IMPROVED SPECTROMETRIC CAPABILITIES FOR IN-SITU MICROSCOPIC IMAGERS

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Introduction: The Mars Exploration Program places the first life detection missions during the middle of the next decade [1]. Nearer-term objectives include the discovery of past or present habitable environments on Mars that could have nurtured microbial life and provided conditions favorable for the capture and preservation of biosignatures. Longer-term objectives include the discovery of accessible sedimentary deposits and/or ices and frozen soils that can provide direct access to ancient (fossilized) and/or recently "cryopreserved" remains of microbial life. Microscopic imaging, when combined with spectroscopic methods, can serve these objectives by enabling assessments of habitability based on observations of mineralogy at a scale relevant to microbial life.

Microtextural analysis of rocks using a hand lens, when combined with a knowledge of mineralogy, provides a powerful combination for assessing the origin of a rock. Armed with such information, the trained field geologist is often a position to immediately assign a rock to one of three basic petrogenetic categories (igneous, sedimentary, or metamorphic) and to begin to interpret past geological processes based on the interplay of textural and compositional information. In addition, comparisons of weathered and unweathered surfaces can reveal important information about the geologic processes currently active at a site.

While experience suggests that much of the basic information needed to interpret the paleoenvironmental context of a rock can be obtained in the field using the simple field methods described above, for precise mineral identifications, quantitative mineral abundances and identification of minor mineral phases present requires more sophisticated laboratory analyses. In standard geological applications, laboratory work usually focuses on the preparation of samples for optical (transmittance, reflectance, and fluorescence) and electron (reflectance and transmittance) microscopy, with supporting geochemical information being provided by such methods as secondary ion mass spectrometry (SIMS), or the electron microprobe. While these are common capabilities of most geology laboratories, their counterparts for in-situ analyses are quite limited by the need to be small, lightweight, and rugged. Contact instruments that can analyze the composition and texture of rocks and soils have a clear advantage over other methods, in requiring little, if any, sample preparation.

An analysis of data obtained by the Mars Exploration Rover (MER) *Spirit* from the Martian basaltic rock *Humphrey* serves to illustrate the accomplishments and limitations of the MER payload currently analyzing the surface of Mars. Humphrey is a fine-grained basalt [2] that was ejected from Bonneville Crater during impact. This rock was analyzed by Spirit on Sol ~60, during its traverse across the plains of Gusev Crater. The Rock Abrasion Tool (RAT) was used to expose the interior of the rock for analysis by the Mossbauer and Alpha Proton (APXS) spectrometers. The Microscopic Imager (MI) obtained images of the "RATed" surface, which showed microtextural features (vesicles) indicative of solidification from a gas-rich basaltic lava [3]. After solidification, the rock suffered fragmentation, internal fracturing, and burial within the regolith (probably during impact deposition). Subsequently, the surface of the rock was altered, developing a shiny weathering rind, or "patina". This process is likely to have involved liquid water [4]. Microimages obtained for Humphrey also suggested that while buried, fluids migrated through the regolith, penetrating the rock and depositing a light-toned mineral within the internal fractures and vesicles of the rock.

The MI instrument provided excellent microscale views of both the weathered and unweathered rock surfaces of Humphrey. However, spatially resolved information about the mineralogy of the rock coating, fracture, and vesicle fills could not be obtained with the payload available. The MER Alpha Proton X-ray and Mossbauer spectrometers are both contact instruments that are used, respectively, to assess rock elemental abundances and Fe-mineralogy. However, data provided by these instruments is integrated over the entire RAT surface and they are, therefore, unable to resolve the composition of small scale microfabric elements, such as thin rock coatings, fracture fills, or amygdules. Consequently, while we suspect that water acted during the post-depositional history of rocks at Gusev Crater, specific proof of aqueous processes is still unresolved because of the inability to obtain microscale information about mineralogy. This poses obvious limitations for assessing habitability at the Gusev Crater site.

The water story at Spirit's landing site is more subtle than that at *Opportunity's*, where there is evidence for a more pervasive and sustained action of liquid water. However, based on what is presently known, the results obtained at Gusev are likely to be broadly representative of most of Mars. Unlike Earth, Mars has been cold and dry for most of its history. In most places and at most times, aqueous processes are likely to have been best expressed at microenvironmental scales. While this suggests a more limited view of habitability for much of Mars over most of its history, nevertheless, a water-filled microfracture in a rock comprises a virtual ocean for most microbes. Detecting such microhabitats is clearly a priority for adequate assessments of habitability of Martian surface environments over the planet's history. It follows that for adequate assessments of past aqueous processes on Mars, future missions will need payloads capable of providing both *textural and mineralogical* information at the microscale.

Multispectral Microscopic Imager: The Multispectral Microscopic Imager (MMI) is being developed to provide this combination of textural and mineralogical information. In its current state of development, the MMI has achieved three key advances relative to previous microimagers: (i) acquisition of actual reflectance spectra in which the flux is a function of wavelength only, rather than a function of both wavelength and illumination geometry; (ii) increase in the number of spectral bands to eight bands; and (iii) extension of the spectral range to 1300 nm in the shortwave infrared (SWIR).

Improved illumination geometry. Accurate reflectance spectra should be a measure of reflectance *as a function of wavelength only* and should be free of instrumental artifacts. The Microscopy, Electrochemistry, and Conductivity Analyzer Optical Microscope (MECA-OM) on *Phoenix* [5] (and the microscope on Beagle-2 [6]) use separate light-emitting diodes (LEDs) for each wavelength and therefore vary the angles of illumination when changing wavelengths. When observing a specularly-reflecting sample, this produces grossly-inaccurate "spectra" since the geometry of the specular surfaces has a stronger effect on the flux collected than does the wavelength. The Mars Hand-Lens Imager (MAHLI) for the Mars Science Laboratory (MSL) uses "white" LEDs with a Bayer-pattern filter on the focal-plane array [7]. The Bayer-pattern approach introduces spatial-registration errors between spectral bands and is not extendable to more than four spectral bands. To transcend these limitations of previous instruments, the MMI uses multi-wavelength LEDs – rather than individual, single-wavelength LEDs – to provide consistent illumination geometry from one spectral band to another and provides a spectral range and resolution that enables mineralogy.

Increased number of spectral bands. Initial, 3-band and 8-band versions of the Multispectral Microimager have been designed, integrated and tested. The 3-band version is shown in Figures 1 and 2, and results from the 8-band version are presented in Figure 3. The design employs multi-wavelength LED illumination to provide a reflectance spectrum for every pixel in its field-of-view, with no moving parts. The 8-band version of the instrument has a resolution of 62.5 µm spatial resolution over 20 x 16 mm field-of-view, with spectral bands centered at 525, 660, 735, 805, 850, 940, 975, and 1300 nm.

In the 3-band version, an illuminator equipped with nine 3-wavelength LEDs was used to investigate the effects of illumination geometry. Figure 1a shows the mode of operation used by previous instruments employing discrete, single-wavelength LEDs. Since different LEDs are used for each wavelength in this case, the variation in illumination geometry produces grossly-inaccurate colors (spectra) as illustrated in Figure 1c. The gray hematite sample shown in Figure 1c does not actually preferentially reflect the red, green, or blue wavelengths exhibited in this image; these features are spurious artifacts caused by the variation in the angle of illumination (heterotropic illumination as illustrated in Figure 1a).

The single-wavelength-per-LED approach also exhibits instrumental artifacts when the sample has crevices or shadowed spaces between particles. When such features are present, portions of the object are in shadow relative to some but not all of the LEDs. For instruments that use separate LEDs for each wavelength, this effect produces grossly-inaccurate spectra for these partially-shadowed areas of the object. This latter effect occurs with diffuse as well as specular objects if they have deep pits, crevices, or partially-shadowed spaces between particles.

In contrast, the MMI approach uses *multi-wavelength* LEDs, allowing the instrument to maintain the same angles of illumination for every wavelength (isotropic illumination as illustrated in Figure 1b). This advance eliminates the grossly-inaccurate spectra produced by the prior approach, as illustrated by comparison of Figure 1c with Figure 1d.

Extended spectral range. Martian mineralogy is a rich mixture of iron-bearing and sulfur-bearing minerals. The Opportunity rover found large exposures of jarosite with hematite spherules at Meridiani Planum. Other hydrous iron sulfates have been identified in the soils of the Gusev crater by the Spirit rover. Extending the spectral range beyond 1000 nm is critical for mineralogy. Iron-bearing minerals (including iron sulfates (e.g. jarosite, melanterite), iron carbonates (siderite), and iron oxides (ferrihydrite, hematite, and goethite) have absorption bands that begin in the visible but extend to longer wavelengths. Visible-range multi-spectral data thus provide a hint of a spectral feature but without the entire absorption band do not allow minerals to be identified unambiguously. The extended spectral range of the MMI will allow mapping of iron mineralogy in sedimentary rocks and in soil horizons thus answering many questions about their petrology.

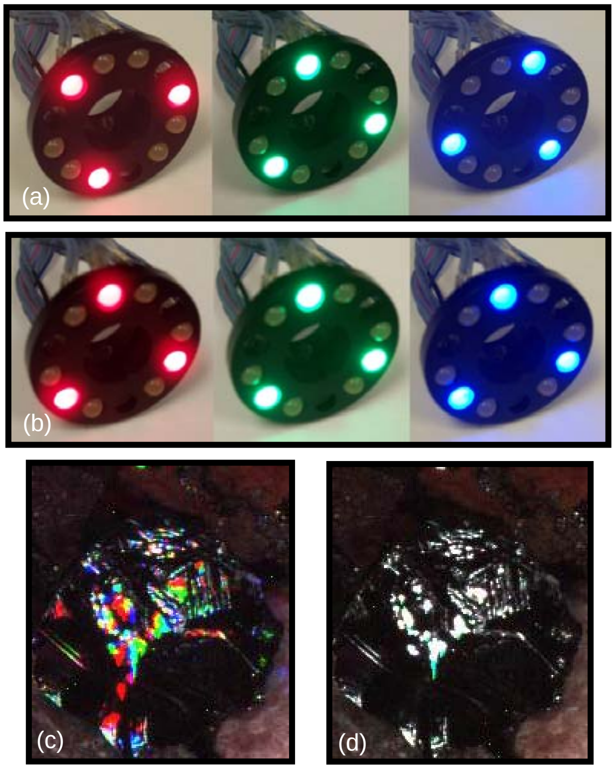

Figure 1: Demonstration of the effect of using separate single-wavelength LEDs versus multi-wavelength LEDs; (a) heterotropic illumination sequence as used by instruments with single-wavelength LEDs in which each wavelength illuminates the object from different set of angles; (b) isotropic illumination sequence using multi-wavelength LEDs in which the illumination angles do not vary; (c) composite image of gray hematite acquired with heterotropic illumination; (d) composite image of the same sample acquired using isotropic illumination.

Preliminary results: Figure 3 shows preliminary results from the 8-band version of the MMI observing a set of mineralogical samples: a false-color image comprised of three of the eight spectral bands and the reflectance spectra of selected sets of pixels. The ability to extract the spectra of any pixels or sets of pixels enables distinct spectra to be distinguished for any desired features or areas in the sample. Note that, since the desired eight wavelengths were not available off-the-shelf in a single LED, the 8-band version of MMI uses three LEDs, with 2-4 wavelengths each, to provide the eight spectral bands, and therefore the specular surfaces in the samples suffer from the undesirable spectral artifacts caused by varying the illumination geometry, as discussed earlier. A new illuminator that will provide consistent illumination geometry for all of 14 spectral bands is currently in development.

Conclusions: These improvements in spectrometric capabilities – for a rugged and compact microscopic imager with no moving parts – advance our abilities to identify past habitable environments for life based on the mineralogy and texture of rocks, with the potential for fossil biosignature detection. The integrated mineralogical and microfabric analyses will allow visualization of the spatial distribution of minerals, placing them within depositional and diagenetic contexts for better assessing their origin. Such observations allow visualization of sedimentary fabrics at a scale comparable to what geologists obtain from thin sections of rocks. This microscale, spatial-spectral mapping approach to petrography provides access to microstructural and diagenetic (post-depositional process) information, essential for the proper interpretation of the origin and aqueous alteration history of rocks and soils.

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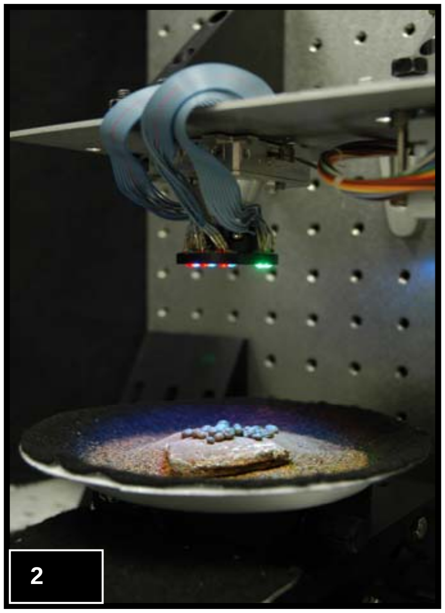

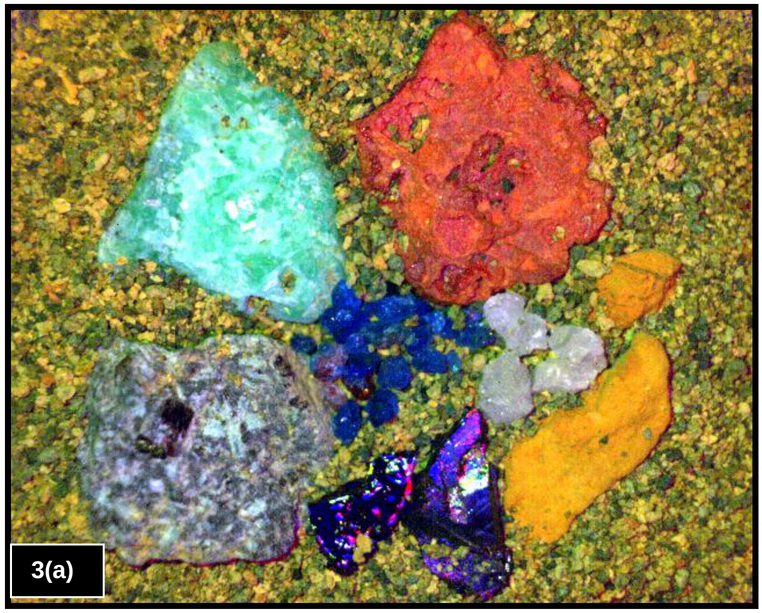

Figure 2: The MMI observing spherical hematite concretions on a back-ground of JSC-1 Mars soil simulant.

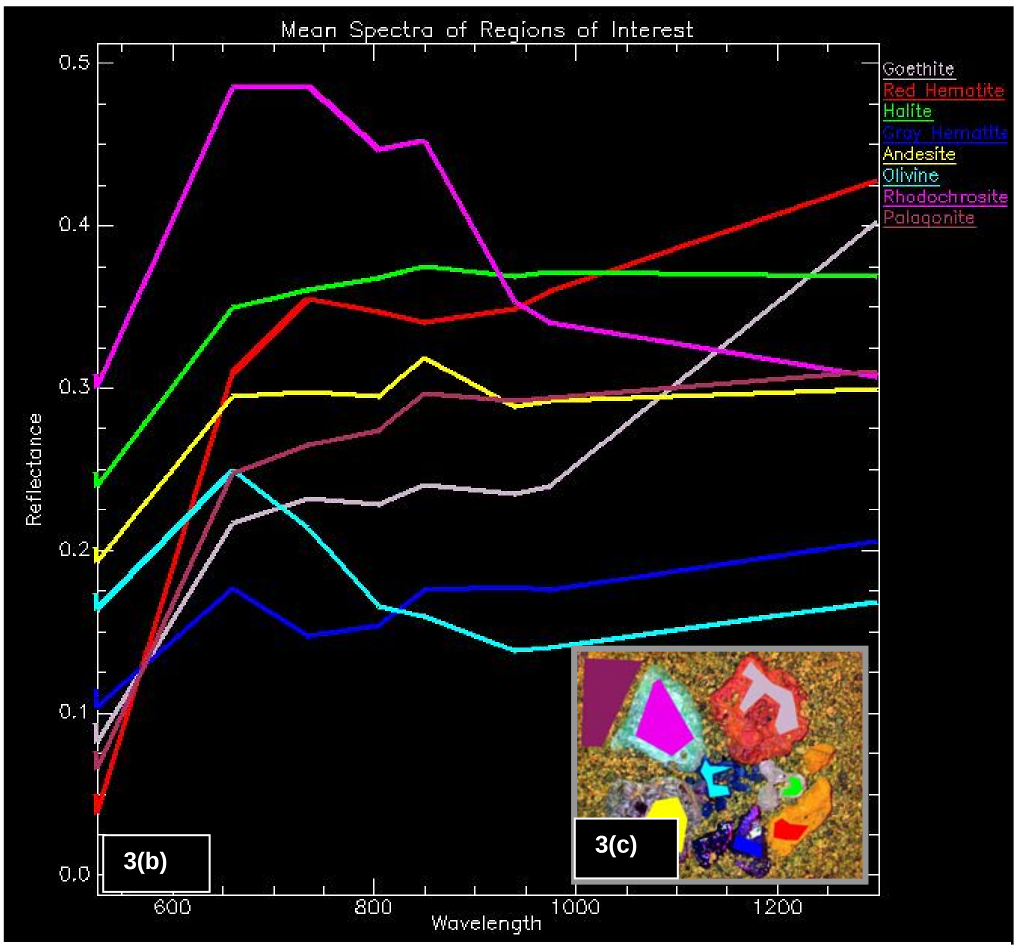

Figure 3: Im-ages and spec-tra collected by the MMI (configured for eight spectral bands) from a collection of geological samples: goe-thite, red hematite, halite, gray hematite, andesite, oli-vine, rhodo-chrosite, and palagonite; **3(a)** false-color visible/near-infrared/shortwave-infrared composite image comprised of the 525, 805, and 1300 nm bands displayed in blue, green, and red respectively; **3(b)** calibrated reflectance spectra of the regions of interest indicated in the key; **3(c)** key marking the regions of interest for which the mean spectra are displayed. The field of view is 20 x 16 mm with a resolution of 62.5 µm per pixel.