Near-Infrared imaging spectroscopy of the surface of Mars at meter-scales to constrain the geological origin of hydrous alteration products, identify candidate sites and samples for future *in-situ* and sample return missions, and guide rover operations.

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Abstract:

Near-infrared (NIR; 1-4 μm) imaging spectroscopy of Mars has proven itself to be critical in the identification and mapping of the distribution of aqueous alteration products on Mars, and has also been a key player in the process of Landing Site Selection for MSL. In this paper, we argue that increasing the spatial resolution to the meter scale from orbit, and mounting a NIR imaging spectrometer or hyperspectral imager on a rover will result in significant scientific benefits including 1) the identification of new hydrous minerals, 2) setting better constraints of spatial and stratigraphic distribution of the hydrous minerals within outcrops, 3) characterization of bed and unit boundaries and transitions, and 4) identification and analysis of smaller features apparent at MOC and HiRISE scales. In addition to improving the scientific return of both orbital and rover missions, high spatial resolution NIR imaging spectrometers will be critical in the traverse selection, operations, and sample acquisition of future rover missions.

Introduction

Near-infrared (NIR, 1-4 μm) imaging spectroscopy at sub-kilometer spatial resolutions has proven, over the past few years, to be the single most effective tool for the identification and mapping of the distribution of aqueous alteration products on the surface of Mars. Analyses of data being returned from Mars Express' Observatoire pour la Minéralogie, l'Eau, les Glaces, et l'Activité (Mex/OMEGA) and Mars Reconnaissance Orbiter's Compact Reconnaissance Imaging Spectrometer for Mars (MRO/CRISM) have led to the discovery of aqueous alteration products that have revolutionized our understanding of past environmental conditions on Mars (Bibring *et al.*, 2006; Murchie *et al.*, 2009a). The variety of minerals detected include sulfates (kieserite, gypsum - *e.g.*, Gendrin *et al.*, 2005; Langevin *et al.*¸2005; Lichtenberg *et al.* 2009), phyllosilicates (Fe/Mg smectites, Al smectites, kaolinite - *e.g.*, Poulet *et al.* 2005), opaline silica (*e.g.*, Milliken *et al.*, 2008), and carbonates (Ehlmann *et al.*, 2008). Additional efforts have allowed us to map distributions of these minerals in a geological context (*e.g.*, spatial relationship to other minerals in the region, stratigraphy, and emplacement in the rock units). Distinct classes of deposits have been identified, including extensive phyllosilicate deposits on the plains around Mawrth Vallis (*e.g.*, Poulet *et al.*, 2005; Loizeau *et al.*, 2007; Bishop *et al.*, 2008) and in Nili Fossae (*e.g.*, Poulet *et al.*, 2005; Mustard *et al.*, 2008; Ehlmann *et al.*, 2009), lacustrine sedimentary units in Holden, Eberswalde, and Terby craters (*e.g.*, Milliken *et al.*, 2007; Noe Dobrea, 2006; Wilson *et al.*, 2007) , fluvial deposits around Valles Marineris (Milliken *et al.*, 2008), and evaporitic sequences in the Valles Marineris region and some highland craters (*e.g.*, Murchie *et al.*, 2009b; Wiseman *et al.*, 2008; Marzo *et al.*, 2009, Wray *et al.*, 2009). Additionally, stratigraphic relationships have been recognized in association with these identifications.

These include the recognition that Fe-phyllosilicates underlie the Al-phyllosilicates and hydrated silica at Mawrth Vallis (*e.g.*, Bishop *et al.*, 2008; Noe Dobrea *et al.*, 2009; McKeown *et al.*, 2009), interstratification of monohydrated and polyhydrated sulfates in the Valles Marineris region (Murchie *et al.*, 2009b; Roach *et al.*, 2009; Bishop *et al.*, 2009), sulfates overlying phyllosilicates at Gale crater (Milliken *et al*, 2009), interstratification of kaolinites and phyllosilicates at Columbus crater (Wray *et al.*, 2009), and the co-existence of polyhydrated sulfates and hematite in the Chaos units east of Valles Marineris (Noe Dobrea *et al.*, 2008). The identification of these new minerals, their geological context, and their stratigraphic relationships has allowed constraints to be placed on the geological and environmental conditions that led to their genesis (*e.g.*, Bibring *et al.*, 2006; Mustard *et al.*, 2008; Bishop *et al.*, 2008; Noe Dobrea *et al.*, 2008; Ehlmann et al., 2009; McKeown et al., 2009; Roach et al., 2009).

The use of orbital NIR hyperspectral datasets has also been paramount in the identification and selection of candidate landing sites for the Mars Science Laboratory (MSL). There was a strong push during the Second and Third MSL Landing Site Workshops to ensure that the candidate landing sites presented evidence of hydrous minerals in CRISM or OMEGA data. As a result, all of the finalist and semi-finalist landing sites selected by the planetary sciences community at the Second and Third Landing Site Workshops contained geologically interesting terrains associated with NIR spectroscopic detections of hydrous minerals.

The insistence of selecting a landing site based on remote NIR detection of hydrous alteration products in the region of interest appears in stark contrasts to the absence of a NIR spectrometer for remote sensing and surface mapping aboard either MSL or ESA’s ExoMars rover missions.

In this paper, we make the case that NIR imaging spectrometers capable of mapping hydrous minerals on the surface of Mars are essential. We strongly advocate for the necessity of a NIR imaging spectrometer for detection of hydrous minerals at meter-scales from orbit that will provide enhanced scientific return, as well as critical input for future landing site selection and rover transit. We also highly recommend the need for hyperspectral NIR imagers on landed rovers that will be capable of producing maps of the surrounding mineralogy at centimeter to decimeter scales and will be critical in guiding targeting for rover *in-situ* exploration and sample acquisition for analysis and return to Earth.

Scientific objectives

The first remote detection of hydrous minerals associated with rock units on Mars were performed with OMEGA at spatial resolutions of 0.3 – 5 km/pixel. The increase in resolution provided by CRISM data (20 m/pixel at full resolution) resulted in the detection of several mineralogical species that had not been detected by OMEGA due to the relatively small size of the outcrops, as well as more precise mapping of mineralogy to geologic units. Hyperspectral imaging and mineralogical mapping at CRISM resolutions has allowed remote sensing observations to be used for geological studies, especially when combined with imaging data from the High Resolution Imaging Science Experiment (HiRISE) and the Context Imager (CTX), both aboard MRO. Mineralogies have been associated with specific rock units, stratigraphic relationships have been determined, associations with morphological units have been identified, and in many cases, geological origins have been constrained due to the results from hyperspectral NIR imagers.. However, it is often the case that even in these studies the spatial resolution is insufficient to accomplish all of these tasks to the degree desired, particularly in small exposures where it is difficult to correlate spectral signatures to morphological units, and where sub-pixel mixing of the spectra from different minerals tends to make mineralogical identifications difficult, if not impossible.

Increasing the spatial resolution to the meter scale would result in four scientific benefits:

1) discrimination of outcrops and mineral signatures that were mixed at the decameter scale and hence inseparable previously;

2) assignment of better constraints on the spatial and stratigraphic distribution of the hydrous minerals within outcrops;

3) characterization of bedding and unit boundaries/transitions;

4) identification and analysis of smaller features apparent at MOC and HiRISE scales (*e.g.*, small-scale stratigraphy, fracture fill, rover “excavations” of near-surface materials, potential hydrothermal features such as mounds/vents, and fresh gully deposits).

Understanding the spatial and stratigraphic distribution of hydrous minerals in outcrops is critical in constraining the geological origin of layers bearing hydrated minerals because the nature of the boundary zone between mineralogical units bears information characterizing the geologic conditions that might have led to changes in mineralogy. An important example of this is the ability to distinguish between the deposition of sediments (*e.g.*, in lacustrine systems) and alteration of in-place rock units both (i) by searching for the presence of alteration fronts in the form of graded transitions between units (which typically have scales smaller than 20 meters) and (ii) by studying the correlations between physical layers and mineralogical zones.

A concrete example that is of particular interest in our understanding of the history of water on Mars is the study of highly leached alteration minerals. Of these, kaolinite-group minerals stand out because they have been detected in multiple places on Mars and their formation typically requires the leaching by water in an open system. Where identified, these minerals are usually found in layers stratigraphically above other alteration minerals, suggesting that they are the products of an alteration front, or that they were deposited subsequent to the emplacement of the previous set of hydrate-bearing layers. The best test to constrain the correct scenario would require a search for a gradation in the relative abundance of these alteration minerals as a function of depth over scales of a few meters, and also searches for areas where mineralogical boundaries do not follow physical layers. Thus identification of most likely formation history in such a case could enable the differentiation between the presence of a lacustrine system where precipitation of hydrates took place, versus a system where top-down alteration occurred due to leaching by a water source that was readily available from the surface, possibly in the form of precipitation. However, these hypotheses cannot be directly addressed given the current resolution limits.

Relevance to landing site selection and rover activities, and sample selection

The heavy influence of CRISM results on the selection of landing sites for MSL stands in stark contrast to the absence of an imaging spectrometer aboard the rover itself. There are currently four finalist landing sites for MSL: Holden Crater, Gale Crater, Eberswalde

Crater, and Mawrth Vallis. In all cases, Fe/Mg smectites have been identified through analyses of CRISM data. In the case of Holden and Eberswalde, the presence of these phyllosilicates appears to occur in association with layered fluvial/lacustrine deposits. In the case of Mawrth Vallis, thick, layered deposits of Fe/Mg smectites are found to stratigraphically underlie layered units bearing Al-smectites, hydrated silica, and kaolinites. In the case of Gale Crater, Fe/Mg smectites are found to stratigraphically underlie sulfates (Thomson *et al.*, 2008; Milliken *et al.*, 2009). However, the origin of the hydrated minerals at Mawrth Vallis and at Gale Crater are not well understood, primarily because cannot fully describe the nature of the transition between mineralogical layers and whether the observed mineralogies are associated with specific sedimentary units. It may not be possible to constrain this further without observations at higher spatial resolutions, or a landed mission.

Neither MSL nor ExoMars carry a NIR imaging spectrometer capable of mapping the hydrous mineralogy of the surrounding terrains. It is already apparent that planning for these rovers' routes will be performed using a combination of CRISM and HiRISE data. Targeting of specific rocks for *in-situ* studies by MSL will likely be achieved in a relatively ad-hoc manner, relying on CRISM mineralogical maps to identify areas of interest to navigate to, followed by multispectral images acquired with MastCam in the visible/NIR region (0.3 – 1 μm) and visible laser-induced breakdown spectroscopy (VLIBS) data acquired with ChemCam to identify the rocks of interest. Having space-borne mineralogical maps of the region of interest at the meter-scale would not only facilitate target identification, but would greatly enhance the return of rover missions by providing a tangible geological framework in which to pose pointed questions that can be addressed with *in-situ* observations. This asset would benefit future rover missions by being complementing a rover-mounted NIR hyperspectral imaging system which would allow for identification of targets at cm scales. This is of particular importance to the analytical instruments on board the rover that can only analyze a limited number of samples during the lifetime of the mission, and critical to a sample return mission where the number of samples that can be returned is extremely limited.

Potential technological challenges and possible solutions

Attempting meter-scale hyperspectral NIR observations from orbit will pose a variety of challenges. These include difficulties achieving sufficiently high signal-to-noise ratios (S/N) for the identification of spectral features, on-board data storage, and processing capability (e.g., data compression). The technology to address issues with data storage and processing capability is available, but specific efforts should be carried out to qualify this technology for space. However, achieving an adequate signal-to-noise ratio (S/N) is of concern.

In order to achieve high enough S/N at 18 meters/pixel, CRISM uses a gimbal system to keep the spectrometer pointed at a target as the spacecraft overflies the it and hence increase the exposure time. Given a similar detector setup and sensitivity, this strategy may not be applicable if the spatial resolution is to be increased by a factor of 10. Instead, it may be necessary to broaden the bandpass for each channel. This strategy is employed with the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), which has a spectral resolution of 10 nm per channel between 0.4 and 2.5 μm (CRISM has a spectral resolution 6.55 nm per channel). Even at the 10-nm spectral resolution, AVIRIS is capable of resolving diagnostic features for identification of important alteration products. The experience that has been acquired over the past several years with CRISM will prove useful at defining the band centers for these diagnostic absorptions.

According to Swayze et al. (2009 *personal comm.*), the minimum spectral resolution allowable for mineralogical identification is ~20 nm/channel. Current studies suggest that orbital instruments can sustain a factor of five increase in spatial resolution by broadening bands and using improved optics before this resolution threshold is crossed. This would allow spatial resolutions somewhat better than CTX (5 m/pixel), but not as good as MGS/MOC (~1.5 m/pixel). Regardless, this resolution would be a great advance over currently available orbital imagers and would be adequate to resolve a new level of structure, as can be seen in comparisons between THEMIS/VIS imagery (18 m/pixel) and CTX imagery (5 m/pixel). It would also greatly assist with planning rover traverse, rover targeting operations, and sample selection. However, it is imperative that future technological development focus on improving the S/N of NIR mapping spectrometers in order to reach the ~m/pixel threshold that separates HiRISE from MOC observations.

Insofar as a rover-mounted imaging spectrometer is concerned, the greatest limitation would be found in the available bandwidth. A typical full MER/PanCam panorama contains 27 azimuths, 3 tiers, and 13 filters at 2 bits/pixel and occupies 2.1 Gbits of memory. An imaging spectrometer would have potentially more than100 channels and proportionally increased memory requirements. Our experience with CRISM and OMEGA is that if we are to map the distribution of hydrous minerals, we need at the very least 0.8-2.6 micron imaging at selected wavelengths. Optimally, we would seek to have 10 nm spectral sampling in the regions of 1.3-1.5 μm, and 1.8-2.6 μm in order to characterize the major hydrous absorptions of this spectral region.

Recommendations

Two major recommendations stem from this paper.

1) The development of a near-infrared mapping spectrometer capable of a spatial resolution on the scale of meters/pixel is critical toward further constraining the geological origin of hydrated minerals on Mars, and also to assist in landing site selection studies, rover activity planning, and sample return selection. Given the current state in detector technology and requirements on S/N and spectral resolution, we find that an improvement of 5x in spatial resolution is feasible and advisable for future orbital missions.
2) The development of a near infrared mapping rover-mounted spectrometer is *critical* for successful scientific operations of future rover missions, especially if the mission will be directed at the study of hydrate-bearing outcrops. Such a spectrometer should have a spectral range of at least 0.8-2.6 μm with channels at selected wavelengths to map the distribution of already-known species. Higher spectral resolution in diagnostic spectral ranges would allow for the identification of additional mineralogical species.

It is therefore evident that if future missions will focus on understanding the aqueous history of Mars and seek to maximize the scientific return from rover missions, it will be critical to acquire hyperspectral images at high spatial resolutions both from orbit and from rover-based platforms.

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