Exploration of the Relationship between Information Content and Signal-to-Noise Ratio and Spatial Resolution in AVIRIS Spectral Data

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1.0 INTRODUCTION

In the all the years that the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) has flown, there have been recurring discussions and debates about the underlying information content of AVIRIS data. Each AVIRIS image contains thousands of spatial elements. Each spatial element has 224 spectral measurements in the solar reflected portion of the spectrum.

One view on information content is that there are always more than 224 different materials in an AVIRIS image, so the information content is limited by the 224 spectral measurements. In this case, the AVIRIS data information dimensionality would always be 224 for every AVIRIS data set. This view might be true if every material in the AVIRIS image had a unique spectral signature (in the AVIRIS spectral range) and if the material was present in high concentration and if AVIRIS data had no noise.

An alternate viewpoint is that in most image data sets, there are only a few materials in high concentrations and only a limited number of materials have unique spectral signatures and that imaging instruments have significant noise and digitization limitations. This leads to the perspective that there are relatively few dimensions of information in AVIRIS data sets—perhaps only 6 to 10. This paper reports results from an investigation of the information content of AVIRIS data. Four questions related to information content were explored: (1) What is the underlying information content in an AVIRIS data set? (2) how does the signal-to-noise ratio (SNR) of the AVIRIS spectra effect the information content? (3) how does the spatial resolution effect the information content? and (4) how does information content vary from one environment to another?

2.0 AVIRIS DATA

AVIRIS is an imaging spectrometer that measures images of the earth's surface (Green et al., 1998). The images cover a field of view of 30 degrees, with a spatial resolution of one milliradian. For every spatial element in an AVIRIS image, a spectrum is measured covering the range from 400 to 2500 nm at nominally 10-nm intervals. AVIRIS data are spectrally, radiometrically, and spatially calibrated in the laboratory (Chrien et al., 1990, 1994, 1996, 2000) and the calibration is validated in the flight environment (Green and Pavri, 2000). The precision, or SNR, of AVIRIS data has been improved every year that AVIRIS has flown.

The AVIRIS data used for this investigation were acquired from the low-altitude airborne platform in 1998 and 1999. An example AVIRIS image is shown in Figure 1. This is an image the from Cuprite, Nevada, which is geologically an interesting area. Many different surface materials are known to occur at Cuprite. The elevation of the ground in conjunction with the altitude of the aircraft lead to a surface spatial resolution of approximately 2 m. These AVIRIS low-altitude data are not georectified. The process of georectification often results in the rejection and replication of spectra in various portions of the image. Rejection and/or replication of spectra could confuse as assessment of data set information content. AVIRIS calibrated radiance spectra were used for this investigation. Because radiance spectra were used, spectral information pertaining to the atmosphere will contribute to the total information content assessment of the AVIRIS data. Figure 2 shows several sample AVIRIS radiance spectra from the Cuprite, Nevada, data set. AVIRIS low-altitude calibration spectral radiance data sets were used for this investigation of AVIRIS data information content.

Figure 1. Ungeorectified AVIRIS low-altitude image of Cuprite, Nevada, acquired on the 11th of October 1998.

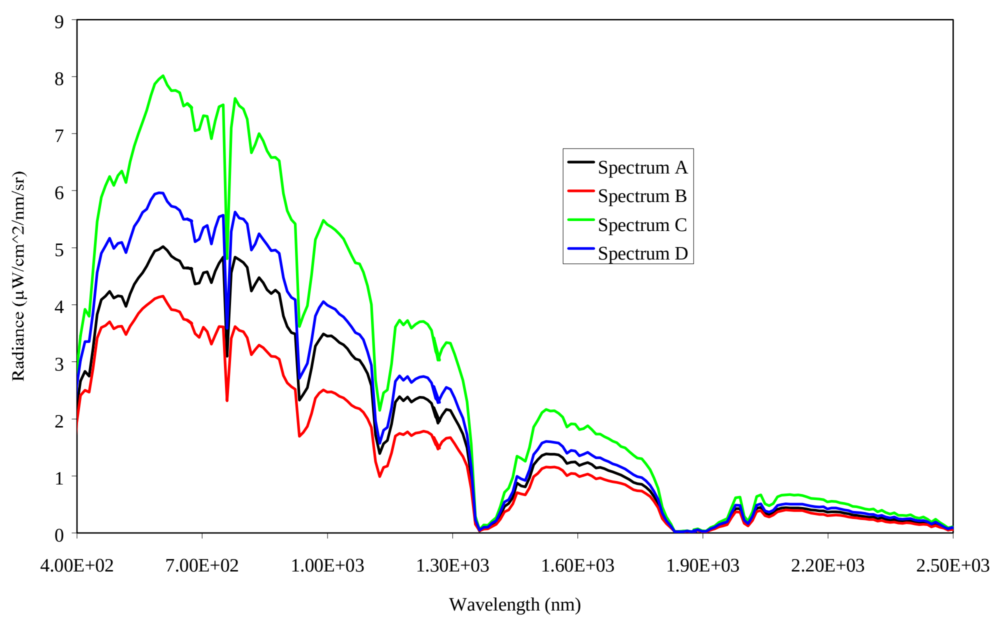

Figure 2. AVIRIS radiance spectra from the 11th of October 1998 AVIRIS Cuprite, Nevada data set.

3.0 INFORMATION CONTENT BASIS AND ALGORITHM

There are numerous potential strategies to assess the information content of an AVIRIS data set. The method adopted for this investigation is the Minimum Noise Fraction (MNF) transformation (Green et al., 1988). The MNF transform requires a calculated noise covariance matrix as well as the AVIRIS data set. The noise covariance matrix is used to decorrelate and normalize the AVIRIS data such that the noise has a unity covariance in all spectral channels. A principal components analysis is then applied to this normalized data set. The result of the MNF transform is that the principal component images with eigenvalues near a value of one are noise dominated. The images with eigenvalues greater than one contain information above the noise. Using the MNF transform, the information content of an AVIRIS data set will be determined by the number of MNF transform images with eigenvalues above a designated threshold that is above a value of one. This number gives the information dimensionality for the data set. In this investigation the AVIRIS noise covariance was derived using a method that assesses the correlation of signals in adjacent spatial elements (Switzer and Green, 1984). The method was applied consistently to each data set.

The MNF transformation offers a uniform, consistent strategy to assess the information dimensionality of any AVIRIS data set with respect to a noise baseline threshold. Figure 3 shows the results from applying the MNF transform to the AVIRIS low-altitude 1998 Cuprite, Nevada, data set. The first 96 MNF transform images are shown in order from left to right and top to bottom. In the first row of 16 MNF transform images, spatial information is clearly expressed. In the second row, spatial information is present, but the clarity and contrast of the spatial content is decreasing. In the third row of the MNF images, spatial content fades further, to near absence at image 48. In the following rows, spatially coherent features are effectively absent. Figure 4 shows a plot of the eigenvalues versus eigennumber for the MNF transform images of this data set. At eigennumbers greater than 48, the eigenvalues of the MNF images are near the value one. This is consistent with the spatial content analysis of Figure 3 for the first 96 MNF transform images. Using this approach, dimensionality is equated with information content. Higher dimensionality implies more information. The information content is calculated based upon a threshold eigenvalue that establishes the number of information-containing dimensions of the AVIRIS data set.

4.0 SPATIAL RESOLUTION AND SIGNAL-TO-NOISE RATIO AND INFORMATION

The relationship between information content and spatial resolution and SNR was investigated by increasing the effective SNR of an AVIRIS data set by spatially averaging. A two-by-two average of AVIRIS spatial elements will effectively lower the random noise by a factor of two, increasing the SNR by two. Through this averaging process, the spatial resolution is decreased and the SNR is increased. Figure 5 shows the first 96 MNF transform images after a 2 by 2 average of the 1998 low-altitude AVIRIS Cuprite, Nevada, data set. The spatial resolution in the averaged data set is approximately 4 m, and the SNR is double the original data set. In this set of images, spatially coherent features are present well beyond the first 48 MNF transform images. This extension of spatially coherent features in the MNF transform image sequence shows that the information dimensionality of the data has increased with the increase in SNR, even with a decrease of spatial resolution. This increase in information dimensionality is also shown in Figure 6 as plots of eigenvalues versus MNF transform image eigennumber for a range of spatial averages. Results from averages of 2 by 2, 4 by 4, and 8 by 8 spatial elements

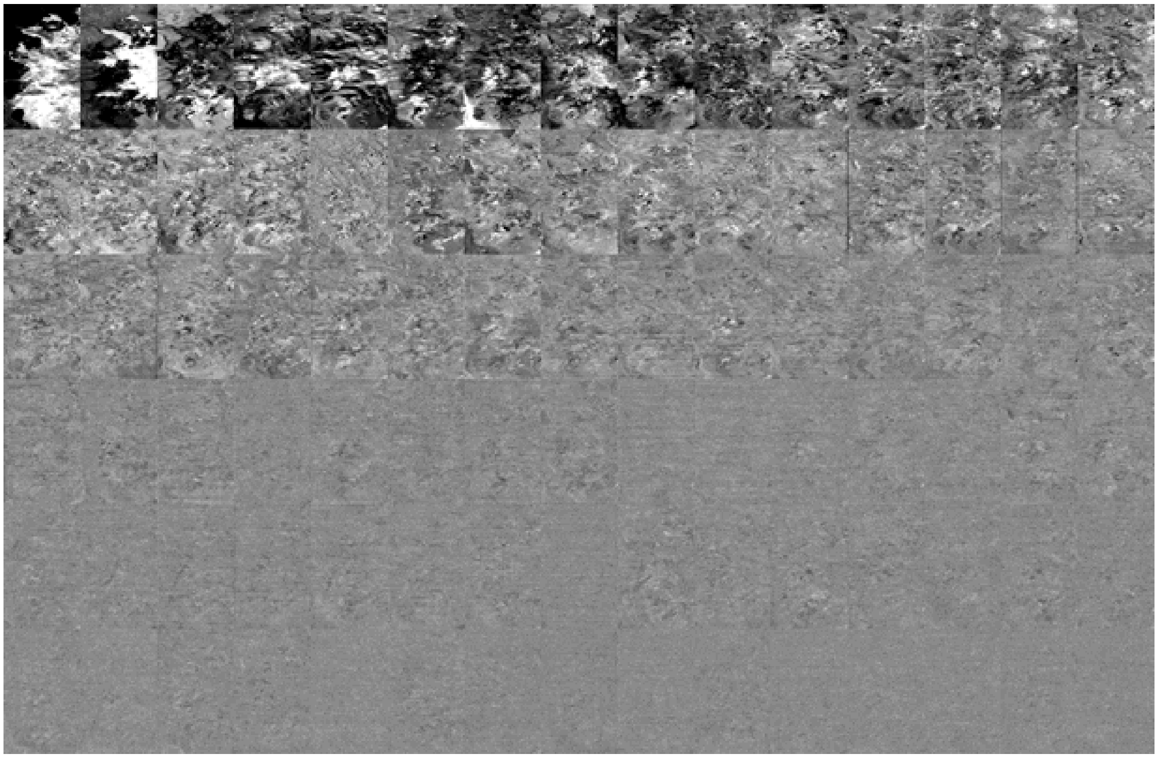

Figure 3. A grid of 16 × 6 output MNF transform images from the baseline AVIRIS Cuprite, Nevada, 1998 data set. Spatially coherent features are an indication of information. Spatially coherent features are largely gone above MNF image 48.

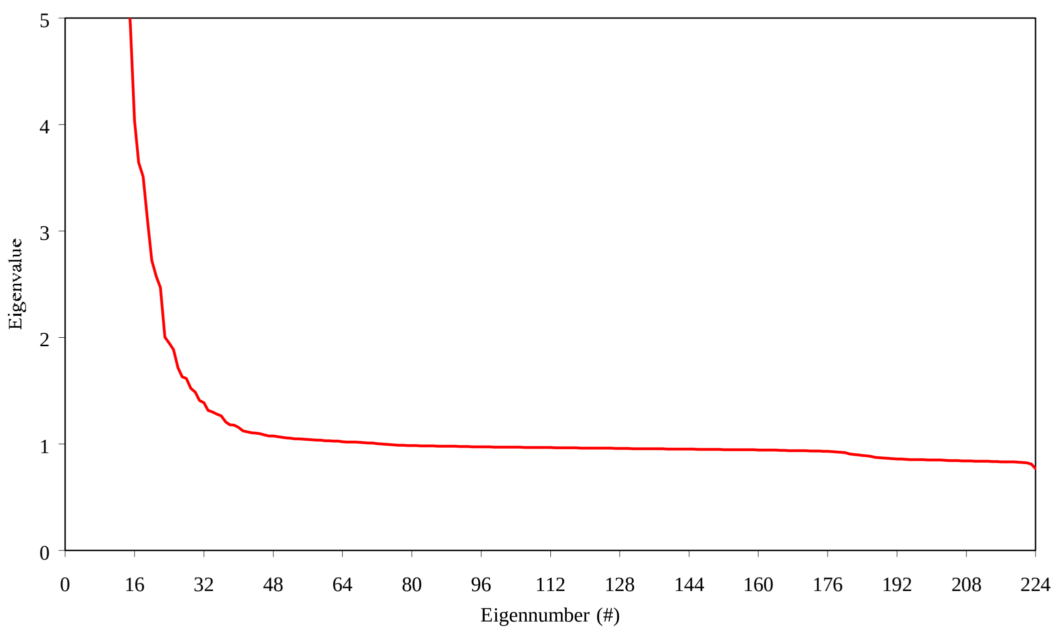

Figure 4. Eigenvalue versus eigennumber for the 224 MNF transform images from the 1998 AVIRIS low-altitude Cuprite, Nevada, data set.

are shown. A conservative threshold eigenvalue of 1.25 has been set for information. Above this threshold, the MNF transform image is considered to have useful spatially coherent information above the noise level of the data. This threshold provides a basis for comparison within a data set and between data sets. By this measure, this AVIRIS data set has a baseline information content of 36 in the measured 1 by 1 spatial data. The 2 by 2 average data set has an information dimensionality of 53. In the case of the 8 by 8 spatial element average, a dimensionality of 90 is calculated for the 224 spectral measurements of the AVIRIS Cuprite data set. The Cuprite data set information content increases with an increase in SNR, even with a loss of spatial resolution.

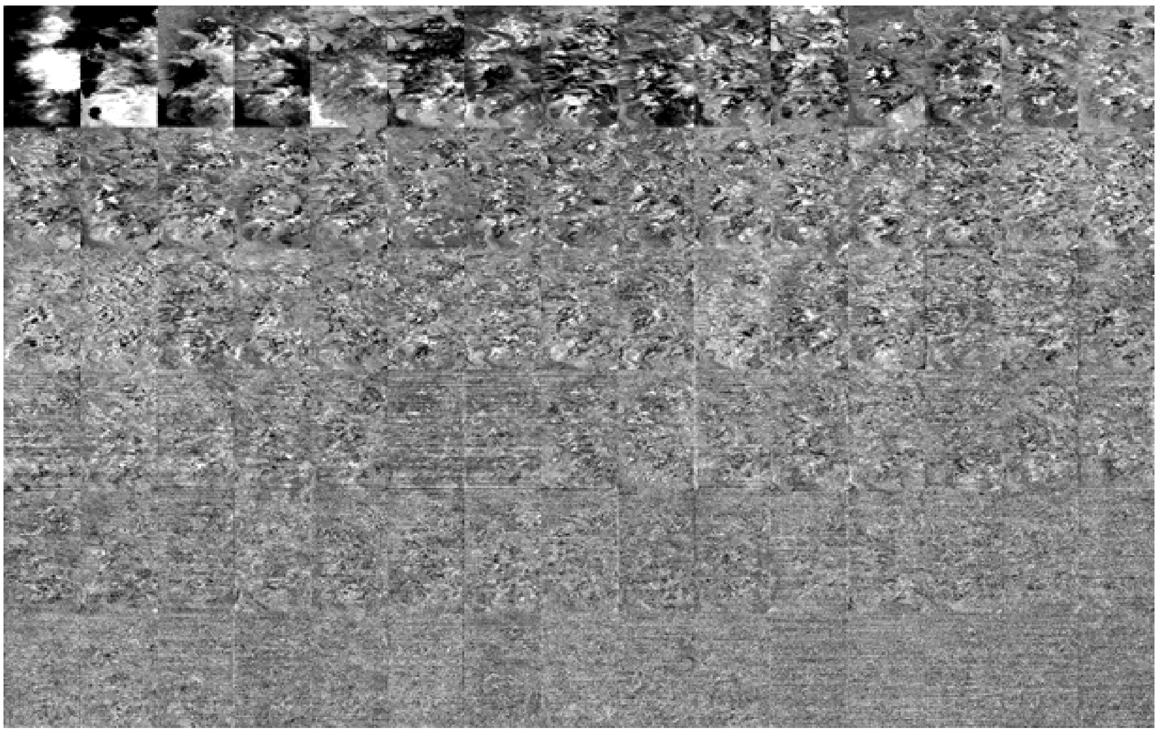

Figure 5. A grid of 16 × 6 output MNF images from the 2 × 2 average of the AVIRIS Cuprite, Nevada, 1998 data set. Spatially coherent features are an indication of information. Spatially coherent features are still present at MNF image 60 and higher.

5.0 RESULTS FOR AVIRIS DATA SETS FROM OTHER ENVIRONMENTS

The surface composition and illumination properties vary from data set to data set. Therefore, the relationship between information content and SNR and spatial resolution will vary from data set to data set. To explore this variation, AVIRIS data sets were analyzed representing a range of different earth surface environments. Figure 7 shows an image from a low altitude AVIRIS data set acquired over the Conagaree Swamp National Monument, South Carolina, in 1998. This image has a nominal 4-m spatial resolution and is largely forested with a range of trees and other vegetation species. Figure 8 shows the MNF transform results for the original 1 by 1 data as well as for 2 by 2, 4 by 4, and 8 by 8 spatial element averages. The threshold of 1.25 for the eigenvalues gives a baseline dimensionality of 24 for the 1.1 case. The MNF image at which the 1.25 eigenvalue threshold is reached does not shift significantly between the 1 by 1

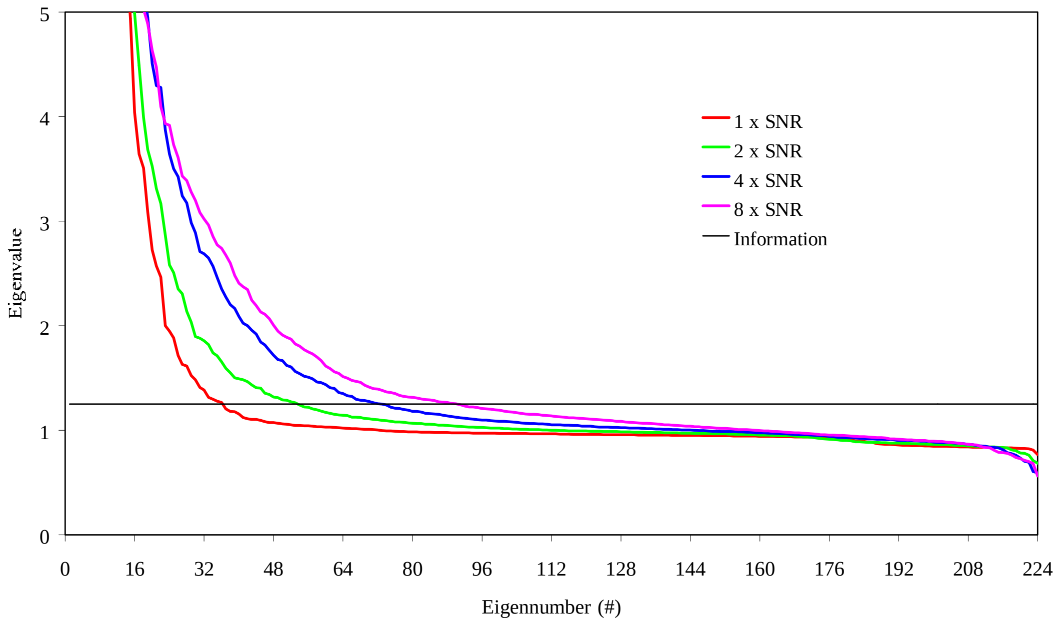

Figure 6. Plots of MNF eigenvalues versus eigennumbers for the 1998 AVIRIS Cuprite, Nevada, data set. As the effective AVIRIS SNR is increased by averaging, the number of MNF images with eigenvalues above the designated information threshold increases.

and 2 by 2 spatial resolution cases. This suggests that the loss of spatial resolution reduced the dimensionality to roughly the same degree as the improved signal-to-noise increased the dimensionality. This might be expected for a forested region with canopy dimension near the 1 by 1 spatial resolution of AVIRIS. In this case, many of the AVIRIS spectra represent single canopy spectra with unique spectral characteristics. These unique canopy spectra account for some portion of the MNF transform calculated-information dimensionality. In the 2 by 2 spatial averaged case, the effective SNR is increased, but adjacent canopy spectra are averaged and the unique spectral signatures are diluted. In the 4 by 4 and 8 by 8 spatial averaging cases, the number of MNF transform images above the eigenvalue threshold increases. Threshold information dimensionalities of 32 and 57 are calculated for the the 4 by 4 and 8 by 8 cases. This suggests that at these coarser spatial scales, the significantly higher signal-to-noise enhances the data set information dimensionality even with the loss in spatial resolution.

A second vegetation-dominated AVIRIS data set was examined. A portion of an AVIRIS data set acquired over the Santa Monica Mountain, California, on the 5th of October 1998 was used. An AVIRIS image from this data set with nominally 4- by 4-m spatial resolution is shown in Figure 9. The vegetation is largely chaparral, with some exposed rock and soil. Figure 10 shows the MNF transform results for different spatial averages of the data. With the 1 by 1 spatial resolution, the information dimensionality of the data set was 40, based upon the 1.25 eigenvalue threshold. For each case, as the data were spatially averaged to increase the signal-to-noise, the information content increased, even with the loss of spatial resolution. The information dimensionality reached 77 in the case of the 8 by 8 spatial average data set.

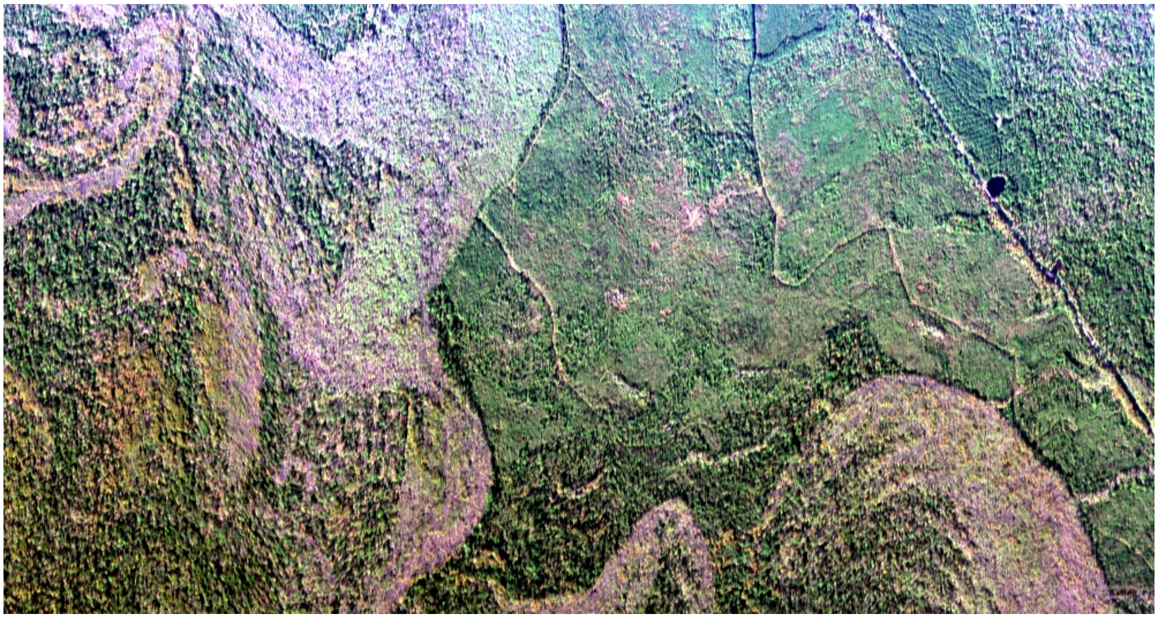

Figure 7. Ungeorectified AVIRIS low-altitude data acquired over the Congaree Swamp on the 26th of October 1998.

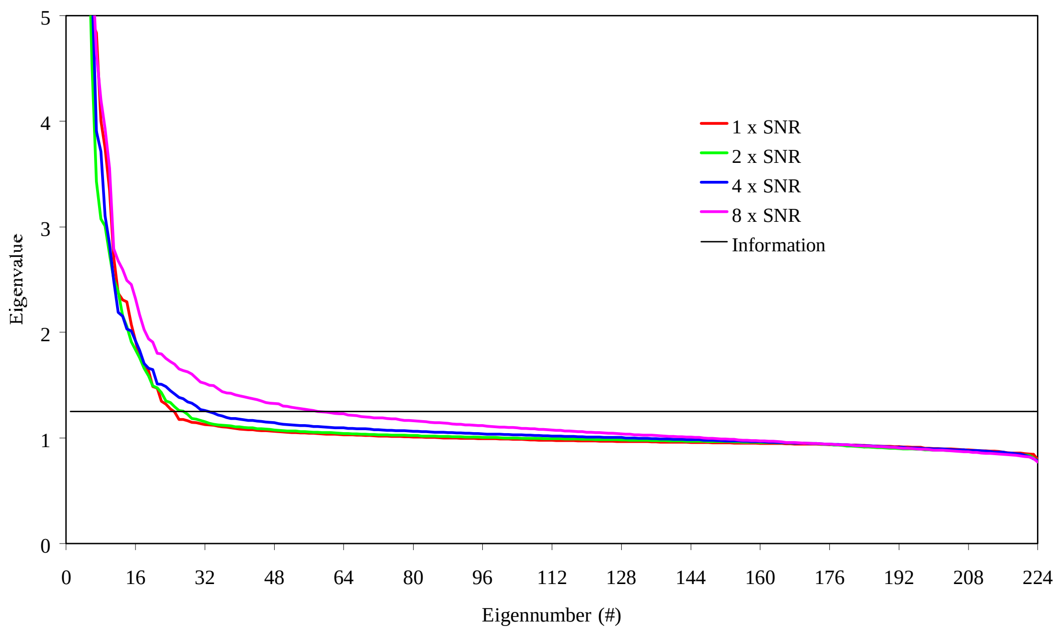

Figure 8. Plots of MNF eigenvalues versus eigennumbers for a forested portion of the 1998 AVIRIS Congaree Swamp data set. As the effective AVIRIS SNR is increased by averaging, the number of eigenvalues above the designated information threshold increases.

A largely urban data set was included in this AVIRS data information content analysis. Figure 11 shows a portion of a low-altitude AVIRIS data set acquired in San Diego, California, on the 12th of October 1999. These data are nominally 4-m spatial resolution. Figure 12 shows the results of the MNF transform calculations. For the 1 by 1 spatial case, information dimensionality was 57, based upon the 1.25 eigenvalue threshold. In the 2 by 2 case the information dimensionality did not increase, suggesting that the unique spectral signatures at the 1 by 1 spatial scale were diluted by the spatial averaging and that this dilution was not overcome by the increase in SNR. In the 4 by 4 and the 8 by 8 spatial averaging cases, the MNF transform information dimensionality increased with respect to the 1 by 1 case. An information dimensionality of 84 was calculated for the 8 by 8 spatial average case.

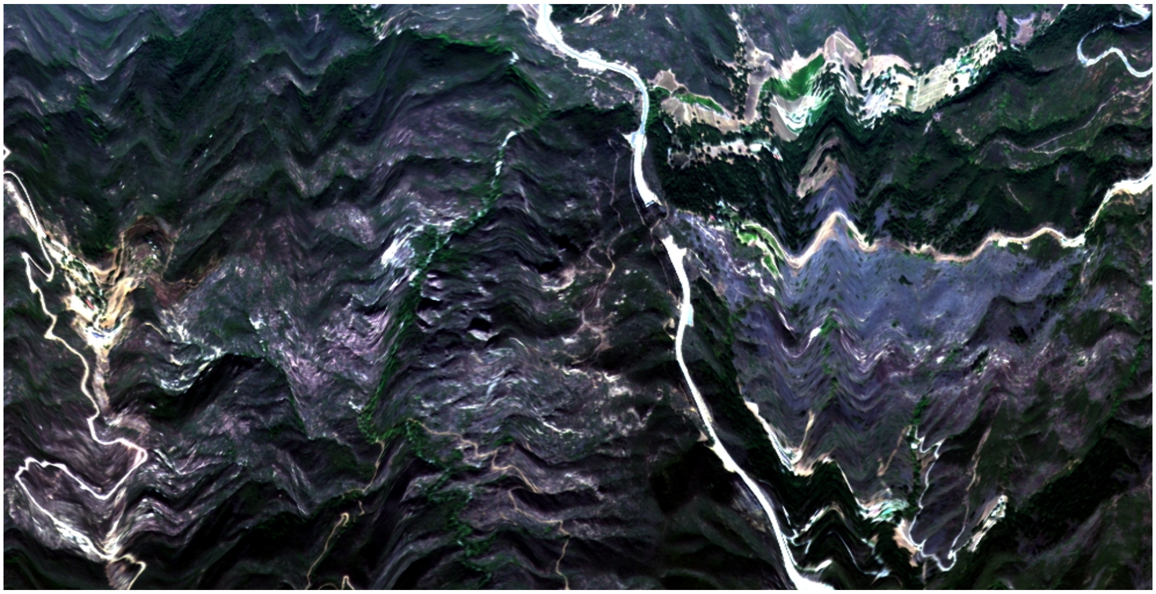

Figure 9. Ungeorectified AVIRIS low-altitude data acquired over the Santa Monica Mountains, California, on the 5th of October 1998.

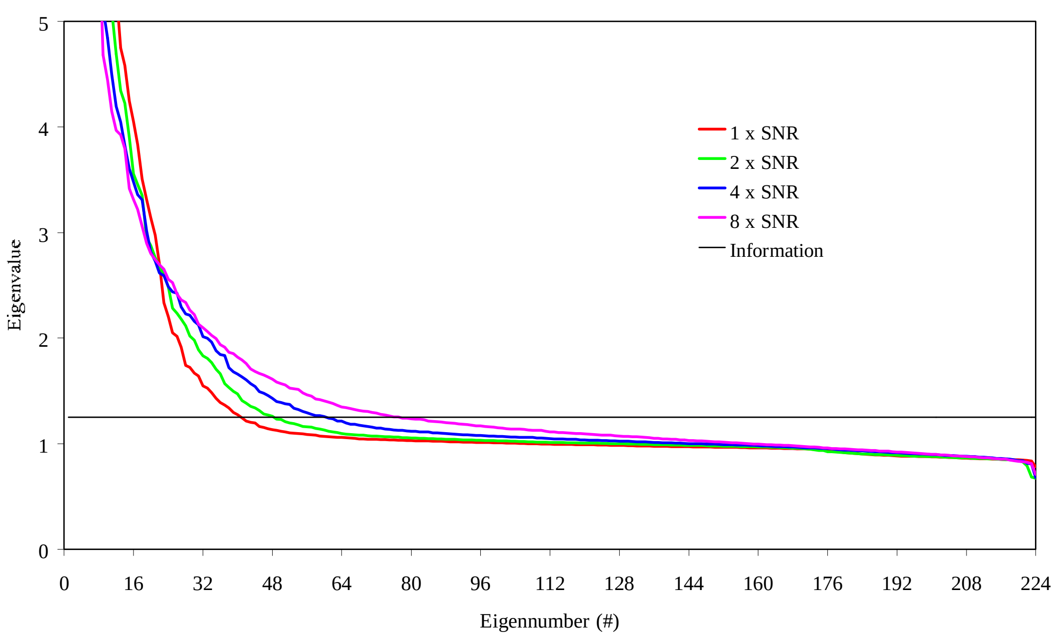

Figure 10. Plots of MNF eigenvalues versus eigennumbers for a portion of the 1998 AVIRIS Santa Monica Mountains data set.

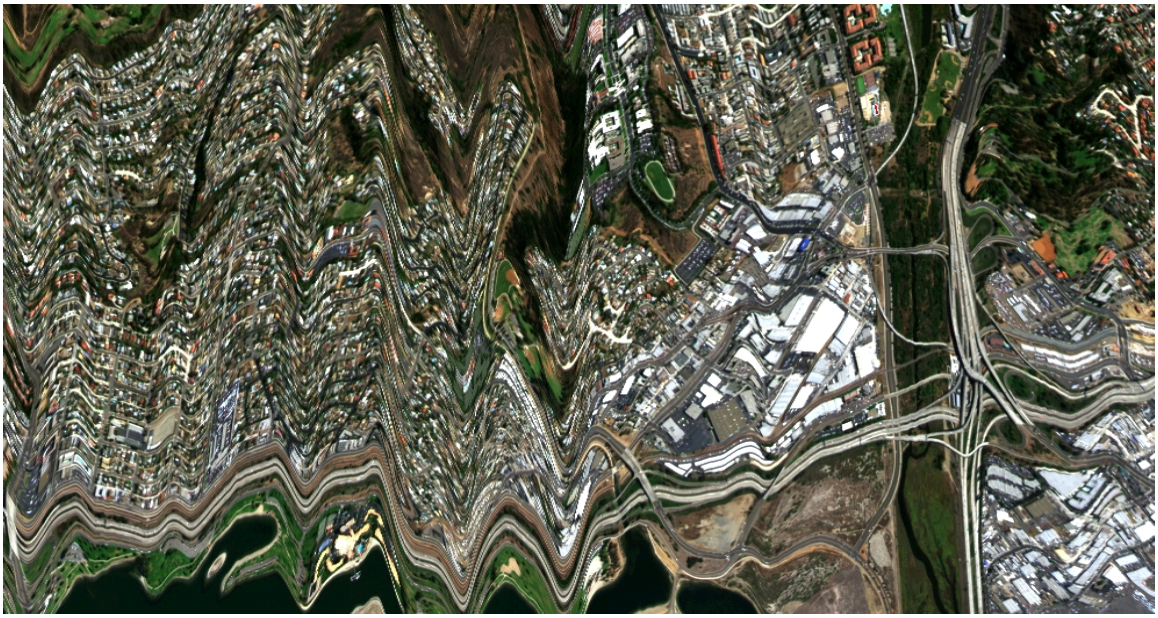

Figure 11. Ungeorectified AVIRIS low-altitude data acquired over portions of San Diego, California, on the 12th of October 1999.

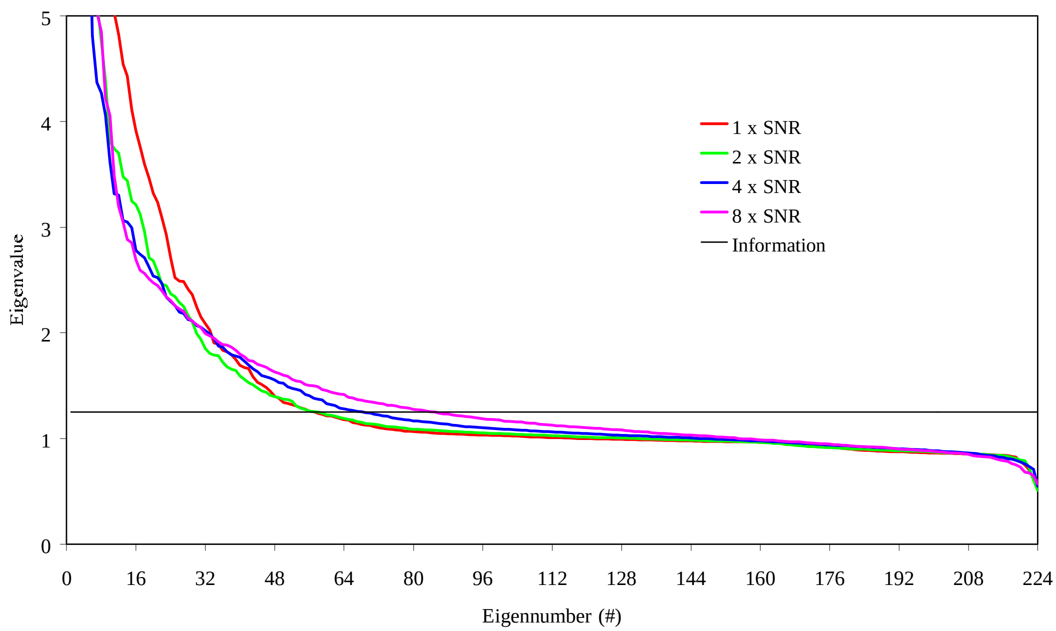

Figure 12. Plots of MNF eigenvalues versus eigennumbers for a portion of the 1999 AVIRIS data set acquired over San Diego, California.

The final environment examined in this investigation was a coastal water data set. Figure 13 shows a portion of a low-altitude AVIRIS data set acquired in the near shore environment adjacent to San Diego, California, on the 12th of October 1999. Figure 14 shows the results of the MNF transform information dimensionality analysis. The dimensionality of the 1 by 1 case is 15 for the 1.25 eigenvalue threshold. The dimensionality increases for the 2 by 2, 4 by 4, and 8 by 8 spatial averaging cases. It is surprising that the information dimensionality for this water environment increased significantly with an increase in SNR. Water environments are usually considered simple, with relatively few components. In this case, the complexity of the components in the coastal environment in conjunction with the multiple scattering of nature light will generate nonlinear spectral effects. These nonlinear spectral effects will significantly increase the dimensionality as assessed by the MNF transform algorithm in a high SNR data set.

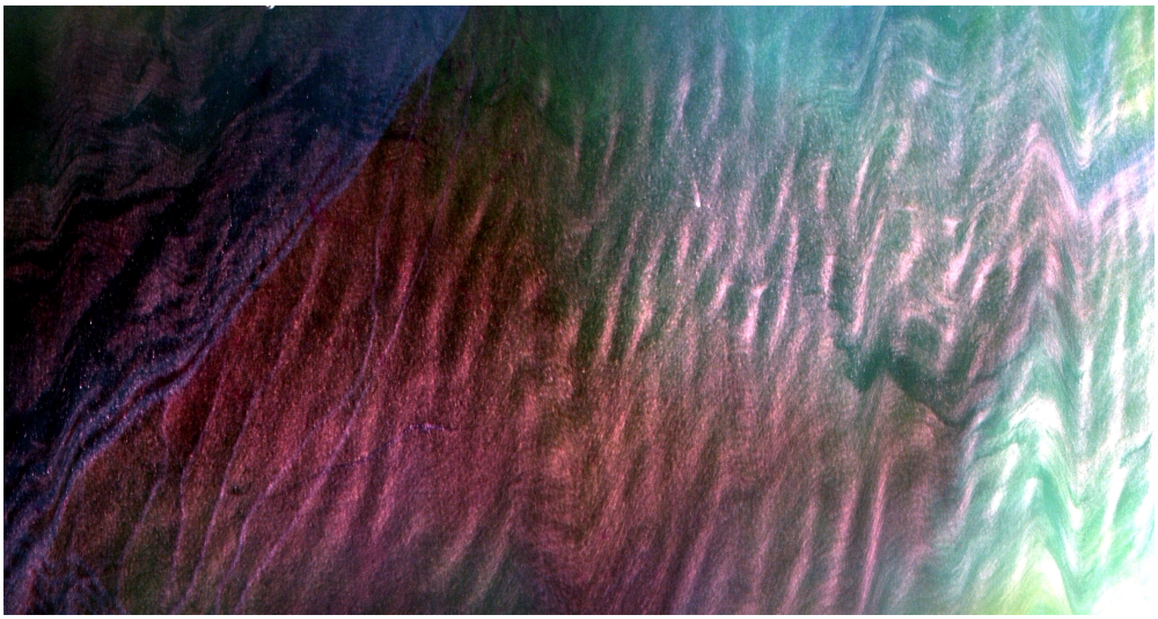

Figure 13. Ungeorectified AVIRIS low-altitude data acquired in coastal waters of Southern California near San Diego on the 12th of October 1999.

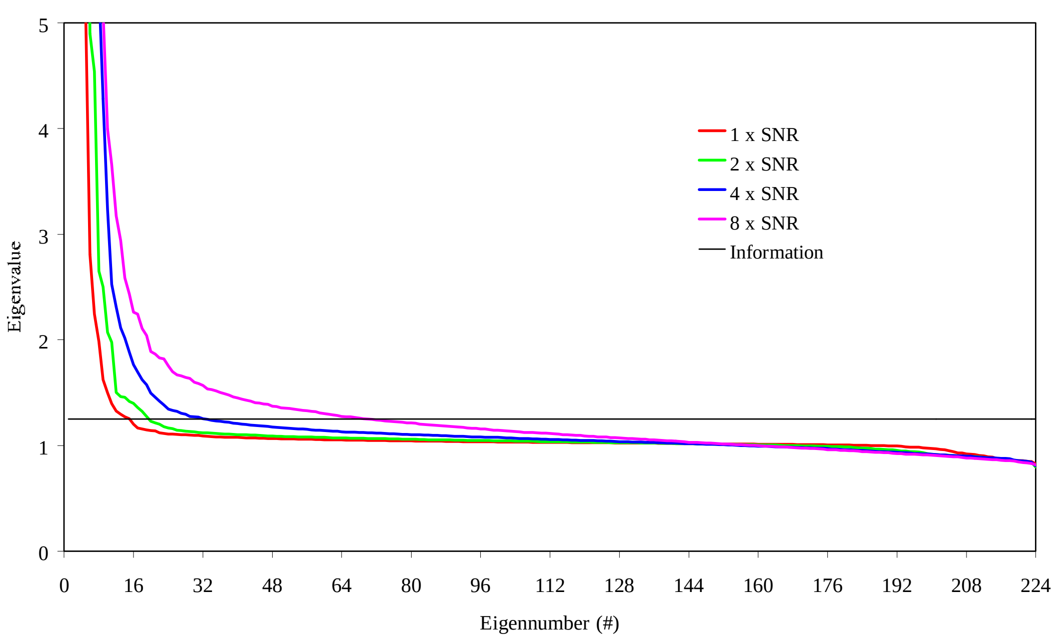

Figure 14. Plots of MNF transform eigenvalues versus eigennumbers for the 1999 data set acquired off the coast of Southern California.

6.0 DISCUSSION

There are numerous strategies for assessing the information content of an AVIRIS data set. For this investigation, information content has been linked to the MNF transform image dimensionality above a designated threshold. It is worth noting that this assessment of information content would miss the information in an image consisting of only a signal spectral signature. In this case, the MNF transform would report an information dimensionality of one. A spectroscopic analysis of a single spectral signature scene might identify ten or more components based upon the molecular absorption and component scattering signatures. In contrast, a scene with the three materials that interact to produce nonlinear spectral signature effects will produce an MNF transform dimensionality greater than three, because the MNF transform assigns dimensionality without accounting for nonlinear interactions.

7.0 CONCLUSION

Using the MNF transform as a basis, a variety of AVIRIS low-altitude 224 spectral measurement, data sets have been examined to determine their baseline information dimensionality. For the baseline data sets, the information dimensionality varied from 15 for a coastal ocean region to 57 for a portion of the city of San Diego, California. This information dimensionality is a function of surface materials present, spectral variability, and spatial distribution of the materials as well as the SNR of the AVIRIS data. To explore the effects of SNR and spatial resolution, the baseline AVIRIS data sets were spatially averaged into 2 by 2, 4 by 4, and 8 by 8 data sets. The effect of spatial averaging is to increase the SNR and to reduce the spatial resolution of the data. For the Cuprite, Santa Monica, and coastal ocean data sets, the information dimensionality increased with each increase in data SNR, even with the loss of spatial resolution. For the Cangaree Swamp and San Diego city data, the information dimensionality only increased in the 4 by 4 and 8 by 8 spatial averaging cases. The 2 by 2 spatial averaging showed no significant increase or decrease in information dimensionality. Both of these data sets have a distribution of different surface components (tree canopies and buildings), with scales close to the original AVIRIS spatial resolution of 4 m. The 2 by 2 spatial averaging diluted the unique spectral signatures, thus lowering the information dimensionality to the same extent that the higher SNR increased the information dimensionality. As the SNR was increased by factors of 4 and 8, the information dimensionality as assessed by the MNF transform increased to high fractions of the 224 potential dimension of the AVIRIS spectral measurements. By this measure, SNR is the critical determining factor for the information content in AVIRIS and AVIRIS-like imaging spectrometer data.

8.0 REFERENCES

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9.0 ACKNOWLEDGMENTS

The majority of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. I would like to express my appreciation for the efforts of the AVIRIS team at the Jet Propulsion Laboratory.