A COMPREHENSIVE NUMERICAL PACKAGE FOR THE MODELING OF MARS HYPERSPECTRAL IMAGES.
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Introduction Visible and near infrared imaging spectroscopy is a key remote sensing technique to study and monitor planet Mars. Indeed it allows the detection, mapping and characterization of minerals as well as volatile species that often constitute the first step toward the resolution of key climatic and geological issues. These tasks are carried out by the spectral analysis of the solar light reflected in different directions by the materials forming the top few millimeters or centimeters of the ground. Indeed, in the visible (VIS) and near infrared (NIR) ranges, many species of interest (carbonates, hydrated minerals, ices, etc.) present numerous and distinctive absorption bands. The chemical composition, granularity, texture, physical state, etc. of the materials determine the existence and morphology of these bands. Radiative transfer models simulating the propagation of solar light through the martian atmosphere and surface and then to the sensor aim at evaluating the direct and quantitative link between parameters and spectra. Then techniques must be applied to the models in order to invert the link and evaluate the properties of atmospheric and surface materials from the spectra. Processing of all the pixels of an image finally provides physical and structural maps.

Imaging spectrometers, which are currently on-board two martian orbiters, provide three (two spatial and one spectral) dimensional hyperspectral images. Constant technological improvements promote the acquisition of dramatically expending image collections. In March 2006 the OMEGA instrument (Mars Express, ESA) has already collected 310 Gbytes of raw images. A new generation of imaging spectrometers has already emerged with an additional angular dimension for a better characterization of planetary materials and separation of atmospheric versus surface signals. Planetary sites will now be observed not only vertically but from different view points on the satellite trajectory. The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on the Mars Reconnaissance Orbiter (MRO) is the first hyperspectral multi-angle (HMA) imager to operate from deep space. These new instruments will again accentuate the size (several tera-bytes) and complexity of the martian remote sensing data.

As a consequence the community that faces this growing collection of hyperspectral images is urged to develop very efficient yet accurate numerical models and tools for their physical analysis. A couple individual projects have emerged with the start of the Mars Express mission. We have also contributed to this effort by building a comprehensive numerical package for the modeling and inversion of Mars polar hyperspectral images. The following paragraphs describe the different components of the system and the way they operate in sequence.

Atmospheric radiative transfer *Gas* A dozen atmospheric absorption bands due to gaseous CO_2 and marginally to H_2O are present on the near infrared spectra and sometimes overlap the mineral and ice signatures. We calculate the transmission function of the atmosphere along the incoming and outgoing paths, for each pixel of our spectral images, and as a function of wavelength. For that purpose, we employ a line-by-line radiative transfer model [1] fed by the vertical compositional and thermal profiles predicted by the European Mars Climate Database (EMCD) [2] for the dates, locations, and altitudes of the observations. Because the complete calculation is very time-consuming, it is only performed for a limited ($\preceq$ 200) number of reference points representative of "regions" sliced according to regular bins in the latitude, longitude and altitude dimensions. Three spectra are generated for the maximum, mean and minimum altitude of a given region. Then the transmission spectrum of all the pixels belonging to the region is interpolated from the triplet depending on their individual altitude. Possible deviation of pressure from the EMCD value due to meteorological variability can be taken into account. All the transmission spectra corresponding to an image are organized in a "ATM" image cube.

Aerosols To achieve the required efficiency for the system, we consider only one homogeneous plane-parallel layer of aerosols that can occupy different altitude ranges. The aerosols (dust, water ice), that we consider as being spherical particles, are characterized by their optical constants and their power law size distribution. We first use an algorithm by [3] to calculate the single scattering albedo, phase function and optical depth of the complete layer (gas+aerosols). Second, following [4], we apply the Green's function method to the total one-dimensional radiative transfer problem. The atmospheric transport is mathematically separated from the lower boundary condition (the surface). This implies that the total radiance that reaches the sensor can be expressed by an analytical solution involving any arbitrary non-lambertian surface reflectance and the intrinsic radiative properties of the atmosphere. We obtain the latter, i.e. the diffuse reflection and transmission functions, by running a modified version of the analytical radiative transfer model of [5]. The integration of these different elements leads to a very efficient numerical scheme for the alteration of any spectro-photometric signatures of the surface by a "standard" atmosphere.

Surface radiative transfer The modeling of the surface bidirectional reflectance is performed with a simulation of the radiative transfer of solar light through layered, icy or mineral materials [6]. It takes into account the geometry of observations, e.g. nadir pointing and low sun illumination for most OMEGA polar acquisition, as well as shadowing effects due to macroscopic roughness [7]. Each layer is first treated separately depending on its texture: granular or compact with inclusions. For granular mixtures of H_2O, CO_2 and dust, Hapke's formalism [8] makes it possible to calculate the single scattering albedo and the optical depth while for an ice slab the same quantities are computed using the model of [9]. Then we carry out an adding scheme to calculate the bidirectional reflectance of the stack of layers from the individual reflection and transmission function. We take into account the Fresnel reflection and refraction of photons occurring at each interface between a compact layer and a granular one (or the atmosphere). For that purpose, we assume that these interfaces have a small, but significant roughness with a gaussian statistic of slope distribution.

Building databases of synthetic spectra We calculate huge collections of synthetic spectra by direct radiative transfer modeling in order to perform the inversion of hyperspectral images. The calculation is based on a qualitative description of which components are present in the image and how the latter are distributed and mixed spatially within the pixel both at the surface and in the atmosphere. The user also provides the extent and the sampling of the related free parameter space. Both kind of information are entered through a graphical interface that drives a program aimed at generating the needed input file for the modeling. We are always limited by storage capacity on hard-disks or in memory during processing and the required computing resources to generate the databases increases exponentially with the number of free parameters. Our strategy to address these problems is two-fold: (i) we just calculate size-limited key databases that correspond to the surface alone and they are subsequently combined linearly (geographical mixtures), interpolated (in the angular dimensions of the reflectance) or altered (by the atmosphere or by surface roughness) on-the-fly according to the needs of the KNN algorithm (see next paragraph). (ii) we reduce the size of the databases by adopting smart strategies for the representation of the bidirectional reflectance and for its reduction in the spectral dimension [10].

Inversing physical models for the study of hyperspectral images Optimized K Nearest Neighbor algorithms (KNN) can search through one or several virtual database(s) to seek the solutions (combinations of physical parameters) that provide the best fits for each observed pixel of a hyperspectral image. As a result distribution maps of compounds as well as maps of physical, chemical and structural properties are built and are used to address the geological or climatic problems of interest. Despite huge quantity of data to calculate and store, the advantage of using synthetic database for the inversion of images are: (i) access to potentially multiple solutions, (ii) robustness of the inversion process, (iii) good compatibility with distributed computing.

Conclusion The main original aspects of our system is to implement and integrate all the elements needed to achieve the modeling of Mars hyperspectral images: direct radiative transfer through the atmosphere and icy surfaces, building huge database of synthetic spectra corresponding to the variations of model parameters, search of solutions through the latter to fit the observation. We just start the operational exploitation of the system for the analysis of the OMEGA/MEX dataset covering the polar regions. More generally the anticipated outcome is better and richer products for the study of the atmosphere and the surface of the red Planet.

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