

USE OF MULTIPLE ENDMEMBER SPECTRAL MIXTURE ANALYSIS AND RADIATIVE TRANSFER MODEL TO DERIVE LUNAR MINERAL ABUNDANCE MAPS. L. Li.¹ and P. G. Lucey², ¹Indiana University-Purdue University, 723 W. Michigan Street, Indianapolis, IN 46202, email:ll3@iupui.edu, ²University of Hawaii, Institute for Geophysics and Planetology, 1680 East-West Road, POST 515, Honolulu Hawaii, 96822.

Introduction: Determination of mineral composition of the lunar surface is fundamental for understanding the origin and geologic evolution of the Moon. Such compositional information can be used to examine the magma ocean model of lunar crust formation and to investigate lunar crustal structure, basaltic volcanism, crater/basin structure and ejecta emplacement, as well as lunar soil mixing mechanisms. While exploration of the Moon is entering an explosive measurement phase with the ongoing flotilla of remote sensing spacecraft of this decade, lunar mineral maps will not issue from a mission because a well performing remotely mapping method is not available. Current radiative transfer modeling (e.g., Hapke's work) is time consuming when applied for both multispectral and hyperspectral mapping, and other empirical approaches (e.g. spectral band and band ratios) perform poorly for some minerals (e.g., plagioclase and olivine). The proposed approach is a combination of state of the art methods for deriving mineralogy from individual spectra of lunar materials in which spectral mixing analysis (SMA) is used to reduce time needed to derive mineral maps from large lunar data sets and a radiative transfer model (RTM) used for the individual spectrum analysis. This hybridized method is tested with lunar global Clementine ultraviolet (UV)-visible (VIS) multispectral (0.45-1.0 μm , 5 color) image at 1 km spatial resolution.

Multiple Endmember Spectral Mixture Analysis (MESMA): SMA is a commonly used method for subpixel detection and classification of remotely sensed data [1-6]. Linear SMA assumes that the reflectance of each mixed pixel is a linear combination of spectra of distinct components (endmembers) with the weights representing the abundances of endmembers resident in a mixed pixel. SMA produces a series of images that contain the estimated abundance of endmember materials. The maximum number of components that SMA can map is limited by the number of bands in the image data. In relatively small regions with only a few geological components, SMA can be used to map the compositional distribution with reasonable accuracy [6, 7]. However, over large regions extending to global scales the number of lunar surface components exceeds the number of bands in Clementine UV-VIS multispectral data, violating the assumptions of traditional SMA. MESMA was proposed to overcome the limitations of traditional SMA [8]. MESMA assumes that although an image contains a large number of spectrally distinct components, indi-

vidual pixels contain a limited subset of these whose number is fewer than the number of bands. MESMA decomposes each pixel using different combinations of possible endmembers, starting with a two-endmember model and constructing a three-endmember model if two-endmember models don't meet the criteria of endmember selection. Large endmember models can be tested when needed. In this way, a large number of end-members are utilized across a large scene. [8] used MESMA of only 13 endmembers (5 fresh and 1 mature highland, 5 mature and 2 fresh mare materials) to decompose Clementine UVVIS images of the Moon from 70°S to 70°N. Figure 1 shows a color composite of fraction images for three endmembers among these 13.

Radiative Transfer Model (RTM): Radiative transfer models allow computation of the reflectance spectra of mineral, and mixtures of minerals. Hapke's work [9-10] is the basis of the techniques we use. We have fully implemented Hapke's work to enable computation of simulated lunar and asteroid spectra, include varying relative abundances of the minerals, varying grain sizes, and varying degree of space weathering [11-12]. This formulation is the basis for the mineral mapping approach presented here and published in brief in [11]. In principle, one could use the radiative transfer model to iteratively invert the reflectance spectrum to mineral abundance (and other parameters). In practice this inversion is too slow to analyze the billions of spectra present in the Clementine and upcoming data sets. [11] followed an alternative approach where computationally intensive radiative transfer models are used to precompute model spectra that cover the entire range of possible variables. These pre-computed spectra are used as a lookup table against which the measured spectra are compared. The parameters that gave rise to the model spectra that match the measured spectrum are then assigned to the spectrum under analysis. The lookup table method is more efficient than iteration when the number of entries in the table is smaller than the number of pixels times the typical iterations. The precomputed lookup table used by [11] had 286,000 entries. Typical iterative solutions require computing at least 100 models per fit so the lookup table is more efficient if more than 2860 spectra are analyzed. In [11] 400,000 were analyzed representing the least mature 3% of data at 1 km resolution. The Clementine 100-m sampling data has about 5 billion spectra so this method is impractical, especially with hyperspectral data. A combination of MESMA and RMT offers a solution to this problem.

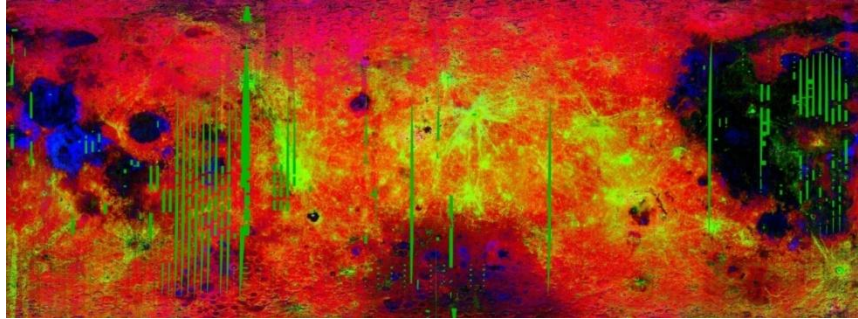


Figure 1. A color composite of 13-endmember MESAM fraction images for mature highland (R), fresh anorthositic rock (G) and blue mare (B).

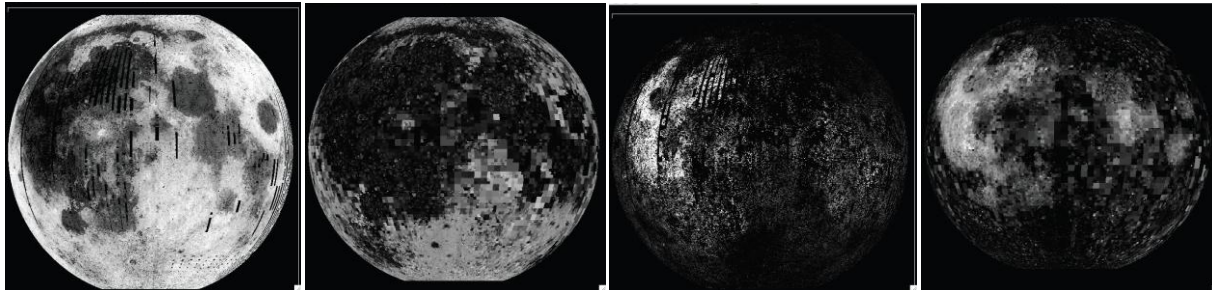


Figure 2. Hybrid Radiative transfer/MESMA plagioclase (first from left) and olivine (third from left), Lucey's [11] plagioclase (second from left) and olivine (fourth from left). Note the much higher spatial resolution of the hybrid product.

Results and Discussion: Using the existing MESMA decomposition we prototyped the method described. Each of the 13 endmembers presented in [8] was analyzed using iterative radiative transfer inversion giving mineral abundances (and space weathering components) which were then used to convert individual MESMA fraction images into mineral abundance maps. The combination allows the use of iterative inversion of RTM to derive mineral abundance because only 13 spectra need to be decomposed. Examples comparing this method (Figure 2) with the data in [11] show good correspondence of olivine, plagioclase and clinopyroxene maps, and illustrate the superior image quality of the method. The large differences in orthopyroxene distribution (not shown) are likely because this global MESMA application of 13 components did not contain an adequate endmember. In addition to time, this approach should be more robust against noise, especially for mature areas. It has been previously shown, at least for Clementine data, that the noise in Clementine data limits the degree of maturity that allows a particular spectrum to be analyzed. Space weathering dilutes the spectral signature of the mineral components, while signal to noise stays constant (or even drops as mature surfaces are darker than immature surfaces). For Clementine data, the spectral differences associated with compositional differences of 10% in mineral abundance drop below the noise when optical maturity drops below about 0.3

(though this is composition dependent). This limits the spectra that can be analyzed on a per-pixel by straight radiative transfer basis to about 5% of the lunar surface (Lucey [11] interpolated across mature gaps to produce the maps shown in Figure 2). In contrast, when using SMA/MESMA there will typically be a large population of near-pure mature endmember pixels that can be averaged to increase signal to noise ratios.

Conclusion and Future Work: The new approach was applied to Clementine 1 km resolution data to general lunar mineral abundance maps. MESMA was first used for decomposition of mixed pixels, and the endmember spectra were analyzed with a spectral interpreter, which is baselined as RT-lookup. Mineral and glass component abundances detected and quantified by the spectral interpreter were remapped back on the basemap using the components maps produced by MESMA. Future work will test this method with 100 m Clementine UVVIS-NIR images and validate the mapping results.

Acknowledgement: This work is supported by NASA LASER grant NNX08AZ06G (PGL).

References: [1] Pieters C. M. et al. (1985), *JGR*, 90,12,393-12,413. [2] Adams J. B. et al. (1986), *JGR*, 91, 8098-8112. [3] Pinet P. et al. (1993), *Science*, 206, 797-801. [4] Smith M. O. et al. (1985), *JGR*, 90, c797-c804. [5] Staid M. I. et al. (1996), *JGR*, 101, 23,213-23,228. [6] Li L. and Mustard J. F. (2000), *JGR*, 105: 20,431-20450. [7] Mustard J. F. et al. (1998), *JGR*, 103, 19,419-19,425. [8] Li L. and Mustard J. F. (2003), *JGR*, 108, 7-1 to 7-14. [9] Hapke B. (1993), *Theory of Reflectance and Emittance Spectroscopy*, Cambridge Univ. Press. [10] Hapke B. (2001), *JGR*, 106,10,039-10,073. [11] Lucey P.G.(2004), *JGR*,31, doi:10.1029/2003GL019406. [12] Lucey P. G. (2006), *JGR*, 111, doi:10.1029/2005JE002661.