High Spatial Resolution Visible Color Units on Mars from the Mars Odyssey THEMIS/VIS Instrument.

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Introduction: The Visible Imaging Subsystem (VIS) on the NASA Mars Odyssey spacecraft's THEMIS instrument has been obtaining high spatial resolution 5-color visible wavelength images of Mars since mapping began in February 2002 [1,2]. VIS is a 1024×1024 interline transfer CCD camera that uses narrowband interference filters bonded to the CCD to acquire multispectral images from Mars orbit at central wavelengths of 425, 540, 654, 749, and 860 nm (±25 nm). This abstract describes the newest data reduction and calibration methods used to process VIS data, and presents some initial results on surface color properties at high spatial resolution.

Calibration and Data Processing: Raw VIS images returned from the spacecraft suffer from a number of the "usual" calibration challenges inherent in CCD imaging, as well as from unique calibration and processing issues related to the VIS design and the specific environment in which VIS is operating. These issues include (a) Bias and dark current signals which need to be removed; (b) pixel-to-pixel responsivity (flatfield) variations that need to be characterized and accounted for; (c) frame transfer smear signal resulting from the finite time it takes to transfer charge to the CCD serial register and the fact that the frame transfer masks are not completely opaque; (d) scattered light impinging on the VIS field of view; (e) derivation of a set of coefficients to convert corrected DN values to radiance; (f) mapping and coregistration of different wavelength bands; and (g) Generation of "true color" display products.

(a) Bias and Dark Current. Bias signal is characterized and removed from VIS images using images obtained over the nightside of the planet. Typical bias signal levels are only a few DNs and there is a repeatable spatial pattern to the signals. Dark current has not been detectable in flight because of the low operating temperatures and the extremely short exposure times (less than 10 msec) used for VIS images.

(b) Flatfield. Pixel to pixel responsivity variations arise from intrinsic variations in the detector, spatial variations in the transmissivity of the color filters, or geometric effects from the THEMIS optics. These effects were assessed using a combination of pre-flight calibration files and in-flight averages of hundreds of images to generate "superflat" frames. In practice, flatfield variations are not completely separated from scattered light artifacts (see (d)), so the calibration pipeline handles both effects simultaneously.

(c) Frame Transfer Smear. Charge generated by the VIS CCD pixels is transferred to a masked register adjacent to each pixel for eventual clocking and transfer off the chip. However, the frame transfer time is much longer than the exposure time and the masked areas are not completely opaque. The result is extra signal added to the desired signal, in proportion to the distance of each pixel from the CCD horizontal register. This is commonly known as frame transfer smear, and can be accurately characterized and removed using a combination of knowledge of the CCD timing and specially-designed zero exposure time images. The zero images provide measurements of only the frame transfer smear component. We have obtained in-flight zero measurements over a variety of albedo terrains in order to characterize both the magnitude and "color" of the frame transfer smear, in order to model and remove it as part of our processing pipeline.

(d) Scattered Light. The beam from the THEMIS telescope impinging on the CCD slightly overfills the field of view. Some of this out of field light is reflected off structures in both the VIS detector and telescope assemblies, imparting a scattered light signal onto the raw images. Fortunately, the scattered light pattern is repeatable, and in-flight observations are helping to characterize and remove it from the desired signal. Accurate knowledge of the scattered light and frame transfer smear components has also allowed us to develop an accurate exposure time prediction model so that we can optimize the desired signal level in each wavelength even in the presence of these "contaminating" signals.

(e) Radiance Conversion. The above steps result in a set of instrumentally-calibrated images expressed in "corrected DN" values. Because the measurement environment experienced by VIS in orbit is substantially different than that which was able to be simulated during pre-flight testing, we

have relied almost entirely on in-flight observations to derive a set of absolute radiometric scaling coefficients. Our approach is twofold: (1) We use our "superflat" observations in each filter to derive an average 5-color Mars corrected DN spectrum as observed by VIS. We then use well-calibrated Hubble Space Telescope (HST) Wide Field/Planetary Camera 2 clear-atmosphere observations from 255 to 1042 nm [3] to generate an average HST spectrum of Mars using data obtained only at the same average incidence angle as the VIS measurements. This average HST spectrum is then convolved to the VIS bandpasses and the ratio of it to the average VIS corrected DN spectrum results in a set of scaling coefficients to convert corrected DN per msec to $W/m^2/nm/sr$. (2) The validity of this approach is being tested by new sets of simultaneous VIS and HST observations during 2003. The first set of simultaneous measurements was performed on March 8, 2003; 29 sets of 5-color VIS sequences were acquired within two hours of HST multispectral imaging from 220 nm to 892 nm using HST's new Advanced Camera for Surveys (ACS) instrument; 10 of these VIS image sets were acquired at exactly the same time as the HST measurements. Initial analysis of these simultaneous observations shows that our default average-based radiance coefficient approach appears to be accurate to within ~5% for VIS bands 1 through 4, and within ~15-20% for VIS band 5 (860 nm), which has the largest scattered light component. These results are preliminary and will be augmented by additional simultaneous HST/Odyssey observing campaigns. Notably, a planned campaign during the August 2003 opposition will take advantage of the fact that HST will be able to obtain a spatial resolution of ~4 km/pixel using ACS, meaning that typical 36 m/pixel color VIS image strips will correspond to about 5x15 HST pixels, a statistically more significant number for refining the calibration coefficients.

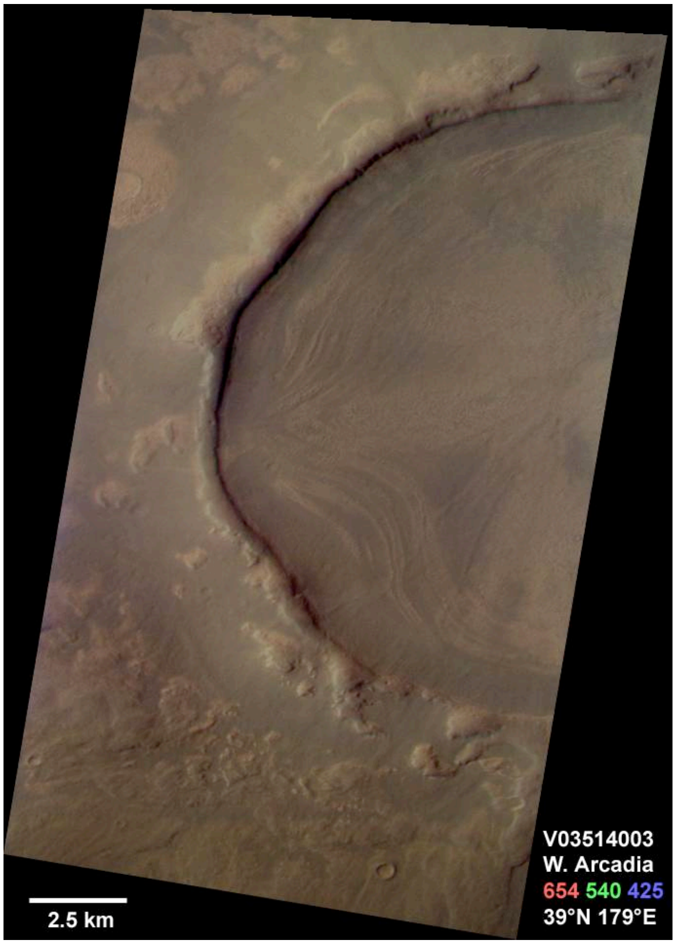
(f) Mapping and Spectral Coregistration. Calibrated radiance images are map projected using SPICE pointing information that predicts the corners and center latitude and longitude of each VIS framelet based on knowledge of the spacecraft's orbit and attitude history. Our mapping software warps each framelet onto a simple cylindrical grid, but does not yet take into account the small amount of geometric optics distortion across the VIS field of view. Each band in a VIS multispectral sequence maps to a slightly different part of the surface [2]. Dead-reckoning the pointing and mapping this way does not result in a perfectly coregistered set of multispectral images, however, because of small pointing uncertainties and distortion errors. Therefore, after each band is mapped, we use an autocorrelation routine to co-align the bands (usually using the 654 nm band as the reference) for multispectral analysis and spectrum extraction. As part of this mapping process, we also generate "backplanes" of additional information (latitude, longitude, incidence, emission, and phase angle for each pixel) that are needed for photometric correction and/or radiative transfer modeling of the calibrated data.

(g) True Color Images. For education and public outreach as well as aesthetic purposes we are also generating sets of "true color" VIS images using the radiometrically calibrated data. The intention of these products is to simulate the color of the surface as it would be seen by a person with an average human photopic response function, were they riding along with Odyssey at Mars. Our radiance images are first converted to the CIE's xyz color space (x and y are chromaticity; z is brightness [4]) using the CIE's standard "D65" color matching functions [5]. The xyz colors are then converted to the Web-friendly sRGB color system and written to TIFF files that preserve the sRGB standard color map and allow the colors to be uniformly displayed by many different software packages or Web browsers.

VIS images are currently downlinked using a combination of 12 to 8 bit companding and lossless DCT compression. Possible use of lossy compression is being investigated for future enhancement of the total VIS surface coverage.

Results: Examples of some mapped and coregistered images are provided below, along with some typical 4-color VIS spectra extracted from these data (band 5 is still problematic). Several themes are emerging from this high resolution multispectral imaging campaign: (1) Color variations are usually subtle–many occur but often at the limits of VIS resolution; (2) Dark, apparently aeolian deposits exhibit different colors, suggesting particle size and/or compositional variations; and (3) An enigmatic class of “blue” crater floor deposits has been identified but its composition or origin is not yet understood.

References: [1] Christensen, P.R. *et al.* (1999) *LPSC XXX*, Abstract #1470. [2] Bell III, J.F. *et al.* (2003) *LPSC XXXIV,* Abstract #1993. [3] Bell III, J.F. *et al.* (2003) submitted to *Icarus*. [4] *e.g.*, hyperphysics.phyastr.gsu.edu/hbase/vision/cie.html [5] Estrada, P.R. & J.N. Cuzzi (1996) *Icarus, 122,* 251.



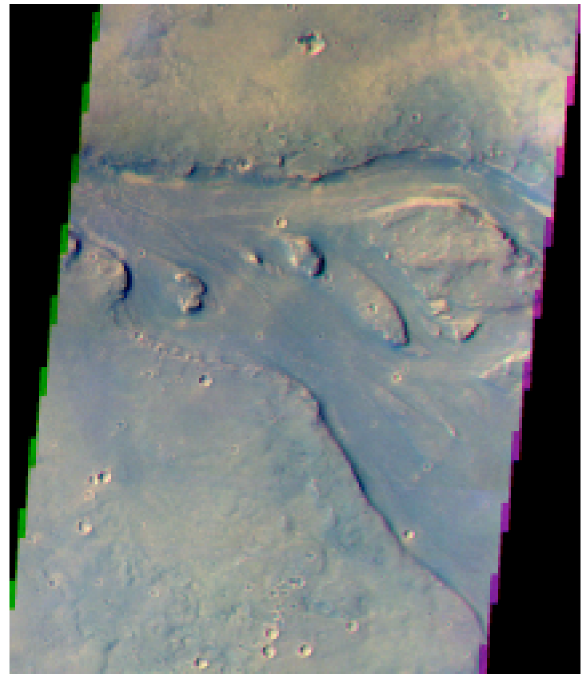
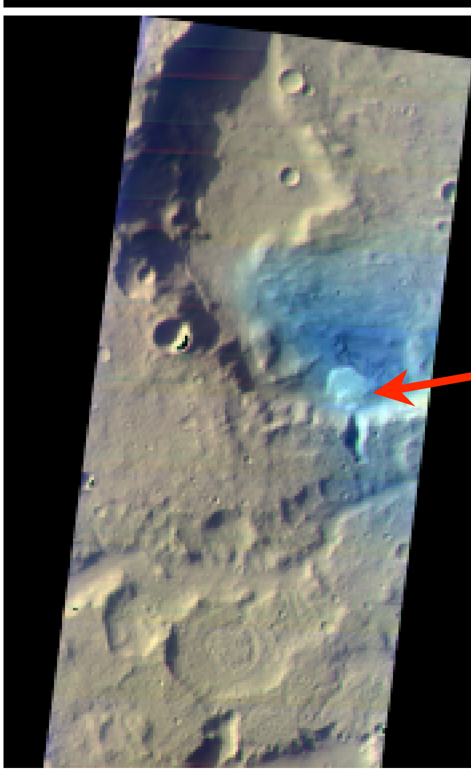


Figure 1 (left) Approximate true color image of an unnamed 23 km diameter crater in western Arcadia Planitia, near 39°N, 179°E. The crater shows a number of interesting internal and external features that suggest that it has undergone substantial modification since it formed. (top) Approximate true color image of part of the low albedo channel floor of Granicus Vallis, near 28°N, 132°E (V03578003). North is up in all mosaics shown.



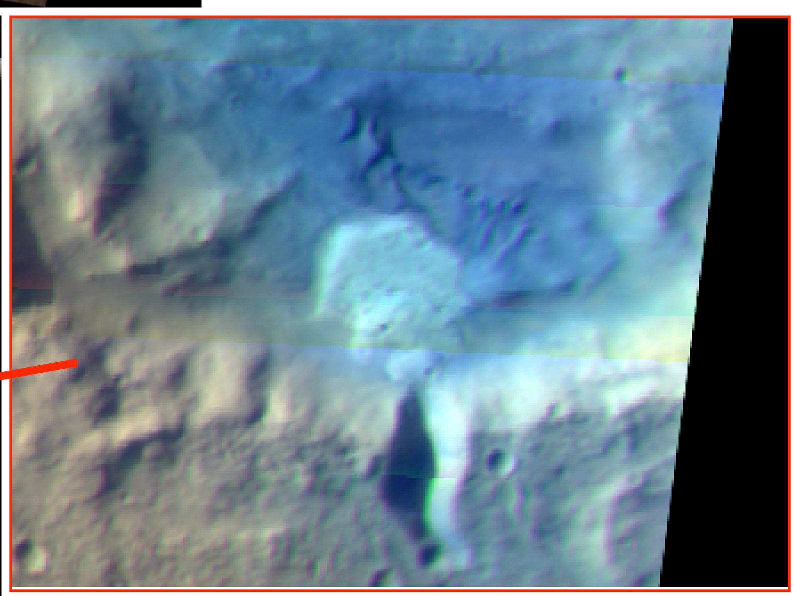


Figure 2. (left) False color RGB composite of part of VIS image V04277003 showing craters in Aeolis near 13°S, 157°E. The enlarged segment (top) shows an example of an enigmatic and substantially "bluer" deposit on the floor of one crater. The deposit is heavily cratered and appears near the downslope mouth of a small valley incised in the crater wall. The higher albedo deposit itself is surrounded by a diffuse and also bluer floor unit.

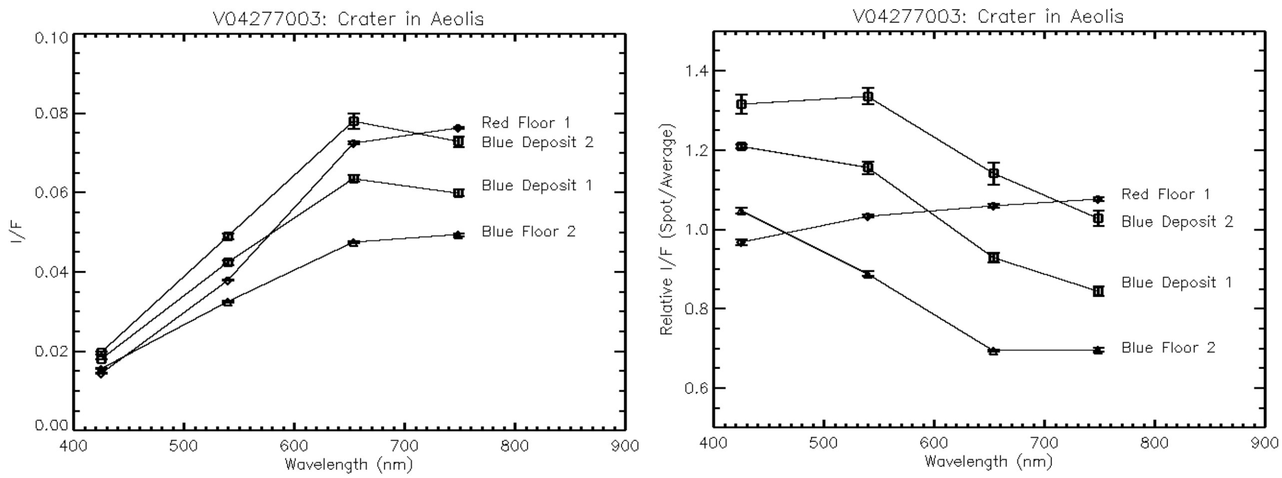
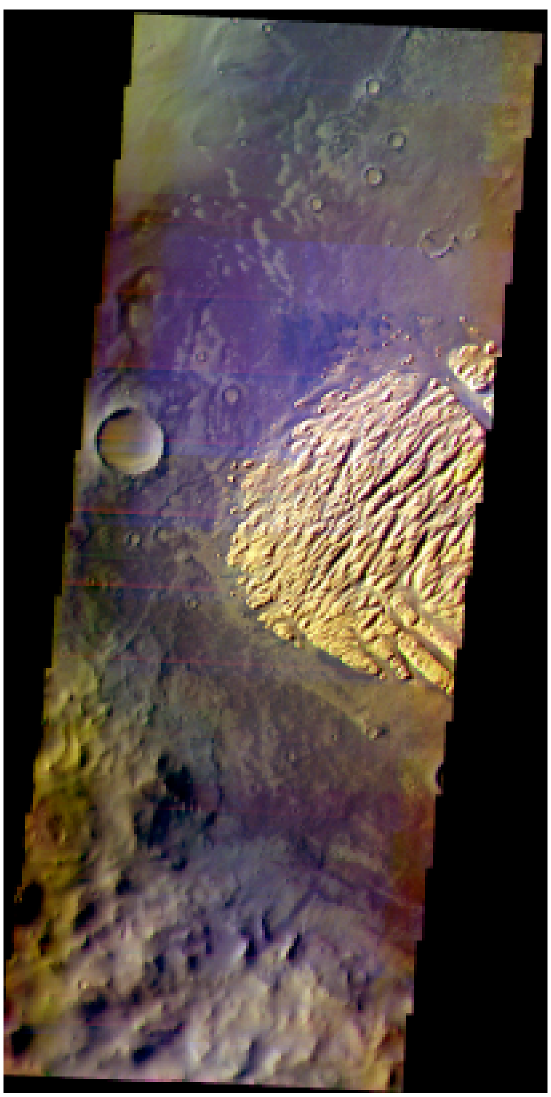


Figure 3. Examples of 4-color VIS spectra extracted from different units in Figure 2. (left) I/F spectra (I is detected radiance and πF is the incident solar radiance in that bandpass); "Blue Deposit 1" and "Blue Deposit 2" are from the higher albedo floor deposit adjacent to the small valley; "Blue Floor 2" is from the surrounding diffuse and bluer unit; "Red Floor 1" is from the surrounding crater floor region that does not show this unique spectral signature. Even the "blue" deposits can be seen to be quite red in color. The relative differences are better shown in the spectra on the right, where the average spectrum of the whole scene has first been divided out. The blue deposit is 20-30% brighter in VIS band 1 than the average. The calibration of band 5 (863 nm) is not yet adequate to allow spectral analysis.



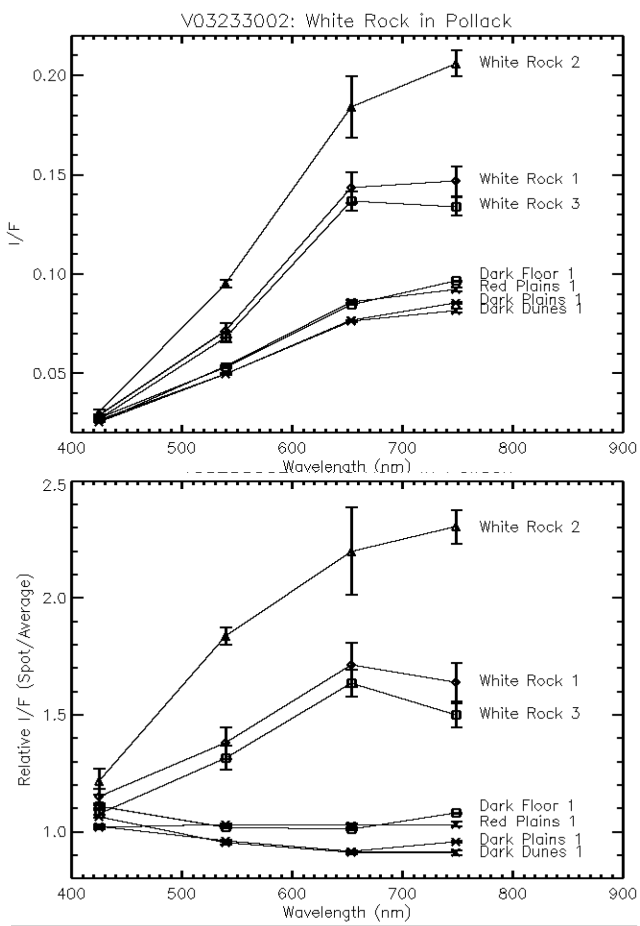


Figure 4. (left) False color RGB composite from VIS image V03233002 of the deposit known as "White Rock" in Pollack crater, near 8°S, 25°E. (top) I/F spectra from the deposit–which is clearly not white–and the surrounding crater floor and dunes; (bottom) Average-removed spectra.