRGB images from the Pancam True-Color Images site with very good match in digital counts (despite the gamut-clipping used). They were then re-processed as CIECAM02 color appearance images for visual comparison with the colorimetric versions. See Figure 7 and Figure 8 for sample images.

Images

[Note: The images in this paper do not have the proper surround for the target viewing conditions.]

Compared to the colorimetric images, most of the CIECAM images do have much less of a red cast. Many also show neutral-colored objects as more neutral (see Figure 6 below), which would be expected under complete adaptation. At least one of the images, however, shows the sky going almost neutral – I don't think this would be expected. This might indicate a wrong value for the scene illuminant or possibly issues with using CIECAM02 when the (luminous) sky is involved.

Conclusions

Real-color images from the surface of another world are very difficult to produce. If the available camera is multi-spectral, and calibration data is available for the imaging system and concerning the illuminant, then the images can be processed to display colorimetrically correct colors. But colorimetry alone does not predict the color appearance to the human observer. The resulting colorimetric images can be further processed using a color appearance model, such as CIECAM02, or even an image appearance model like iCAM, to arrive at our best estimate prediction of the appearance of the original scene. Such images could represent the best-effort true color images since they would represent the best possible effort to predict the actual color appearance as perceived by humans on the surface of Mars.

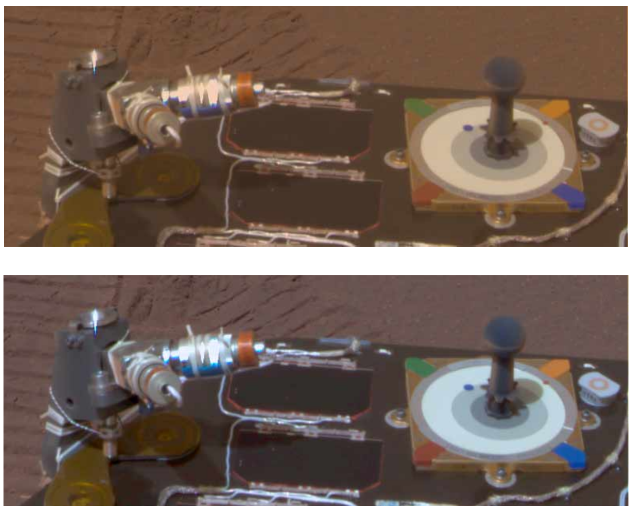


Figure 6: *Comparison of Colorimetric image (above) and CIECAM02 image (below). Neutral patches on calibration target appear more neutral.*

At least these images would display the best possible *prediction* of the actual color appearance. Confirmation would have to await the arrival of human eyes on the surface of the world to confirm those predictions. And while the *initial* appearance of the Martian surface may be ruddy as shown in the Colorimetric approach images, after short period of time when chromatic adaptation is complete, the scene should then take on the appearance as shown in the true color-appearance images.

Future Work

Since the viewing conditions play such an important role in applying any color appearance model to such images, one of the main areas of future work would be to obtain accurate and reliable values for the Martian illuminants for each of the images. Clearly some of the early images include the calibration target – which was designed and installed on the rovers for just such a purpose. Measurements can be taken from the direct and diffuse illuminated portions of the targets to arrive at a good estimate of the scene illuminant. Another source would be the specular reflections – though those values would be biased towards the direct illumination from the Sun and include less of the diffuse illumination from the sky. Lastly, the illumination could also be obtained using some algorithms that digital cameras often use to estimate the scene illuminant.

Once the illuminant values are obtained from large number of Martian images, then a composite Martian Illuminant (M1) could be derived. This value could be useful for scenes taken when the other methods don't seem to work well or produce wildly differing results.

Once the range of illuminants has been identified, then a psychophysical experiment could be performed to determine the degree of adaptation of the human visual system under that range. This would allow a more reliable value to be used for the degree of adaptation in the CIECAM02 conversion.

References:

[1] Gallery of Spirit and Opportunity Images, http://origin.mars5.jpl.nasa.gov/gallery/all/

[2] J. F. Bell III *et al,* "The Panoramic Camera (Pancam) Investigation on the NASA 2003 Mars Exploration Rover Mission", Lunar and Planetary Science XXXIV, 2003.

[3] J. F. Bell III *et al,* "Mars Exploration Rover Athena Panoramic Camera (Pancam) investigation", Journal Of Geophysical Research-Planets, 108: (E12) art. no.-8063 NOV 29 2003.

[4] J. F. Bell III *et al,* "In-Flight Calibration and Performance of the Mars Exploration Rover Panoramic Camera (Pancam) Instruments", Submitted to *J. Geophys. Res.*, April 2005.

[5] J. F. Bell III, *et al,* "Pancam: A Multispectral Imaging Investigation on the NASA 2003 Mars Exploration Rover Mission", The Sixth International Conference On Mars, 2003, Pasadena, California.

[6] J. Bell and D. Savransky, "Estimating the True Colors of Mars", http://marswatch.astro.cornell.edu/pancam_instrument/true_color.html

[7] J. Bell *et al,* "MER/Pancam Data Processing User's Guide", ver 1.0, July 2004. pds-imaging.jpl.nasa.gov/ Atlas/MER/documents/pancam_ug.pdf

[8] NASA Planetary Image Atlas, http://pdsimg.jpl.nasa.gov/cgi-bin/MER/search?INSTRUMENT_HOST_NAME=MARS_EXPLORATION_ROVER

[9] Planetary Data System (PDS) Home (Images), http://pds.jpl.nasa.gov/

[10] R. Berns, *Billmeyer and Saltzman's Principles of Color Technology*, 3rd edition, Wiley & Sons, New York, 2000.

[11] ASTM E 308-99, "Standard Practice for Computing the Colors of Objects by Using the CIE System", ASTM, 1999.

[12] R. M. Markeiwicz, *et al*, "The Martian Sky and its Illumination of the Martian Surface", Poster, The Fifth International Conference On Mars, July 18-23, 1999 - Pasadena, California.

[13] N. Thomas *et al*, "The color of the Martian sky and its influence on the illumination of the Martian surface", J. Geophys. Res. Vol. 104 , No. E4 , p. 8795. [Abstract only]

[14] D. Catling *et al*, Mars General Circulation Modeling Group FAQs, http://www-mgcm.arc.nasa.gov/mgcm/HTML/FAQS/sky.html

[15] R. Hunt, *The Reproduction of Colour*, 5th edition, Fountain Press, Kingston-upon-Thames, UK, 1995.

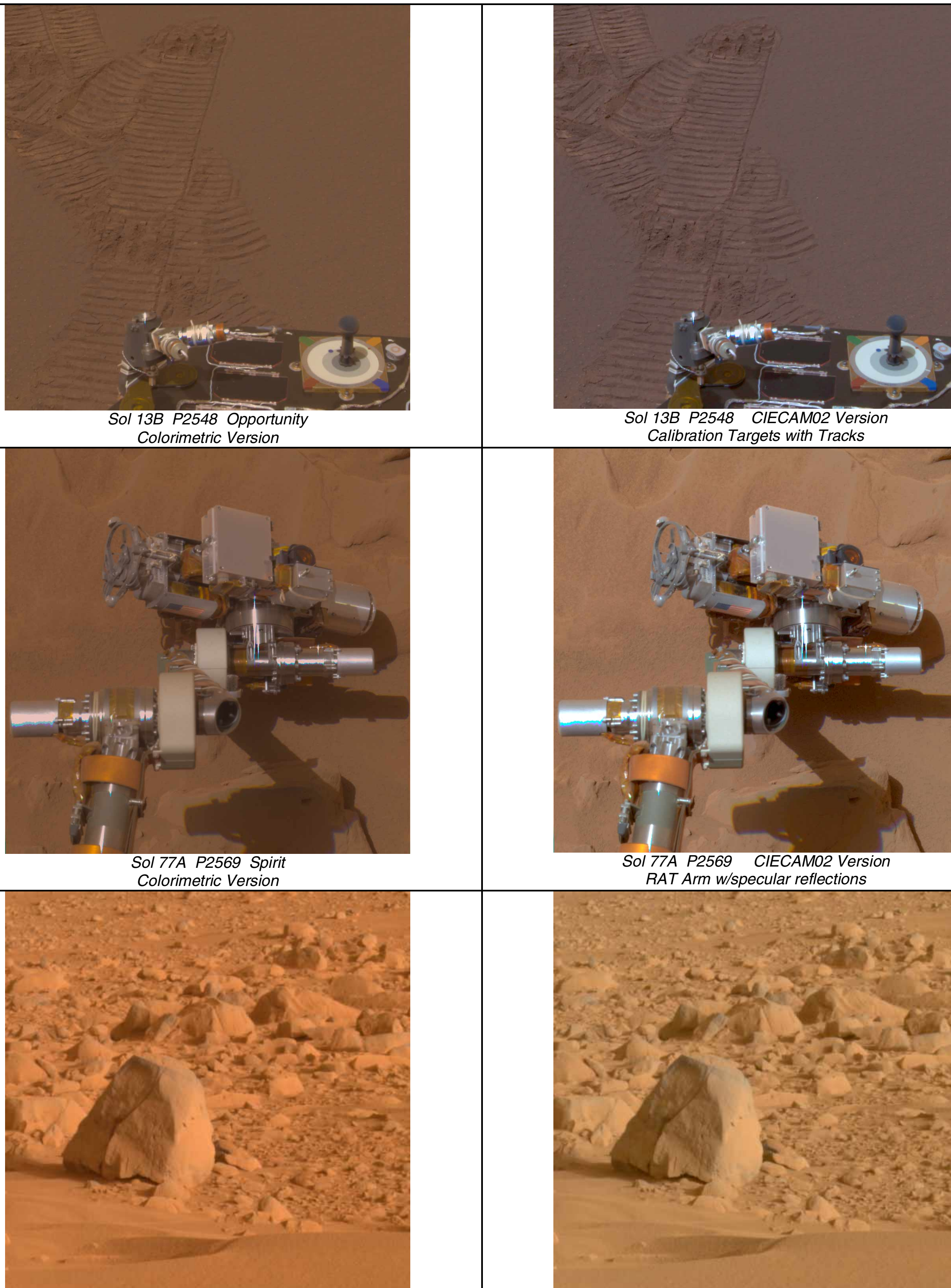
[16] N. Moroney, "Usage guidelines for CIECAM97s", PICS 2000: Image Processing, Image Quality, Image Capture, Systems Conference, vol 3, March 2000 , Volume 3; pp. 164-168.

[17] CIE TC1-34 Final Report, *The CIE 1997 Interim Colour Appearance Model (Simple Version), CIECAM97s,* 1998.

[18] N. Moroney *et al*, "The CIECAM02 Color Appearance Model", IS&T/SID 10th Color Imaging Conference, pp. 66-72, 2002.

Author Biography

Jim Hewitt holds degrees in Applied Physics/Computer Application from Brigham Young University (BS 1988), Computer Science from California State University – Chico (MS 1996), and Imaging Science: Color Imaging from Rochester Institute of Technology (MS 2006). He joined Hewlett-Packard Co. in 1995 where he is currently working as a Color Scientist. His interests include color printing, digital photography, and astronomy.



Sol 13B P2548 Opportunity
Colorimetric Version

Sol 13B P2548 CIECAM02 Version
Calibration Targets with Tracks

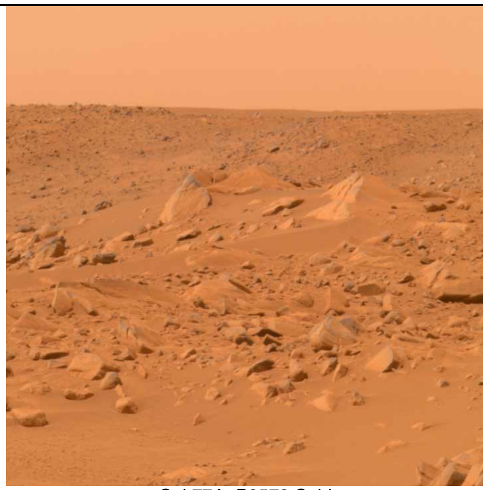
Sol 77A P2569 Spirit
Colorimetric Version

Sol 77A P2569 CIECAM02 Version
RAT Arm w/specular reflections

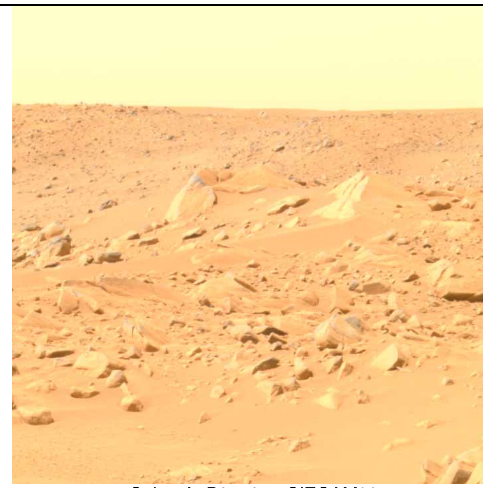
Sol 77A P2570 Spirit
Colorimetric Version

Sol 77A P2570 CIECAM02 Version
Color is not as ruddy.

Figure 7: *Colorimetric images versus CIECAM02 Images.*

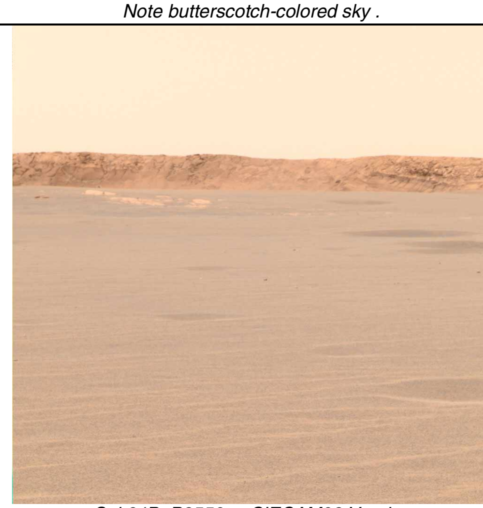


Sol 77A P2572 Spirit
Colorimetric Version



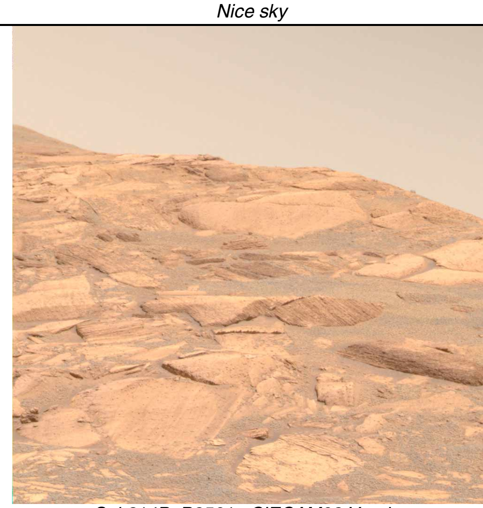
Sol 77A P2572   CIECAM02
Note butterscotch-colored sky .

Sol 94B P2556 Opportunity
Colorimetric Version



Sol 94B P2556   CIECAM02 Version
Nice sky

Sol 314B P2561 Opportunity
Colorimetric Version



Sol 314B P2561   CIECAM02 Version
Sky has gone almost neutral – probably indicates an issue with the illuminant used.

Figure 8: *More Colorimetric images versus CIECAM02 Images.*