Multiresolution Analysis of Urban Reflectance

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Abstract—**Quantitative analysis of urban reflectance characteristics can provide insights into the spatial and temporal variations in urban reflectance that modulate solar energy fluxes through the urban environment. Characterization of urban reflectance may also facilitate development of algorithms for classification of urban landcover. The characteristic scale of urban reflectance variations is generally between 10 and 20 m and therefore comparable to the Ground Instantaneous Field of View of most operational sensors. This results in spectral heterogeneity that limits the accuracy of pixel-based classifications of urban imagery. Multisensor analyses of urban reflectance indicate that many urban areas can be described as mixtures of three or four spectral endmembers. Most urban building materials lie along a continuum between high and low albedo endmembers but vegetation is a persistent and distinct component of the urban mosaic. Nonlinear mixing generally diminishes with increasing vegetation cover such that linear mixing models may be generally appropriate for urban vegetation estimation. Preliminary analyses of Landsat imagery in a number of urban areas worldwide suggests that linear mixing models with three and four endmember may be generally applicable to urban areas. Spectral heterogeneity at scales of tens of meters may be a more consistent characteristic of urban reflectance than any single reflectance spectrum.**

Index Terms—**AVIRIS, Ikonos, scale, urban, vegetation.**

INTRODUCTION

INTRA-urban variations in optical reflectance exert a strong influence on environmental conditions and energy fluxes by selective absorption and reflection of solar radiation. These energy fluxes are a major determinant in the physical conditions of the primary human habitat. Recent estimates indicate that over 45% of the world's human population now lives in urban areas with over 60% projected by 2030 [1]. Our understanding of the built environment depends upon our ability to observe and quantify the physical conditions of urban areas. Understanding the characteristics of urban reflectance is also necessary to develop robust classification methods to quantify the spatial extent of human settlement patterns. Spatial and temporal distribution of human settlements has environmental and socioeconomic consequences but current knowledge of settlement distribution lacks both detail and consistency.

Urban vegetation has a strong influence on the spatial and temporal variations in urban reflectance. Vegetation influences urban environmental conditions and energy fluxes by selective reflection and absorption of solar radiation [2] and by modulation of evapotranspiration [3],[4]. The presence and abundance of vegetation in urban areas has long been recognized as a strong influence on energy demand and the urban heat island [5]. Urban vegetation may also influence air quality and human health [6] because trees provide surface area for sequestration of particulate matter and ozone.

The objective of this paper is to summarize results of recent and ongoing studies of urban reflectance characteristics. The work is intended to advance two distinct lines of research. Characterization of urban reflectance requires quantification of spatial and spectral variability across a range of scales. In this case, the central question is how the aggregate properties of the urban mosaic influence energy flux on different temporal and spatial scales. Characterization of urban reflectance also facilitates the use of optical remote sensing for large scale mapping of human settlement patterns. For this application, it is necessary to quantify spectral consistencies among different urban areas.

CHARACTERISTIC SCALES OF URBAN REFLECTANCE

The overall reflectance of the urban mosaic is determined by the combination of building materials and the characteristic scale of individual features of consistent reflectance (roofs, streets, trees, etc). Optical sensors have limited swath widths and spatial resolutions so the measured radiance is a result of both the Ground Instantaneous Field of View (GIFOV) of the sensor and the scale of the features in the urban mosaic. If the GIFOV is much smaller than the scale of the features then they will be adequately sampled and thereby recognizable in the image. If the GIFOV is comparable to the scale of the features then the measured radiance will generally result from a combination of surfaces of different reflectances within the GIFOV. To understand the characteristics of urban reflectance it is necessary to quantify the scales of individual features.

The two dimensional (2D) spatial autocorrelation of an image provides information about the spatial scale of the variance. The width of the central peak of the autocorrelation function is determined by the scale at which the largest amplitude features decorrelate and thereby provides one indication of the dominant scale of image texture. This is particularly well suited to urban areas because settlement patterns often have quasi-periodic spatial structures that are easily quantified by the autocorrelation function. Figure 1 shows the result of a study of 12 contrasting urban areas worldwide [7] with a consistent 10 to 20 meter scale length. This suggests that most urban structures have scales comparable to the GIFOV of operational sensors like Landsat and SPOT. This, in turn, explains why images of urban areas rarely resolve individual structures and are characterized by spectrally mixed pixels. It is therefore appropriate to consider urban reflectance in the context of spectral mixing.

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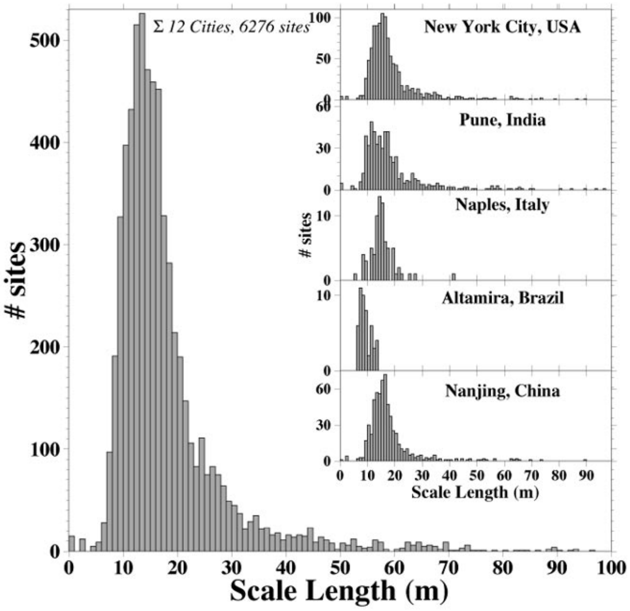


Fig. 1.Characteristic scales of urban reflectance. The histograms show distributions of scale lengths for 6276 urban sites in 12 cities derived from Ikonos 1 m panchromatic imagery. Each scale estimate is the result of a 2D spatial autocorrelation of a 200x200m site. The majority of sites have characteristic scales between 10 and 20 m. Sites with larger scale lengths are generally large undeveloped areas, intraurban agriculture or water.

SPECTRAL MIXING

The characteristic spatial scale and the spectral variability of urban landcover poses serious problems for traditional image classification algorithms. In urban areas where the reflectance spectra of the landcover vary appreciably at scales comparable to, or smaller than, the Ground Instantaneous Field Of View (GIFOV) of most satellite sensors, the spectral reflectance of an individual pixel will generally not resemble the reflectance of a single landcover class but rather a mixture of the reflectances of two or more classes present within the GIFOV. Because they are combinations of spectrally distinct landcover types, mixed pixels in urban areas are frequently misclassified as other landcover classes. Conversely, the definition of an urban spectral class will often incorporate pixels of other non-urban classes as well.

Building materials dominate net reflectance in most cities but in many cases vegetation also has a very strong influence on urban reflectance. If an urban area contains significant amounts of vegetation then the reflectance spectra measured by the sensor will be influenced by the reflectance characteristics of the vegetation. Macroscopic combinations of homogeneous "endmember" materials within the GIFOV often produce a composite reflectance spectrum that can be described as a linear combination of the spectra of the endmembers [8]. If mixing between the endmember spectra is predominantly linear, and the endmembers are known *apriori*, it may be possible to "unmix" individual pixels by estimating the fraction of each endmember in the composite reflectance of a mixed pixel [9],[10]. A variety of methods have been developed to estimate the areal abundance of endmember materials within mixed pixels [9] - particularly for use with imaging spectrometers in geologic remote sensing [10]. If the areal abundance of vegetation present within an urban pixel can be estimated accurately then it may be possible to monitor the spatial and temporal variations in urban vegetation - even when the vegetation occurs at scales finer than the spatial resolution of the sensor.

Analysis of Landsat TM imagery suggests that the spectral reflectance of the New York metropolitan area can be described as linear mixing of three distinct spectral endmembers [11]. Dimensionality of a spectral mixing space can be estimated from the variance partition indicated by a Principal Component rotation of the image bands. The eigenvalue distribution associated with the rotation gives a quantitative estimate of the amount of variance in each transformed dimension and the resulting images show the spatial distribution of spectrally distinct endmembers (e.g. [9],[10]). Scatterplots of the low order components show the topology of the mixing space and indicate spectral endmembers by their locations at the periphery of the mixing space.

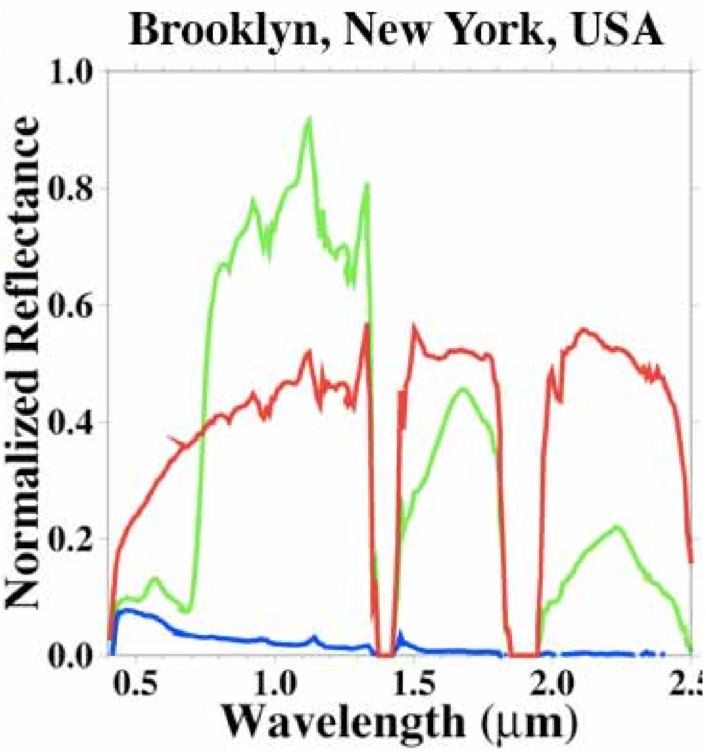
MULTISENSOR ANALYSES

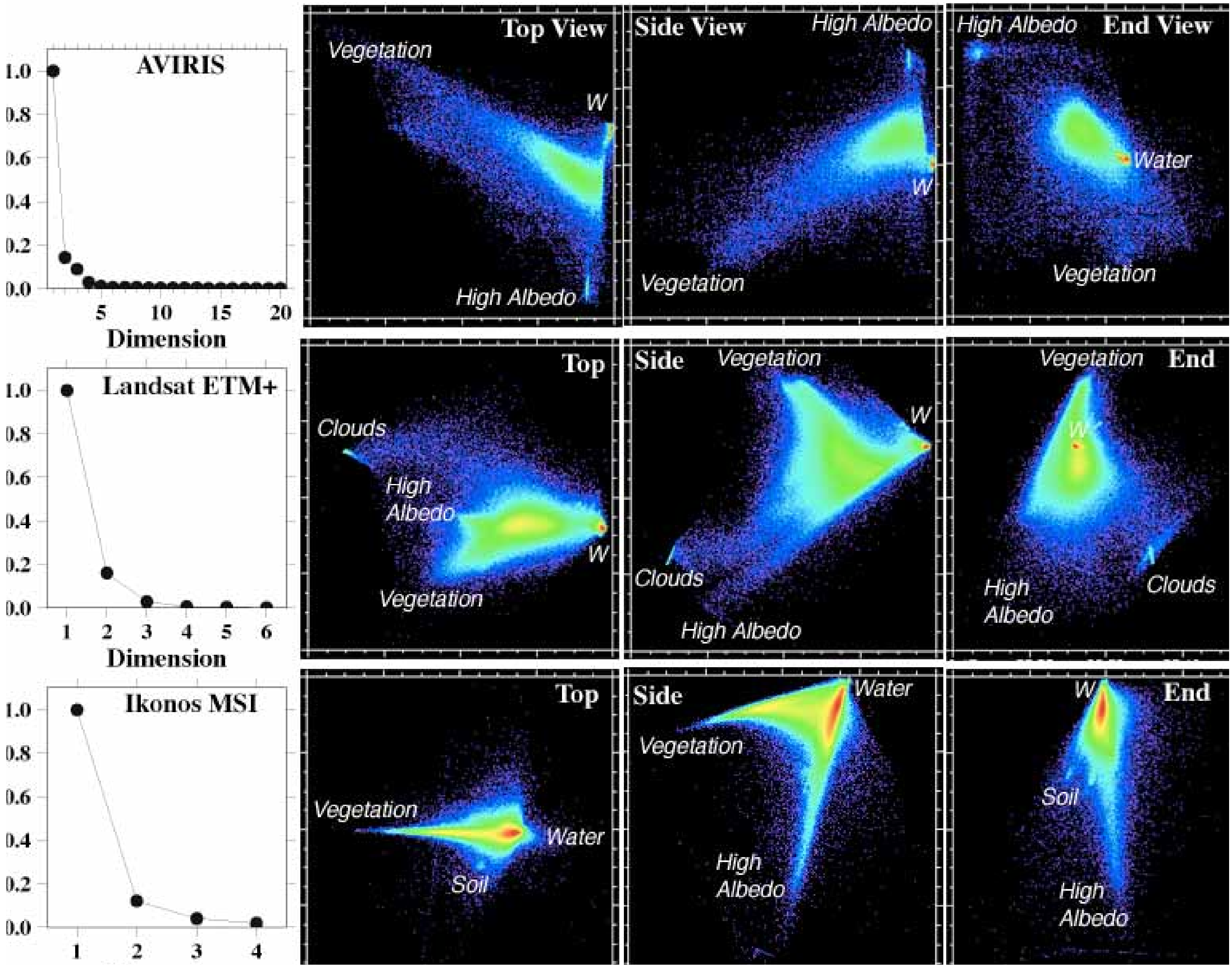
It is possible to assess the consistency of the urban spectral mixing space by comparing images of the same site collected by sensors with different spatial and spectral resolutions. A Minimum Noise Fraction (MNF) principal component transformation applied to AVIRIS, Landsat and Ikonos imagery scenes consistently shows two dominant eigenvalues and a sub-planar triangular mixing space. The triangular distribution in MNF space bears an obvious similarity to the well known Tasseled Cap distribution discovered by Kauth and Thomas in 1976. The feature space distributions are similar in the sense that all contain a vegetation endmember that is distinct from a mixing continuum between high and low albedo endmembers and, in some cases, a soil endmember. Figures 2 and 3 show examples of the spectral mixing space for parts of the New York and San Francisco metro areas with eigenvalue distributions suggesting that the majority of scene variance is contained within a two dimensional mixing plane for each sensor.

Fig. 2. (next page) Multisensor analysis of the spectral mixing space for Brooklyn, New York, USA. False-color composites for AVIRIS (20m, RGB=2.2/0.8/0.5 µm) and Ikonos MSI (4m, RGB=0.6/0.8/0.4 µm) show different degrees of spectral mixing. AVIRIS spectra show the High Albedo (red), Low Albedo (blue) and vegetation (green) endmembers residing at the apexes of the mixing space. The eigenvalue distributions for each sensor (left column) indicate that most of the variance is contained in the first two dimensions corresponding to the principal components shown in the Side View scatterplot. The topology of the three dominant dimensions of the mixing space is shown by the scatterplots as different projections of the 3D cloud of pixels associated with the three low order principal components. The side view shows the first (x) and second (y) dimensions while the top and end views incorporate the third dimension. The variance of each dimension is proportional to the relative amplitude of the normalized eigenvalues but the dimensions are rescaled here to show the structure more clearly. In each case, the horizontal axis of the side view is associated with the most distinct endmembers so the distributions would appear as sub-planar triangles if plotted to scale. Detailed color figures available at: *www.*LDEO.columbia.edu/~small/Urban.html

Ikonos MSI

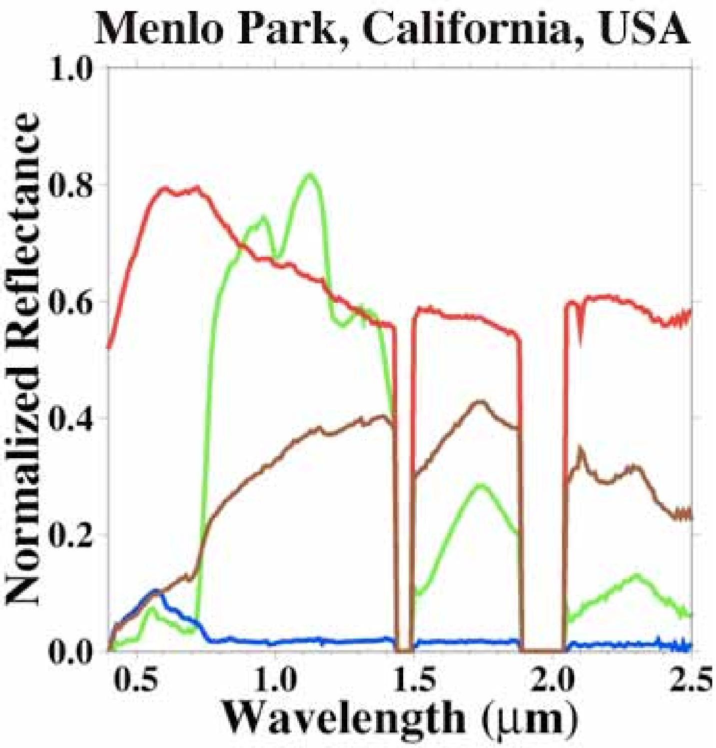
AVIRIS





AVIRIS

Ikonos MSI



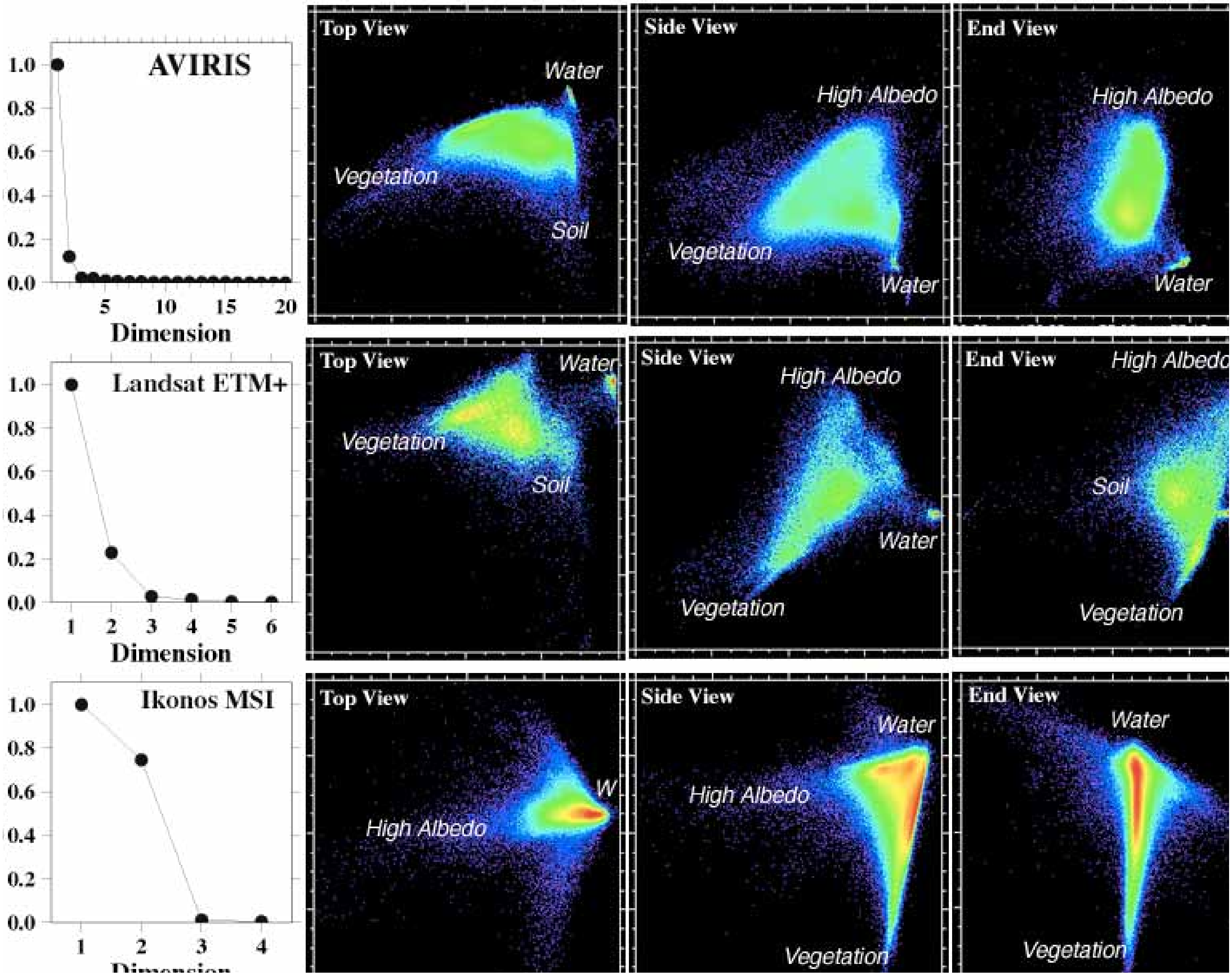


Fig. 3. (previous page) Multisensor analysis of the spectral mixing space for Menlo Park, California, USA. False-color composites for AVIRIS (20m, RGB=2.2/0.8/0.5 µm) and Ikonos MSI (4m, RGB=0.6/0.8/0.4 µm) show similar but distinct mixing spaces as in previous figure. A soil endmember spectrum is also shown here since sparsely vegetated soil is a significant component of the mixing space in semiarid environments. Note the presence of a slight red edge in the soil endmember.

GLOBAL ANALYSIS OF URBAN REFLECTANCE

In order to extend the insights gained from the multisensor analyses discussed previously to other urban areas, it is necessary to determine the degree to which urban reflectance and mixing spaces are consistent across a larger sample. In general, we would not expect urban areas in the U.S.A. to be representative of urban areas worldwide. Analysis of Ikonos MSI imagery does show a remarkable consistency for American cities and for several cities outside the U.S.A. but the limited spectral dimensionality of Ikonos does not discriminate differences in the SWIR. Landsat TM/ETM+ imagery provides both a larger sample of cities and greater spectral dimensionality. Preliminary spectral analyses of Landsat imagery from 27 urban areas worldwide does suggest that three and four endmember mixing models do have general applicability to most urban areas. Figure 4 shows collections of eigenvalue spectra from MNF rotations of two different scales of Landsat imagery. The prevalence of two or three dominant eigenvalues in almost all of the spectra supports the generality of the low dimensional mixing space.

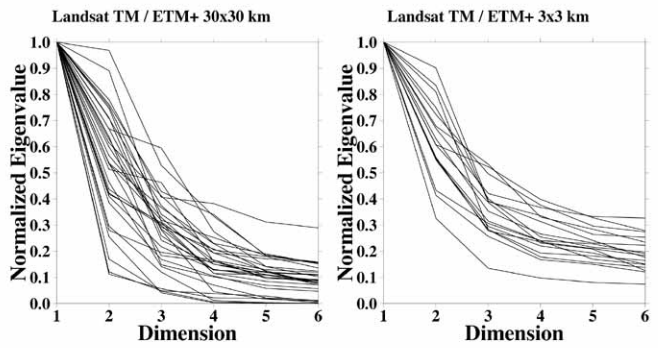


Fig. 4. Spectral dimensionality of major urban areas worldwide. Principal component analysis of Landsat TM/ETM+ imagery of 27 urban areas shows consistent spectral dimensionality for most areas. Eigenvalue spectra from Minimum Noise Fraction rotations generally have distinct breakpoints separating the two or three dimensions containing most of the variance from the remaining three or four dimensions with less information. Spectral mixing spaces associated with the three dominant dimensions usually have three or four spectral endmembers similar to the mixing spaces shown in Figures 2 and 3. The 30x30 km scale of the study areas on the left includes significant amounts of undeveloped land containing spectral endmembers not found in the urban core. Eigenvalue spectra on the right correspond to urban core areas, 3x3 km in area, containing fewer landcover types than the larger areas. The three endmembers in the two dominant dimensions of these core areas are consistently vegetation, high albedo and low albedo.

CONCLUSIONS

The urban mosaic is composed of a variety of components of varying scale and spectral properties. Spatial autocorrelation analyses of 1m Ikonos panchromatic imagery for 12 cities worldwide indicates that the characteristic scale of urban landcover is generally between 10 and 20m. This explains why imagery of urban areas collected by operational sensors with GIFOVs of 10's of meters is dominated by spectrally mixed pixels. This spectral heterogeneity violates the cardinal assumption of most statistical classification algorithms and contributes to the difficulties commonly experienced with spectral classification of the built environment.

Multisensor analyses of urban reflectance allow the spectral mixing space to be quantified at a range of spatial and spectral resolutions. Comparison of AVIRIS hyperspectral imagery with Landsat ETM+ and Ikonos MSI imagery demonstrates the consistency of three and four endmember mixing spaces in the two urban areas considered. Mixing between high and low albedo endmembers and a vegetation endmember explains the majority of the spectral variance in the urban areas investigated here. Nonlinear mixing is present but consistently diminishes with increasing vegetation cover.

Preliminary analyses of Landsat TM/ETM+ imagery in a variety of urban areas worldwide suggests that the three and four endmember mixing spaces observed here may be representative of urban areas elsewhere. These preliminary analyses also indicate that spectral heterogeneity at scales of tens of meters may be a more consistent characteristic of urban reflectance than the prevalence of any single spectral signature. If this is the case then it may be possible to develop classification algorithms for urban landcover than use spectral heterogeneity at these scales to discriminate between anthropogenic and natural landcovers.

ACKNOWLEDGMENT

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