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IN CONJUNCTION WITH WAVELET/KLT DATA COMPRESSION**

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SPECTRUM Analysis of Multispectral Imagery in Conjunction with Wavelet/KLT Data Compression

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Abstract

The data analysis program, SPECTRUM, is used for fusion, visualization, and classification of multispectral imagery. To facilitate data transmission and storage, a compression algorithm is proposed based on spatial wavelet transform coding and KLT decomposition of interchannel spectral vectors, followed by adaptive optimal multiband scalar quantization. The performance of SPECTRUM clustering and visualization is evaluated on compressed multispectral data. 8-bit visualizations of 56-bit data show little visible distortion at 50:1 compression and graceful degradation at higher compression ratios.

I. SPECTRUM data visualization.

This paper describes the authors' research on the problem of compressing multispectral data prior to image classification and analysis. The raw data used in this study is Landsat Thematic Mapper (TM) 7-channel imagery, with 8 bits of dynamic range per channel. A typical quarter-frame of TM data is roughly 3000×4000 pixels, or about 84 megabytes of data. Displaying and manipulating this much data on a workstation computer with an 8-bit monitor is extremely time-consuming unless the raw data is first reduced in size. The program and graphical user interface, SPECTRUM [1], written by researchers at Los Alamos National Laboratory and the University of New Mexico, greatly facilitates supervised data manipulation by operating on quantized multispectral data. SPECTRUM is part of the public-domain KHOROS image processing package distributed by the University of New Mexico [2].

The 7-dimensional spectral vectors associated with each spatial node in the image are clustered into 256 clusters using an accelerated variant of the k -means algorithm [3], an unsupervised data clustering procedure. Data is then vector quantized and displayed as an 8-bit false color visualization of 256 characteristic vectors (usually the cluster means) that represent the 2^{56} possible raw data vectors. Since vectors with

similar spectral characteristics wind up in the same cluster, the k -means clustering effects a fine-grained classification of the data without any human intervention. Supervised manipulation and analysis of the data typically takes the form of identifying and highlighting or measuring spectrally similar regions in the image that correspond to some surface feature of interest, such as agriculture or urban development. By associating each pixel in the display with a spectrally homogeneous cluster and manipulating the 8-bit color table identified with those clusters, SPECTRUM allows the user to select instantaneously all pixels in the dataset that belong to the same cluster. Thus, for instance, the user can locate an identifiable region of healthy vegetation, which might be displayed using pixel values representing 2 or 3 different clusters, and then select all pixels in the image corresponding to those clusters simply by manipulating the display's color map. This is much faster than operating on unclustered raw data with a 56-bit bandwidth.

II. Redundancy reduction.

Because there is a great deal of spatial redundancy in high-resolution sensor data, it is desirable for transmission purposes to compress the raw data. Moreover, there also exists a certain degree of interchannel correlation in multispectral data that can be exploited to produce additional compression. DCT-based image coding algorithms have been used in the past to remove the spatial component of this redundancy, coupled with an interchannel Karhunen-Loève transform (KLT) to remove interchannel correlations; see Huisman *et al.* [4]. One unfortunate side effect, however, is that block transform coding, such as the DCT, suffers from tiling artifacts at high compression ratios; these artifacts are visually annoying and can interfere with automated data analysis systems (e.g., neural network-based image classifiers). This is a serious defect since the high-frequency noise removal usually associated with data compression tends to improve, rather than degrade, the performance of automated analysis systems [5].

More recently, multispectral compression schemes have been proposed using wavelet transform coding to remove the spatial redundancy in multispectral imagery. Epstein *et al.* [6] performed an interchannel KLT decomposition of TM data, followed by a 2-dimensional spatial discrete wavelet transform (DWT) using non-perfect reconstruction linear phase quadrature mirror filters. The KLT/DWT output was quantized using uniform scalar quantization and compressed by run-length and Huffman coding. Use of a wavelet transform eliminates tiling artifacts in the compressed imagery, and the authors of [6] report that the results are "suitable for rapid browsing applications" at compression ratios of around 80:1. This approach was refined by Markas and Reif [7], who investigated using histogram equalization to improve the KLT coding gain and hierarchical bitmap encoding of the quantized wavelet transform coefficients. They report high-quality reproduction ("perceptually lossless") at compression ratios of around 20:1.

Also in recent work, the present authors combined DWT coding and vector quantization (VQ) to compress multispectral data [8], an approach that requires a training process to produce customized VQ codebooks. We have subsequently decided that, when used in conjunction with subband coding, there is relatively little additional gain to be had from vector—as opposed to scalar—quantization. This conclusion is based in part on our experiences while developing the FBI's wavelet-scalar quantization (WSQ) specification, a nation-wide standard for archival-quality compression of digitized fingerprint images [9, 10]. The WSQ algorithm is based on adaptive uniform scalar quantization of a 64-subband DWT decomposition; the findings of Hopper and Preston [11] indicate that scalar quantization of a highly refined subband decomposition produces results comparable to VQ coding by allowing subband bit allocation to take advantage of nonuniformities in the data's spectrum and by spatially decorrelating the data, which negates most of the advantage of VQ. Advantages of the scalar approach include lower encoding complexity and the fact that adaptive scalar quantization is image-dependent and therefore requires no training stage.

III. DWT/KLT compression.

In this work we present our results on compressing TM data using a DWT/KLT algorithm for removing data redundancy. In contrast to the approach taken in [6, 7], we have discovered that, at high bit rates, we obtain superior results if interchannel KLT coding is done *after* the spatial DWT is performed. In addition

to the numerical evidence to be presented later, there are several plausibility arguments we can offer as to why this should be so. First, the DWT produces coding gain by exploiting data correlations in two dimensions and should therefore yield more coding gain than 1-dimensional KLT coding. This assessment is supported by the information-theoretic analysis of Chen *et al.* [12], who found that spatial correlations are generally greater than interchannel correlations and concluded that "there is little advantage in using spectral information in addition to spatially neighboring pixels." While Epstein *et al.* [6] did establish that adding interchannel coding yields better performance than spatial coding alone, performing the KLT *first* disturbs the smoothness of the data with respect to the spatial coordinates and therefore cuts into the more significant DWT coding gain.

A second reason why it makes sense to perform the spatial DWT first is that the spatial frequency subbands that result are then KLT-encoded separately; i.e., one computes KLT decompositions for N small subbands rather than a single, large KLT for the whole scene. We conjecture that image features from different length or resolution scales probably have different spectral characteristics, which means that KLT-encoding them separately should yield better coding gain. Since the total number of interchannel vectors is not changed by the DWT, the cost of constructing N subband covariance matrices is the same as the cost of constructing a single covariance matrix for the whole image. The additional computational cost of performing 7×7 covariance matrix diagonalizations for 16 subbands is a very small portion of the total encoding task and adds little to the overall numerical complexity. KLT encoding of DWT subbands also makes it easier to incorporate spectral data acquired at different scanning resolutions. For instance, a thermal channel scanned at twice the ground-sampling distance as shorter-wavelength channels can be identified with first-level lowpass DWT subbands for the sake of forming interchannel vectors for KLT coding.

It is interesting to note that the early work of Huisman *et al.* [4] using DCT coding applied the spatial transform prior to interchannel KLT coding, which was done on a block-by-block basis rather than according to frequency subbands. Since there is no blocking inherent in the DWT, compressed images exhibit no tiling artifacts at high compression ratios. Instead, image degradation takes the more graceful form of a gradual blurring or loss of fine details as the compression ratio increases. At moderate compression ratios, this has the effect of acting as a high-

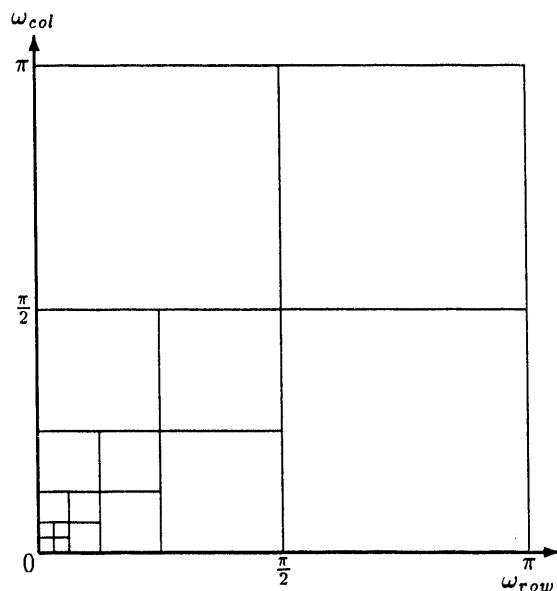


Figure 1: Frequency support of DWT subbands.

pass noise filter, and Hopper and Preston [11] observed improved success rates for minutiae detection using WSQ-compressed images (versus uncompressed data) with the UK Home Office's automated fingerprint matcher; DCT-based JPEG compression consistently *decreased* minutiae-detection performance.

IV. Numerical results.

A WSQ/KLT algorithm was applied to Landsat TM images of the former Soviet Union, which were clustered by SPECTRUM for data visualization. The filters were 7-tap/9-tap linear phase perfect reconstruction filters corresponding to a family of regular biorthogonal wavelets, implemented using symmetric boundary extrapolation. The subband decomposition used in these experiments is the 5-octave splitting shown in Figure 1. Each of the 16 multispectral subbands was then transformed into its optimal 7-dimensional KLT decomposition, resulting in $7 \times 16 = 112$ DWT/KLT subbands. Uniform scalar quantization of these subbands was performed using a bit allocation that minimizes a weighted mean-square distortion metric subject to a user-imposed constraint, r , on the overall compression; quantizer output was compressed by zero-run-length and Huffman coding. Thus, the user can specify a target bit rate of, e.g., $r=0.5$ bits/pixel (bpp) per channel, which would correspond to 16:1 compression for 8 bpp/channel data, and the quantized data will come in at a compression ratio of around 16:1. Actual observed compression ra-

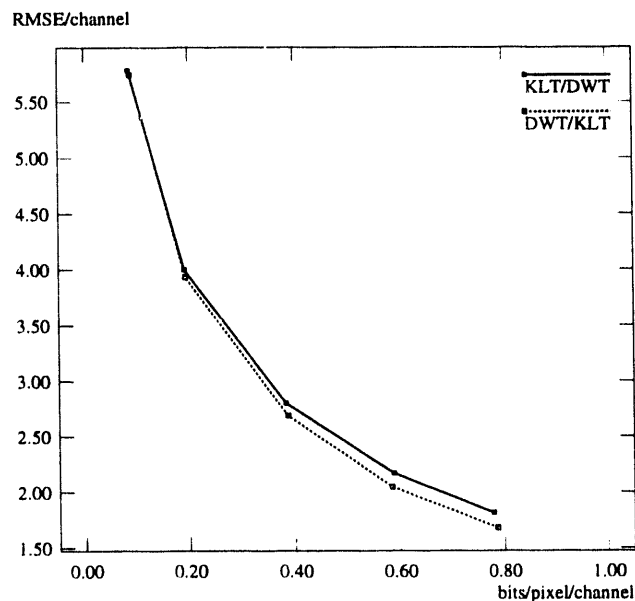


Figure 2: Rate-distortion curve, Chernobyl image.

tios are normally somewhat higher than predicted due to variable amounts of lossless coding gain, principally from run-length coding of zeros in highpass-filtered subbands. The important point is that r gives the user control over the *lossy* component of the compression process, namely, the quantization of the floating-point wavelet/KLT coefficients. Except for the addition of KLT interchannel coding, this strategy is similar to the one employed in the FBI standard [9, 10].

Two TM images were processed in this experiment: a 1024×1024 -pixel scene of the region surrounding the Chernobyl power plant, taken a few months before the unfortunate reactor malfunction, and a 2048×2048 image of Moscow and surrounding countryside. (We believe in testing on large, statistically heterogeneous images.) Both images were compressed using the above DWT/KLT procedure at a variety of bit rates, r , between 1 and 0.1 bpp/channel. For comparison, the images were also processed, at the same bit rates, with the interchannel KLT performed *before* the spatial DWT (the *KLT/DWT* method). The rate-distortion characteristics of both methods on the Chernobyl image are shown in Figure 2; the curves for the Moscow image are nearly identical. Distortion is reported as root mean-square error (RMSE) per channel, the average RMSE for the 7 spectral channels. Bit rates are the actual observed compression factors; e.g., at $r=1$ bpp/channel, both methods achieved sufficient additional lossless coding gain to come in at just under

0.8 bpp/channel (just over 10:1 compression).

At this high bit rate one can see the advantage of the DWT/KLT approach over the KLT/DWT method in the form of slightly lower RMSE. The trend is consistent throughout the range of bit rates tested, although most significant in the high-quality regime, and also occurs in the Moscow image with comparable magnitude. In our presentation we will also show an example of a KLT/DWT artifact from the Chernobyl image at $r=0.5$ bpp/channel in which a road appearing in the visible spectrum—but not present in thermal channel #6—gets “smeared” into the thermal channel by the KLT and appears in the visualization of channel 6; this artifact does not appear with DWT/KLT compression.

Figure 3 displays a portion of a SPECTRUM visualization of the Chernobyl image, both before and after DWT/KLT compression with $r=0.15$ bpp/channel (53.3:1); the actual observed compression ratio was 63.3:1 and the RMSE/channel was 4.92. SPECTRUM generated an 8-bit color map for a 256-vector codebook of cluster means by using blue to display the pixel intensity in channel 1 (visible blue), red for channel 4 (near IR), and green for channel 5 (mid IR); the image has been converted to gray-scale for this publication. The same color formula was used to display the compressed data. The Chernobyl reactor is located in the developed region at the upper end of the lake. A man-made dike extends from the shore near the power plant down the middle of the lake, separating warm water released by the power plant from the colder water at the upper end of the lake.

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Figure 3. SPECTRUM visualization of Chernobyl Landsat image, original data (top) and after wavelet-KLT compression (bottom) with $r=0.15$ bpp channel. Actual observed compression ratio was 63.3:1.

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