

MULTIPLE SCATTERING MODELING PIPELINE FOR SPECTROSCOPY OF ASTEROIDS AND METEORITES.

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Introduction: We are combining a set of numerical tools to analyze the reflectance spectra of granular materials. Our motivation for this study comes from the present lack of such tools when it comes to intimate mixing of materials, including space-weathering effects with nano- or micron-sized inclusions in the host matrix. The current common practice is to apply a semi-physical approximate model such as some variation of the Hapke model (e.g., [1]) or the Shkuratov model [2]. These models are expressed in a closed form so that they are relatively fast to apply. They are based on simplifications on the radiative transfer theory. The main drawback of introducing such simplifications is that the validity of the model is not always guaranteed, and the derived physical properties related to the particle scattering properties can be unrealistic [3]. The Hapke space-weathering model, for example, does not include correct size dependence for the nanophase iron inclusions [4].

The analysis pipeline: Our numerical tool consists of individual scattering simulation codes and a main program that chains them together, calling the codes and converting the output of one code as input for the next code. The chain for analyzing a macroscopic target with space-weathered mineral would go as follows:

- Scattering properties of small inclusions inside an absorbing host matrix can be derived using exact methods solving the Maxwell equations of the system. From the scattering properties, we use the so-called incoherent fields and the corresponding incoherent Mueller matrices as input for the next step [5].
- Scattering by a single regolith grain is solved using a geometrical optics method accounting for surface reflections, internal absorption, and possibly the internal diffuse scattering [6,7].
- The radiative transfer simulation is executed inputting the regolith grains in the previous step as the basic scatterers in a macroscopic spherical, planar, or arbitrary shaped volume element.

For the most realistic asteroid reflectance model, the abovementioned chain would produce the scattering properties of a planar surface element. Then, a shadowing simulation over the target surface elements would be considered, and finally the asteroid phase function would be solved by integrating the bidirectional reflectance distribution function of the planar element over the object's realistic shape model.

For mixing intimately two or more minerals with sizes larger than the wavelength of light, the first step of the abovementioned chain would be omitted. Instead, the single grain properties would be computed for every material, and then averaged into imaginary average grain. The macroscopic properties would be computed following the recipe above. The tools in the proposed chain already exist, and practical task for us is to tie these together into an easy-to-use public toolchain. We plan to open the abovementioned toolchain as a web-based open service. In detail, we are building this chain in a dedicated (virtual) server, using Django application server and Python environment for the chain main functionality. The individual programs to be ran under the chain can still be programmed with Fortran, C, or other programming language.

References: [1] B. Hapke (2008) *Icarus* 195(2):918–926. [2] Yu. Shkuratov, L. Starukhina, H. Hoffmann, and G. Arnold (1999) *Icarus* 137(2):235–246. [3] Y. Shkuratov et al. (2012) *J Quant Spectrosc Radiat Transf* 113(18):2431–2456. [4] P.G. Lucey and M.A. Riner (2011) *Icarus* 212(2):451–462. [5] K. Muinonen, J. Markkanen, T. Väisänen, J. Peltoniemi, and A. Penttilä (2018) *Optics Letters* 43(4):683–686. [6] K. Muinonen, T. Nousiainen, H. Lindqvist, O. Muñoz, and G. Videen (2009) *J Quant Spectrosc Radiat Transf* 110:1628–1639. [7] J. Martikainen, A. Penttilä, M. Gritsevich, H. Lindqvist, and K. Muinonen (2018) *J Quant Spectrosc Radiat Transf* 204:144–151.