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LOSSLESS COMPRESSION OF AVIRIS DATA: COMPARISON OF METHODS AND INSTRUMENT CONSTRAINTS

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1. INTRODUCTION

A family of lossless compression methods, allowing exact image reconstruction, are evaluated for compressing AVIRIS image data. The methods are based on Differential Pulse Code Modulation (DPCM). The compressed data have an entropy of order 6 bits/pixel. A theoretical model indicates that significantly better lossless compression is unlikely to be achieved because of limits caused by the noise in the AVIRIS channels.

AVIRIS data differ from data produced by other visible/near-infrared sensors, such as Landsat-TM or SPOT, in several ways. Firstly, the data are recorded at a greater resolution (12 bits, though packed into 16-bit words). Secondly, the spectral channels are relatively narrow and provide continuous coverage of the spectrum, so that the data in adjacent channels are generally highly correlated. Thirdly, the noise characteristics of the AVIRIS are defined by the channels' Noise Equivalent Radiances (NERs), and these NERs show that, at some wavelengths, the least significant 5 or 6 bits of data are essentially noise.

2. COMPRESSION SCHEME

The overall scheme adopted for lossless compression comprises three main elements:

(1) prediction of the current pixel's value from prior pixels' values;
(2) differencing to form a residual;
(3) encoding the residual using a variable or fixed rate code.

The residuals are represented using NBIT bits. Any residual outside the range $-(2^{NBIT-1}-1)$ to $+(2^{NBIT-1}-1)$ is an exceedance. For variable rate coding, the residuals falling within this range are Huffman-encoded. The resulting codebook is optimal for each data set. An exceedance is indicated by the value -2^{NBIT-1}, and its value is transmitted in full (16 bits).

For the methods using optimised predictors, there is an overhead caused by the need to transmit prediction coefficients, and this is set at 32 bits per coefficient. This overhead is significant.

3. PREDICTION SCHEMES

14 prediction schemes have been evaluated. Let $x_{i,j,\lambda}$ represents the value of the pixel in row (line) i, column j, channel (band) λ, and $\hat{x}_{i,j,\lambda}$ be its predicted value. Residuals are formed according to the expression:

$$\text{residual} = x_{i,j,\lambda} - \text{nearest integer to}(\hat{x}_{i,j,\lambda}).$$

For schemes using optimised coefficients, the coefficients (variously a, b, c, or d) are calculated by the least-squares minimisation of $\Sigma(\hat{x}_{i,j,\lambda} - x_{i,j,\lambda})^2$, where the summation is taken along a line (j varies, i and λ fixed).

Spatial Methods, Fixed Coefficients

Row:	$\hat{x}_{i,j,\lambda} = x_{i,j-1,\lambda}$.
Column:	$\hat{x}_{i,j,\lambda} = x_{i-1,j,\lambda}$.
Two-point Row-Column:	$\hat{x}_{i,j,\lambda} = (x_{i-1,j,\lambda} + x_{i,j-1,\lambda})/2$.
Three-point Row-Column:	$\hat{x}_{i,j,\lambda} = (3x_{i-1,j,\lambda} + 3x_{i,j-1,\lambda} - 2x_{i-1,j-1,\lambda})/4$.

Spatial Methods, Optimised Coefficients

Optimised Row:	$\hat{x}_{i,j,\lambda} = a + bx_{i,j-1,\lambda}$.
Optimised Column:	$\hat{x}_{i,j,\lambda} = a + bx_{i-1,j,\lambda}$.
Optimised Two-point Row:	$\hat{x}_{i,j,\lambda} = a + bx_{i,j-1,\lambda} + cx_{i,j-2,\lambda}$.
Optimised Two-point Row/Column Row:	$\hat{x}_{i,j,\lambda} = a + bx_{i,j-1,\lambda} + cx_{i-1,j,\lambda}$.

Spectral Method, Fixed Coefficients

Channel:	$\hat{x}_{i,j,\lambda} = x_{i,j,\lambda-1}$.

Spectral Methods, Optimised Coefficients

Mean-corrected:	$\hat{x}_{i,j,\lambda} = a + x_{i,j,\lambda-1}$.
One-point channel:	$\hat{x}_{i,j,\lambda} = a + bx_{i,j,\lambda-1}$.
Two-point channel:	$\hat{x}_{i,j,\lambda} = a + bx_{i,j,\lambda-1} + cx_{i,j,\lambda-2}$.
Three-point channel:	$\hat{x}_{i,j,\lambda} = a + bx_{i,j,\lambda-1} + cx_{i,j,\lambda-2} + dx_{i,j,\lambda-3}$.

Spectral-Spatial Method, Optimised Coefficients

Channel-Row:	$\hat{x}_{i,j,\lambda} = a + bx_{i,j,\lambda-1} + cx_{i,j-1,\lambda}$.

4. TEST DATA SETS

The schemes have been evaluated using 3 data sets: the complete radiometrically rectified data set for a Jasper Ridge image (Run 05, 07/23/90), and the first six and the last six lines of a Moffett Field image (Run 013, 07/23/90). All 224 channels were used. Some values of the 16-bit pixels fall outside the nominal 12-bit range. Negative values are thought to be caused by radiometric rectification, and values above 4095, by noise. The entropies of the three data sets are 9.82, 9.20 and 9.85 bits/pixel, respectively. Straight application of a UNIX-like *compress* algorithm to the two Moffett Field data sets yields compressed files of 10.73 and 11.53 bits/pixel, respectively.

5. RESULTS

Number of bits per residual: The variation of the compressed image entropy as NBIT (see §2) varies from 13 down to 3 bits has been studied, for both variable and fixed rate coding. As NBIT decreases, the number of exceedances increases, and the compression worsens for variable rate coding. Results below are for 8-bit residuals, which entail losses mostly in the range 0.1-0.25 bit/pixel compared with 13-bit residuals. The pattern of loss is similar for all the methods. Optimal values of NBIT are found for fixed rate coding.

Spatial Methods: Of the 8 methods using spatial prediction, the one named "Two-point Row-Column" provided the best performance (6.88, 6.46, 7.10

bits/pixel respectively). To indicate the spread of performance, the worst method for each data set produced 7.42, 6.84 and 7.57 bits/pixel, respectively. The optimised methods produced residuals with lower standard deviations but any reduction in the residuals' entropy was negated by the coefficient overhead.

Spectral Methods: Of the 6 methods using spectral prediction, that called "Two-point Channel" was best (5.90, 5.81, 5.89 bits/pixel). Residuals coded with NBIT=13 improve the compression by no more than 0.10 bit/pixel. The "One-point Channel" method was only marginally worse, by 0.11 bit/pixel for the worst of the three data sets. The compression given by the "Channel-Row" method, which uses both spectral and spatial data, was intermediate between these two methods. Fixed-coefficient Channel DPCM was the worst of all the 15 methods. The "Mean-corrected" method was the second worst method for one Moffett Field data set, but it performed better than all the spatial methods for the other two data sets.

Fixed- vs. Variable-Rate Coding: A similar pattern of results holds for fixed-rate coding. For the best spatial method, "Two-point Row-Column", allocating 8 bits to the residuals provides the best compression overall (8.33, 8.24, 8.45 bits/pixel for the respective data sets). For the spectral methods, 6 bits is the optimum, giving compressed data of, respectively, 7.38, 7.39, 7.47 bits/pixel. Fixed-rate coding is worse than variable-rate coding by about 1.5 bits/pixel.

Dependence of Results on Data: The results for the best spatial method show a spread in compression of 0.64 bit/pixel depending on the data set for variable-rate coding, and of 0.21 bit/pixel for fixed-rate coding. For the best spectral method, the comparative figures are 0.09 and 0.09 bit/pixel. The results for the spectral method are more consistent, varying less across different data sets.

Noise Sensitivity: The variations in the data in Channels 1-4 and Channel 223-224 are dominated by the channel noise (the standard deviation of the data in each of these channels is very close to that channel's NER). If these channels are excluded from the compression evaluation, then the compressions are improved by about 0.2 bit/pixel. There are no exceedances for NBIT=12 and NBIT=13 when these channels are disregarded.

6. ENTROPY LIMITS DUE TO INSTRUMENT NOISE

The noise in each channel causes a spread in values, and so contributes to the entropy of the data. The noise entropy of a single channel can be calculated by using its NER and assuming a probability distribution. The entropy caused by the noise alone has been modelled numerically, by constructing a univariate probability distribution for all 224 channels. Using the NERs given in the Jasper Ridge and Moffett Field ancillary data sets, this noise entropy is found to be 5.28 bits/pixel for a Gaussian distribution of noise in each channel, and 5.03 bits/pixel for a Laplacian distribution. For the three data sets, the entropies of the residuals produced by the "Three-point channel" spectral method are the lowest. For a value of NBIT=8, the entropies are 5.45, 5.36 and 5.45 bits/pixel respectively.

The similarity of the results for the three data sets, and the closeness of these results to the theoretical values supports the suggestion that lossless compression using spectral information is almost limited by the AVIRIS's channel noise. If the probability distribution of the residuals is similar to that of noise, then a Huffman codebook for variable rate coding might be designed on the basis of instrument parameters, and not have to be derived during the compression process.