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Spectral mixture analyses of hyperspectral data acquired using a tethered balloon

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Abstract

Tethered balloon remote sensing platforms can be used to study radiometric issues in terrestrial ecosystems by effectively bridging the spatial gap between measurements made on the ground and those acquired via airplane or satellite. In this study, the Short Wave Aerostat-Mounted Imager (SWAMI) tethered balloon-mounted platform was utilized to evaluate linear and nonlinear spectral mixture analysis (SMA) for a grassland-conifer forest ecotone during the summer of 2003. Hyperspectral measurement of a 74-m diameter ground instantaneous field of view (GIFOV) attained by the SWAMI was studied. Hyperspectral spectra of four common endmembers, bare soil, grass, tree, and shadow, were collected in situ, and images captured via video camera were interpreted into accurate areal ground cover fractions for evaluating the mixture models. The comparison between the SWAMI spectrum and the spectrum derived by combining in situ spectral data with video-derived areal fractions indicated that nonlinear effects occurred in the near infrared (NIR) region, while nonlinear influences were minimal in the visible region. The evaluation of hyperspectral and multispectral mixture models indicated that nonlinear mixture model-derived areal fractions were sensitive to the model input data, while the linear mixture model performed more stably. Areal fractions of bare soil were overestimated in all models due to the increased radiance of bare soil resulting from side scattering of NIR radiation by adjacent grass and trees. Unmixing errors occurred mainly due to multiple scattering as well as close endmember spectral correlation. In addition, though an apparent endmember assemblage could be derived using linear approaches to yield low residual error, the tree and shade endmember fractions calculated using this technique were erroneous and therefore separate treatment of endmembers subject to high amounts of multiple scattering (i.e. shadows and trees) must be done with caution. Including the short wave infrared (SWIR) region in the hyperspectral and multispectral endmember data significantly reduced the Pearson correlation coefficient values among endmember spectra. Therefore, combination of visible, NIR, and SWIR information is likely to further improve the utility of SMA in understanding ecosystem structure and function and may help narrow uncertainties when utilizing remotely sensed data to extrapolate trace glas flux measurements from the canopy scale to the landscape scale.

Keywords: Spectral mixture analysis (SMA); Linear mixture model; Nonlinear mixture model; Endmembers; Short Wave Aerostat-Mounted Imager (SWAMI); Hyperspectral; Multispectral; Ponderosa pine; Tethered balloon

1. Introduction

1.1. Spectral mixture analysis

All land surfaces are spatially heterogeneous at some scale. As a result, most detected surfaces within the IFOV of the remote sensing instrument (herein referred to as a pixel), especially those detected by coarse spatial resolution instruments, are spectrally complex and therefore create a heterogeneous spectral mixture rather than one spectrally "pure" signal within the pixel. However, traditional classification methods often classify the whole pixel as a specific cover type assumed to represent the dominant component within

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the pixel, and stop short of providing additional information about the existence and relative fraction of additional cover types within the pixel. Thus, improving spectral unmixing techniques to quantify land cover types within pixels can greatly benefit surface land cover interpretation and generation of derivative land cover products. Due to the inherent heterogeneity of land surfaces, developing and validating spectral mixture analysis (SMA) techniques to study cover types at the subpixel scale is highly desirable for many applications regardless of the original pixel size. Benefits of sub-pixel land cover quantification range from improved ecosystem change detection (e.g. Monteiro et al., 2003) to potentially increasing our ability to correlate remote sensing data with exchanges of mass and energy between the biosphere and the atmosphere (see Chen et al., 1999; Ogunjemiyo et al., 2003). It may also improve our understanding of the biotic controls on these mass and energy exchanges and may allow us to partition the control of whole systems fluxes among cover types having different phenology.

SMA is an inverse method for deriving fractional coverage of spectrally distinct features within a pixel (Adams & Smith, 1986). In spectral mixture theory, the spectral signal of a pixel can be represented as a mixture of signals contributed by all spectrally "pure" features, or endmembers, within the instantaneous field of view (IFOV) of the sensor at a given time (Peddle et al., 1999; Sabol et al., 2002; Woodcock & Strahler, 1987). Theoretically, if all endmembers within an image can be identified and spectrally characterized, then the pixels may be characterized by how much of each endmember is contained within it. Practical applications of the spectral mixture models, however, are limited by the number of available spectral bands and the diversity among endmembers. High contrast endmembers (i.e. endmembers containing poor spectral correlation) are recommended to obtain spectral mixture models, and highly correlated endmembers should be avoided (Meer & Jong, 2000; Woodcock & Strahler, 1987) because they can exacerbate nonlinearities in spectral mixing and therefore cause uncertainty and error in SMA.

Much progress in spectral mixture techniques using remote sensing data has been made in recent years. Ground feature areal fraction information has been successfully provided by spectral mixture interpretation in many studies (e.g. Garcia-Haro et al., 1996; Jasinski & Eagleson, 1990; Kootwijk et al., 1995; Meer, 1995; Wessman et al., 1997). In addition, SMA theory has been used to quantify vegetation biomass, fraction of absorbed photosynthetically active radiation (FAPAR), leaf area index (LAI), and net primary productivity (NPP) (e.g. North, 2002; Peddle et al., 1999), and to map logging effects (e.g. Monteiro et al., 2003), snow cover (e.g. Painter et al., 1998; Vikhamar & Solberg, 2003), tree cover (e.g. Hansen et al., 2002), and impervious surfaces (e.g. Phinn et al., 2002; Ridd, 1995; Wu & Murray, 2003) in various applications. Clearly, further developments in SMA theory, including advances in error analyses, have the potential to affect studies across a wide range of environmental monitoring applications.

SMA techniques include both linear (e.g. Adams et al., 1995; Bastin, 1997; Foody & Cox, 1994; Meer, 1995; Peddle et al., 1999; Roberts et al., 1998; Rosin, 2001) and nonlinear (e.g. Borel & Gerstl, 1994; Huang & Townshend, 2003; Huete, 1986; Kootwijk et al., 1995; Ray & Murray, 1996; Roberts et al., 1993; Zhang et al., 1998) mixture approaches, each of which contains different levels of computational and conceptual complexity. If multiple scattering can be ignored, the mixed spectrum can be expressed by a linear combination of the endmember spectra based on their areal fractions. In nonlinear spectral mixture models, multiple scattering among components within the pixel is considered and mixed spectra are expressed using nonlinear contributions of multiple endmembers within the pixel. A nonlinear mixture model can better reduce residuals and improve unmixing accuracy, but its multiple scattering effects are not linearly correlated with the endmember areal fractions within the pixel. The greater complexity of nonlinear SMA methods, coupled with the non-intuitive interpretation of nonlinear SMA results (Kootwijk et al., 1995; Ray & Murray, 1996) underscores the need to evaluate both linear and nonlinear SMA approaches in a variety of vegetation structural types to determine their relative and absolute sources of error and uncertainty wherever possible.

Endmember collection and calibration are important in the application of SMA. In some laboratory and field spectral mixture experiments, the endmembers and the mixed signal had been acquired under common illumination and atmospheric conditions, and the calibration between them was not necessary (e.g. Borel & Gerstl, 1994; Ray & Murray, 1996; Zhang et al., 1998). In other applications on satellite or photographic images, image endmembers were selected from the image pixels directly, and again calibration was not necessary because the endmembers were in the same radiometric scale as the other pixels in the imagery. A third class of SMA applications have utilized laboratory collected or field collected reference endmembers to interpret the satellite imagery, with endmembers calibrated to the imagery so that the models could run correctly irrespective of differences in image/endmember acquisition radiometry (e.g. Adams & Smith, 1986; Adams et al., 1995; Sabol et al., 2002). Generally, reference endmembers contain higher purity than image endmembers, and they may produce higher accuracy or better understanding of the SMA. However, because of the uncertainty in pixel geolocation arising from radiometric and georegistration constraints of satellite data, it is difficult to quantify the performance of spectral unmixing techniques between image pixels and actual ground endmember fractional coverage in the field. Here, we introduce a field spectral sampling technique using a tethered balloon-mounted remote sensing system to evaluate linear and nonlinear SMA performance under a condition of high geometric precision over a forested ecosystem.

1.2. SWAMI platform

The orbital altitudes of IKONOS, Landsat ETM+, and MODIS satellite sensors are about 700 km, while the altitude of remote sensing-equipped aircraft is usually higher than 2 km due to safety considerations. To bridge the spatial gap between ground measures and satellite or aircraft measures, a hyperspectral remote sensing instrument platform called the Short Wave Aerostat-Mounted Imager (SWAMI) has been developed (Vierling et al., 2006-this issue). This platform can be attached to the tether line of a research balloon and used to measure the