IMPROVED MAPPING OF THE LUNAR SURFACE USING A MULTIPLE ENDMEMBER MIXTURE MODEL. Lin Li and John F. Mustard, Department of Geological Sciences, Box 1846, Brown University, Providence, RI 02912 (li@ares.geo.brown.edu).

Introduction: Linear and non-linear spectral mixture analysis (SMA) of lunar spectroscopic and multispectral data have been widely used for investigation of lunar surface composition [1-10]. All applications of SMA to multispectral data are limited by the scene dimensionality that limits the number of compositionally distinct endmembers (EMs) for unmixing. For example, Clementine ultraviolet-visible (UV-VIS) multispectral data consists of five wavelength bands, Principal Component Analysis (PCA) shows that only three or four EMs are required to explain the spectral variability of compositional units in the scene. The use of more than four EMs is subjected to the loss of spatial coherence of EM image and a large uncertainty in the fractions. However, the diversity of lunar surface materials may require far more than four EMs to apply a rigorous and accurate SMA even ignoring spectral variability due to particle size, illumination geometry and instrumental effect. A Gram-Schmidt orthogonalization procedure has recently been proposed to overcome this so-called "condition of identifiability" [11]. However this approach is compromised large fitting errors and a lower accuracy of the calculated fractions.

To apply a mixture model that accommodates the spectral diversity of the Moon within the dimensionality constraints therefore requires a different approach. We assume that within a small region (e.g. 1 km²), the lunar surface material may be adequately modeled as a mixture of two to three distinct components with no loss of information or fidelity. Given this assumption, we can then use a "multiple endmember spectral mixture analysis (MESMA)" developed by [12] for mapping vegetation. MESMA is essentially an extended application of traditional SMA. The advantage of MESMA over SMA is that it accommodates within a limited mixing space, the spectral diversity and subtle spectral difference among lunar materials.

Study Area: We select the Mare Serenitatis/Tranquillitatis region to develop and test this approach. This region has been analyzed by many investigators because of its diverse geological processes and material compositions [2, 3, 7, 13, 14, 15]. The distinct compositional units in the region include low-Ti Serenitatis Mare (red mare), high-Ti Tranquillitatis Mare (blue mare), dark mantle material, and highland as well as spectral diversity of these units due to maturity variations.

Data Analysis: Five-filter Clementine UV-VIS multispectral data are used in this study. The data are a subset of Clementine global mosaic image produced by USGS with one kilometer spatial resolution. The reflectance data is then transformed into single scattering albedo [8] prior to apply the MEMSA since the lunar surface is mixed intimately and the reflectance is thus a nonlinear combination of the reflectance of the EMs [9].

Evaluation of the spectral characteristics of the compositional units in this region indicates that seven EMs can span all of observed diversity of material composition within the region. These seven EMs represent mature and fresh red mare, mature and fresh blue mare, mature and fresh highland, and dark mantle material.

Traditional SMA decomposes a scene by using all EMs allowed by the image dimensionality (i.e. scene-based). In contrast, MESMA follows the different strategy (i.e. pixel-based). The strategy in MESMA is to fit the observations with the fewest EMs. This is accomplished in two steps. First the observed pixel spectrum is fit with every possible 2-EM model, saving the model with the lowest fitting errors (RMS) and that also provides fractions that lie between 0 and 1. With 7 EMs this results in 21 2-EM models. The next step is then to repeat the process for the 3-EM models (a total of 35 models). There will always be a 3-EM model that results in a lower RMS than a 2-EM model. This doesn't necessarily mean that every 3-EM model is preferred. The number of EMs which can accurately resolved also depends on the signal to noise ratio [16]. Too few EMs may produce large RMS error, while too many EMs may overfit the noise. Therefore, we used the RMS error as a threshold for determining which model is selected. If a 2-EM model results in a RMS error less than the noise, and the fractions are appropriate, then this model is used and no 3-EM calculations are performed. MESMA yields seven fraction images. Figure 1 (A-D) shows four of them representing red and blue mare, dark mantle and highland. For the purposes of comparison, the best solution possible using traditional SMA is also shown in Figure 1 (E-H) representing fresh red mare, mature blue mare, fresh highland and mature highland.

Result: The abundance distributions of the endmembers characterized by the fraction images of MESMA are generally consistent with the result from previous studies [2, 3, 7], but allow a greater discrimination of surface materials and a higher accuracy of fractions. The mare basalt in the Tranquillitatis basin displays a transition from red mare to very blue mare from northeast to southwest of the basin. Highland contamination into the blue mare by crater rays from the crater Theophilus is evident in the mature highland fraction image. This image also shows the occurrence of highland material in the ejecta deposit and the floor of crater Plinius indicating a vertical mixing process, while crater Dawes and its ejecta deposits have very low or no highland-like materials [3] indicating a very thick mare. Although the origin of crater rays across the Serenitatis Mare is uncertain, the mature highland fraction images shows very strong evidence for highland contamination [3].

An apparent improvement of MESMA over traditional SMA is the ability to quantitatively map the distribution of
more EMs. With traditional SMA, this scene is well modeled statistically using the combination of fresh red mare, mature blue mare, and mature highland. However SMA merges dark mantle into the fraction of blue mare, while the distribution of red mare is partitioned across the fresh red mare, blue mare and mature highland endmembers. In contrast, red and blue mare as well as dark mantle deposits are clearly distinguished with MESMA. The technique of MESMA for the Moon nevertheless requires further refinement (e.g. the highly variable fraction images) and we are currently examining ways to do this.

The observation of blue and red mare fraction images indicates the occurrence of lateral transport of blue mare into red mare across the boundary largely due to the ejecta from craters Plinius and Dawes. In contrast, there is very little observed red mare on the Tranquillitatis side likely due to the absence of any large craters on the red mare side. This new observation argues against the conclusion for the absence of lateral mixing along this boundary [2]. The red mare fraction image also shows the existence of red mare material in the ejecta deposits of crater Pilinus, Dawes, Jansen and an unnamed crater, which suggests that red mare has been excavated from beneath blue mare.

The most important observation in this study is the extensive highland contamination in Tranquillitatis Mare. Highland abundances over this region range from 10% to 20%, and is relatively homogeneously distributed. Considering some uncertainty in data quality, we can’t conclude this is due only to the lateral mixing process. We are currently investigation the implications of these units for the region of the Moon.

**Conclusion:** A multiple spectral EM spectral mixture analysis (MESMA) has been applied to mapping the abundance of material in the Serenitatis/Tranquillitatis region. For large regional analyses, MESMA performs better than traditional SMA because it not only overcomes the limitation of image dimensionality, but provides improved mapping of material abundance as well through pixel-based EM selection. MESMA results in the fraction images consistent with those of traditional SMA, but allows the mapping of more EMs than SMA does. MESMA can define the number of EM for a mixed pixel, but there is no limit to the number of EM that can be used for the whole scene. Therefore, this procedure can be applied to lunar Clementine global mosaic data for various investigations.


Figure 1: Fraction images from MESMA (A-D) and SMA (E-H). (A) red mare, (B) blue mare, (C) dark mantle, (D) highland, (E) fresh red mare, (F) blue mare, (G) fresh highland, (H) highland. While arrow: left-Jansen, right-unnamed crater. Black arrow: left-Plinius, right-Dawes.