HYPERSPECTRAL AND LUMINESCENCE OBSERVER (HALO) MARS MISSION CONCEPT – INNOVATIVE DATA TRIAGE, COMPRESSION, PROCESSING AND ANALYSIS FOR THE HYPERSPECTRAL IMAGER

Edward Cloutis[1], Begoña Vila[2], Andrew Bell[2], and Michel Lamothe[3]

[1] University of Winnipeg, Winnipeg, MB, Canada
[2] COM DEV Ltd., Ottawa, ON, Canada
[3] Université du Québec à Montréal, Montréal, QC, Canada

ABSTRACT

The Hyperspectral and Luminescence Observer (HALO) instrument concept, designed to conduct surface mapping of Mars as part of the Mars Sample Return Network (MSR-NET) program utilizes a number of innovative elements to allow mapping of surficial geology of large parts of Mars at high spectral and spatial resolution, with wide wavelength and areal coverage, and high SNR. Much of this efficiency is gained through the application of Gaussian spectral deconvolution. This approach, which will be implemented on board the spacecraft, can provide an approximate order of magnitude reduction in data volumes, enable scientifically interesting targets to be identified on the fly, facilitate spectral analysis, and provide physically meaningful spectral parameters.

Index Terms— Mars, Gaussian analysis, hyperspectral imagery, data compression

1. INTRODUCTION

The exploration of Mars is accelerating, with an increasing number of agencies and nations involved in the exploration effort. The long-term goals of this exploration effort include the search for signs of extinct or extant life, sample return, and eventually, human missions [1,2]. In order to maximize the science return from a sample return mission in particular, our knowledge of the surficial geology of Mars must continue to improve. Reflectance spectroscopy conducted from orbit has played a key role in the evolution of our understanding of the surface geology of Mars.

By examining the evolution of our knowledge of the Martian surface we can discern the factors that have led to gains in this knowledge. Early Earth-based telescopic studies were limited to resolutions of generally a few hundred km, and suggested that the planet's surficial geology was largely divided into two main classes – light and dark regions of presumed volcanic/igneous rocks which were suggested to differ largely in terms of abundance of windblown dust [e.g., 3]. As spatial resolution, spectral resolution, wavelength coverage, and SNR improved, we began to discern evidence of increasing geological complexity, and suggestions of non-igneous lithologies [e.g., 4]. Orbital data, acquired at resolutions of many km (Phobos ISM), provided additional evidence of geological complexity [5]. Deployment of the OMEGA spectrometer aboard Mars Express, with spatial resolution of up to a few hundred metres, provided the first good evidence of the presence of specific hydrated minerals (sulfates such as gypsum, kieserite, and polyhydrated sulfate; phyllosilicates such as nontronite, chamosite, and montmorillonite) on many parts of the planet [6,7]. When OMEGA was joined by the MRO CRISM instrument, with spectral range and spectral resolution similar to OMEGA, but with much higher spatial resolution (on the order of up to ~18 m), the range of specific minerals detected on Mars vastly increased [e.g., 8, 9]. Increasing geological diversity at even smaller scales is indicated by results from Mars landers and rovers [10] and from high spatial resolution panchromatic imagery [11].

From the perspective of maximizing the scientific return of a Mars sample return mission, identification of targets of high scientific interest will likely require the use of high spatial resolution hyperspectral imagery, as suggested from the above discussion.

While ever-increasing spatial resolution hyperspectral imagery is a desirable goal, this generally comes at a cost. For a fixed volume of data, tradeoffs must be made between wavelength coverage, spectral resolution, spatial resolution, and areal coverage. The issue than becomes one of assessing the trade space to try and maximize the scientific return. In the case of the CRISM spectrometer aboard MRO, wide wavelength coverage and high spectral resolution comes at the cost of coverage of only a small portion of the planet (<1% for the nominal mission).

2. THE HALO MISSION

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As part of a concept study for the Canadian Space Agency, COM DEV Ltd. in conjunction with partners from the University of Winnipeg and the Université du Québec à Montréal, are investigating the optimum trade space for an orbiting Mars hyperspectral imager. The HALO mission concept is designed to deploy a hyperspectral reflectance spectrometer on an orbiter, complemented by an optically stimulated fluorescence spectrometer on a companion lander or landers. The system is being designed for possible inclusion on the proposed ESA-NASA-led Mars Sample Return Network (MSR-NET). Details of the orbiting spectrometer and innovative data processing techniques are provided below.

3. HALO ORBITAL SPECTROMETER CONCEPT

The HALO spectrometer concept builds on lessons learned from previous Mars missions and research conducted as part of a previous concept study – CHIMERA [12]. As currently configured, the HALO spectrometer would be based on a pushbroom dispersive instrument. Wavelength coverage would be 0.9-3.6 μm, with 5-12 nm spectral resolution, spatial resolution of at least 30 m/pixel, and a ~30 km swath width. This combination of wavelength coverage, and spectral and spatial resolution would provide data with an acceptable SNR (>100:1) using the proposed optical design.

In the absence of other innovations, such a mission concept would realistically be capable of imaging, at most, a few percent of the Martian surface. In order to overcome this limitation we are examining a range of concepts beyond "standard" data compression algorithms that would enable us to increase areal coverage with minimal loss of information.

4. HALO DATA PROCESSING

Our approach to increasing areal coverage while minimizing information loss is to integrate a number of disparate techniques. These can be grouped generally into two broad and partially overlapping and complementary categories: (1) data triage; and (2) Gaussian compression.

4.1. Data triage

Large portions of the Martian surface are characterized by a few broadly similar igneous rock types [13]. "Scientifically interesting" terrains are widely scattered and generally of limited areal extent [e.g., 14]. It would be highly desirable to be able to target these interesting terrains for detailed spectral evaluation. These interesting terrains could then be spectrally characterized in detail. To accomplish this, we propose to implement a form of data triage.

As envisioned, data triage could be approached in two ways, both based on the concept of an "agile" spectrometer which would be programmable on the fly and capable of performing some level of data processing and analysis. Both approaches are based on deconvolution of acquired spectra using Gaussian curve fitting (described below).

The first approach would deconvolve all acquired spectra into their constituent Gaussian curves. Gaussian curve fitting would proceed up to some defined threshold of band width and depth. These thresholds could be adjusted to maximize the capture of true surface (and atmospheric) absorption bands and minimize the capture of spurious (noise) absorption bands.

A second related approach to data triage would assess each spectrum against a predefined (and adjustable on-the-fly) "library" of standard spectra. If some threshold and (wavelength specific) parameters of spectral difference are exceeded, these spectra could be either flagged for full Gaussian analysis (below) or the spectral differences relative to the "standard" spectrum would be characterized using Gaussian deconvolution.

The "library" concept could also be modified or implemented such that, for homogenous areas, only a single representative spectrum would be retained, or spectra that are similar to previously acquired spectra would not be saved and analyzed but a simple reference made to the library (e.g., "this spectrum is the same as spectrum *x*").

4.2. Gaussian deconvolution

Gaussian deconvolution of acquired reflectance spectra is at the heart of the HALO concept. Briefly, Gaussian deconvolution involves fitting a reflectance spectrum with a continuum and a series of Gaussian functions. Gaussian analysis has been used extensively in the analysis of mineral spectra [e.g., 15]. Each Gaussian function is characterized by three parameters: (1) centre position, (2) full width at half maximum (FWHM), and (3) depth or intensity (relative to some continuum). Gaussian analysis has also been modified to work in energy rather than wavelength space [16], but recent studies have shown that Gaussians in wavelength space are essentially indistinguishable from modified Gaussians in energy space [17]. Additional research has also shown that Gaussian analysis can be used to identify highly overlapped absorption bands as well as to identify saturated absorption bands [18]. The extensive work that has been done on fitting mineral spectra has amply demonstrated that Gaussian deconvolution is a powerful tool for spectral deconvolution and extraction of a wide range of physically meaningful parameters, such as mineral chemistry [e.g., 19, 20].

We have applied Gaussian deconvolution to a number of Mars-relevant mineral spectra. We have found that a "typical" mineral spectrum can generally be fit with between 5 and 15 component Gaussians (e.g., Figure 1) plus a straight line continuum.

As each Gaussian is characterized by three parameters (position, width, depth), for a spectrum consisting of 9 component Gaussians (e.g., Figure 1), we can represent it using 29 parameters (9 Gaussians x 3 parameters + 2 parameters for straight line continuum: slope and intercept). If the spectrum is also "typical", say 10 nm resolution from 0.3-2.5 µm, it will consist of 220 data points. In this case we have achieved a close to eightfold reduction in data volume, without applying any subsequent compression to the resulting Gaussians.

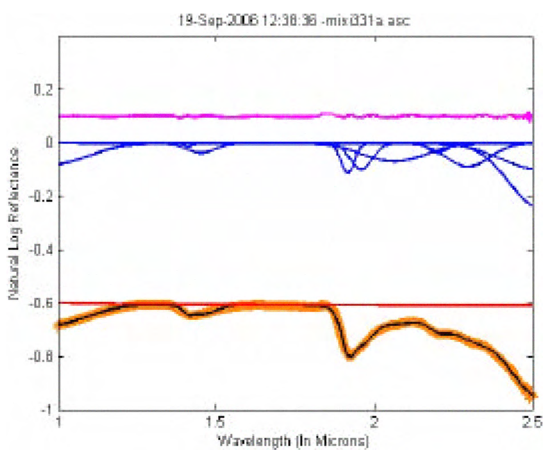

Figure 1. Gaussian deconvolution of a spectrum of huntite (a carbonate mineral present on Mars) [9]. The reflectance spectrum has been fit with 9 Gaussian absorption bands and a straight line continuum.

The use of Gaussian deconvolution provides a number of simultaneous advantages and benefits. In addition to the approximate order of magnitude reduction in data volume that it provides:

? Gaussian deconvolution provides data in a format that is suitable for subsequent analysis based on spectral libraries; i.e., spectral matching based on Gaussian similarities; this curve matching can be performed on the spacecraft (as described above) or on the ground.

? Gaussian curves provide information that is physically meaningful. Each component Gaussian is related to a specific physical mechanism; e.g., "crystal field transition in ferrous iron located in the M2 crystallographic site of a 20 mol % Fe^{2+} orthopyroxene" [19, 20].

? Small variations in absorption band positions can allow severe constraints to be placed on mineral composition. Such variations are preserved in Gaussian analysis. In contrast, small variations in band positions are generally located in the higher orders of principal components, orders that are generally discarded during analysis because the small but significant variations in band positions are often grouped together with noise.

? Gaussian analysis implemented "on the fly" can be used to build up an on-board library for analysis of subsequently acquired spectra. Library searches based on matching Gaussians will be quicker than library searches based on full spectra.

? Absorption bands that arise from the same mechanism (e.g., crystal field transitions in ferrous iron located in a specific crystallographic site) will vary in tandem, for example becoming deeper with increasing grain size. Consequently, spurious identifications can be minimized, or band saturation identified if a suite of Gaussians deviate from the parameters defined for a particular mineral.

5. SUMMARY

Through the use of a variety of innovative technologies, the HALO mission can succeed in providing excellent wavelength coverage, spectral resolution, areal coverage, and SNR. The data processing/compression algorithms that will be implemented will provide at least an approximate order of magnitude reduction in data volumes, output data that are both physically meaningful and readily analyzed, allowing data transmission capabilities to be targeted to scientifically interesting areas.

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