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Simulating hyperspectral images for Martian 3D scenes.

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Abstract We present a tool for simulating hyperspectral images for 3D Martian scenes. Several lines of development are considered for achieving a high degree of realism : high resolution digital elevation models, description of material distribution with fractal characteristics, bidirectional reflectance measured in the laboratory as a function of geometry and wavelength for a series analogue materials, mixing of spectral signatures at different scales, 3D radiative transfer between atmosphere and surface. The simulator addresses two main needs (i) developing and testing methods for the correction of atmospheric and photometric effects images taken by orbiter around Mars (ii) developing and testing methods for the linear and nonlinear spectral unmixing applied to hyperspectral images.

Methods A synthetic hyperspectral image is generated according to a given scene, atmospheric conditions, « sensor » characteristics, and observation geometry. For that purpose several modules are implemented that reflect different steps in the simulation.

Description of the material distribution and abundances. The spatial distribution of materials covering the scene is described by maps of pure component - a.k.a "endmembers" - abundances. The latter are generated by a genetic algorithm - a cellular automaton - reproducing some planetary transport and mixing processes for achieving fractal properties as expected for real scenes in nature. The cellular automaton consists on an iterative process starting with seeds of pure materials distributed within the scene and performing actions between pixels such as mixing and gradient controlled diffusion. The user can define roughly the distribution of the endmembers by defining the seeds, the different probabilities for each action, the size of the neighborhood window, and the total number of iterations. For instance, if the probability of mixing is high the resulting abundance maps will be very mixed.

Spectro-photometric properties of the materials in the scene. In the simulation, the bidirectional reflectance of the surface materials is expressed either using the Hapke model or the Ross-Thick Li-Sparse (RTLS) model: $\rho(\mu_0, \mu, \varphi) = k^L + k^G f_G(\mu_0, \mu, \varphi) + k^V f_V(\mu_0, \mu, \varphi)$ The subscripts refer to Lambertian (L), geometric (G) and volumetric (V) components with f_G and f_V predefined geometric kernels. This model has proved to be accurate in recreating many types of natural surfaces [1]. Several modalities of the RTLS model were extracted by our tool MARS-ReCO [2] for varied Martian geological contexts from the processing of multi-angular hyperspectral observations by the Compact Reconnaissance Imaging Spectrometer for Mars (CRISM). On the other hand the bidirectional reflectance of eight natural well-controlled samples of planetary interest was measured as a function of wavelength in the visible and infrared for a large range of phase angles [10-130^o] with a spectrophoto-goniometer [3].

Modeling of mixtures. The components can coexist at two main subpixel levels: macroscopic (linear spatial mixing) and/or microscopic (non linear granular mixture). In the case of a purely linear mixture, the endmember abundances are areal fractions $a_r, r = 1, ..., R$ (nb of endmembers). In the case of a purely intimate mixture, the endmember abundances are fraction number of grains $f_r = 1, ..., R$ (nb of endmembers). In the case of a mixtures of mixtures, the endmember abundances are built from areal fractions $a_r, r = 1, ..., R + 1$ and fraction number of grains $f_r = 1, ..., R$ so that the abundance of endmember r is $a_r + a_{R+1} * f_r$. The Hapke parameters (w, b, c, θ) of an intimate mixture are obtained from the photometric parameters of each pure compound $(w_r, b_r, c_r, \theta_r)$ and from the abundance maps according to the mixing rules proposed by [4] derived from MonteCarlo raytracing experiments that we parametrized.

Computation of the geometrical and illumination conditions. The scene is also defined by a high-resolution (10m.pixel-1) high quality Digital Elevation Model (DEM) that we generate from the fusion of photogrammetry and photoclinometry information derived from CTX@MRO imagery [5]. Then maps of local geometrical and illumination conditions can be calculated considering the sun elevation θ_S and northern azimuth ϕ_S as well as the viewing zenith angle VZA and the phase angle g as a function of the pixel geographical coordinates. The atmospheric condition is defined by the aerosol radiative properties, their vertical distribution and an integrated Aerosol Optical Depth (AOD). At this point the atmospheric radiative LUT of MARS-ReCO [2] provides the direct and diffuse wavelength dependent illumination for a flat ground. We use an improved version of the parametrization by [6] for adapting these fluxes to any slope characterized by its magnitude and orientation. In addition one needs to consider the fraction of sky visible and to care about possible shadowing and occultation of a given facet by neighboring topography. Highly efficient discrete geometrical calculations implemented on GPU are performed on the DEM for that purpose.

Surface-atmosphere radiative transfer calculations for computing the image. The calculation of the spectral radiance at the sensor is based on (i) the Hapke or RTLS model fed by the macroscopic spectro-photometric parameters for computing the reflectance of the surface and (ii) a 3D surface-atmosphere radiative transfer (RT) scheme inspired by [7] and addressing environmental effects (i.e. reflections of direct and diffuse irradiance from the neighborhood) and the multiple scattering between the surface and the atmosphere. The upward transfer of the surface reflected radiance to the sensor either by direct path or by multiple scattering is implemented with a 1D RT scheme.

Results Series of synthetic images are produced to validate the direct simulation code and to perform a sensitivity analysis of the model regarding its different parameters. In particular we can compare qualitatively and quantitatively real imagery with twin synthetic images produced by our tool according to the same atmospheric and geometric conditions using spectro-photometric properties extracted from CRISM observations by our tool MARS-ReCO (Fig. 1).

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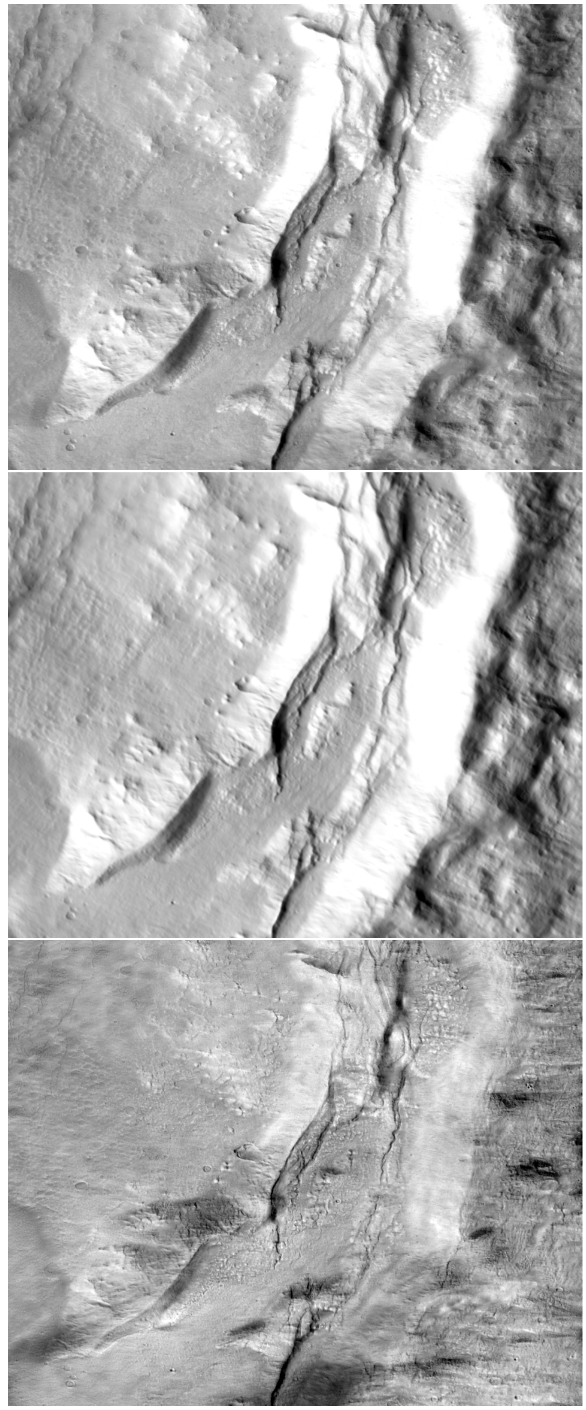

Figure 1: Comparison for a region of interest between an original CTX image (top) and a synthetic counterpart image produced by our tool (middle). For the latter the surface is considered to be homogeneously covered by a single material owning the average spectro-photometric properties of the region as extracted from a CRISM observation by our tool MARS-ReCO. We also show the ratio of the two former images revealing albedo variations intrinsic to the surface independently to the illumination conditions (bottom)

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