Assessment of KLT and bit-allocation strategies in the application of JPEG 2000 to the Battlescale Forecast Meteorological Data

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Abstract— **This paper focuses on the parameters selection that optimizes JPEG 2000 compression for meteorological data. In particular, a procedure for bit rate allocation for different slices of data is proposed. The selection is based on the variances of individual slices and a mixed model approximation of MSE. The solution of the constrained minimization problem for MSE is obtained using Lagrange multipliers. This procedure allows the incorporation of other constraints in this problem such as noninteger bit rates, limited range of possible bit rates, etc. Experimental results are given for all six variables. The reduction of MSE also led to the reduction of maximum absolute error in most cases.**

I. INTRODUCTION: METEOROLOGICAL DATA COMPRESSION USING JPEG 2000

The Battlescale Forecast Model (BFM) data set [1] available for use in this study consists of two hourly outputs, each of which consists of a cube of data for each of six physical variables. Calling the discrete five-dimensional signal $Met(v, t, Z, X, Y)$, the discrete dimensions are 6x 2x64x129x129. The first dimension is the Met variable, the second one is time, the third is vertical height Z, and the other two are X and Y for the two horizontal spatial variables. The above Met data was produced specifically to investigate data compression techniques and these dimensions are not necessarily representative of what is needed in applications. The three-dimensional region of space was measured using terrain following mesoscale resolution. The six variables are: potential temperature T, pressure P, water vapor mixing ratio Wv and the U, V, and W components of the wind speed vector. For each fixed physical variable and each fixed hour, the 3-D set of data consists of horizontal layers of dimension 129 x 129, and each layer corresponds to a specific spatial altitude or height which is the Z direction.

This study focuses only on lossy compression in order to evaluate the potential reductions that are possible for different levels of distortion/error. The original floating point BFM data is first converted to fixed point (16 bits) before any compression is done.

II. SOFTWARE IMPLEMENTATIONS OF JPEG 2000

Two software packages are available in the public domain and which are reference implementations of the Part 1 of the JPEG 2000 standard [2]. They are: JasPer (http:www.jpeg.org) and JJ2000 (http:jj2000.epfl.ch). Other implementations of JPEG 2000 include the Kakadu package (in C) that is included in [2].

The JJ2000 Java package has been used in all the computer experiments included in this paper with the help of a Graphical User Interface (GUI) denoted the JJ2KGUI developed at the authors institution, The University of Texas at El Paso. The JJ2KGUI is a Java front-end to the JJ2000 package that is intended among other things to facilitate the experimentation with J2K compression on multiple slices of data. It can take as input a 3-D floating-point data set which is quantized to fixed-point before being fed slice-by-slice to the JJ2000 coder. The GUI provides the user with useful information such as various metrics, which include the MSE, RMSE, Max Absolute Error, SNR, PSNR, entropy, energy and others. The GUI currently supports various file formats such as PGX, PGM, PPM and NetCDF. NetCDF data format is self-describing and architecture-independent (see www.unidata.ucar.edu).

III. PREVIOUS WORK ON 3-D COMPRESSION

For specific types of 3-D data sets such as multi-spectral images (these are essentially multiple versions of the same scene), compression methods have been proposed in the Part 2 extension of the JPEG 2000 standard [3]. In this paper, we evaluate an approach to 3-D compression that is very similar to the Part 2 which consists of doing pre- and post-processing in one direction before and after being processed by the JPEG 2000 in the other two directions. This paper is an extension of study on BFM data presented in [4] and which uses the KLT transform (see Fig. 1).

More recent work on general approaches to 3-D data compression has focused on medical volumetric data, see [5]. Meteorological data compression is the topic of [4], [6].

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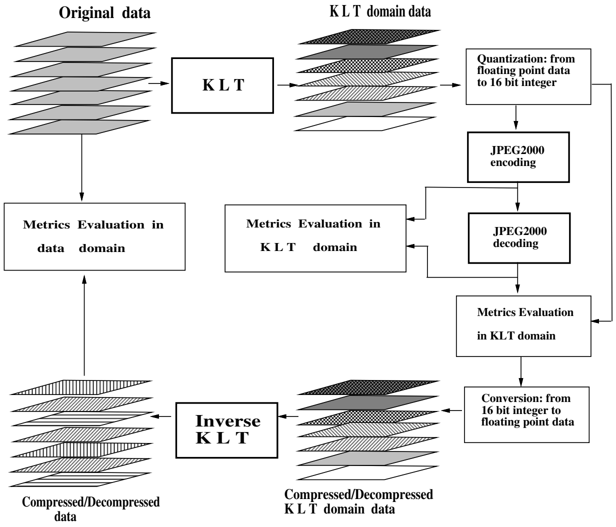

Fig. 1. Diagram illustrating 3-D compression set up.

IV. DISTORTION METRICS

The results of compression will be evaluated in terms of the following distortion metrics:

- MSE_z - mean squared error for level or slice z

$$MSE_z = \sum_{i,j} \left(\frac{1}{n \cdot m}\right) \cdot \left(J2K(I_z)(i,j) - I_z(i,j)\right)^2$$

- MSE - mean squared error for the whole 3-D set of N slices

$$MSE \;=\; \frac{1}{N} \;\cdot \sum_z \; MSE_z$$

- $RMSE$ - root mean squared error $\sqrt{MSE}$
- MAE - maximum absolute error between data cubes

$$\max(|J2K(I_z) - I_z|),$$

where for our case $n = m = 129, N = 64$. Clearly, I_z denotes slice on level z, and $J2K(I_z)$ denotes slice on level z after compression/decompression. When evaluating distortion after inverse KLT transform, it is measured in the data domain. In the next section, distortions involved in bit rate allocation are defined in the KLT domain.

V. BIT-RATE ALLOCATION STRATEGIES

The reference case for comparison of any bit-rate allocation strategy is the case when we assign the same bit rate to each slice denoted one bit rate or (obr) strategy. The results of this case are considered the worst case scenario, and we are expecting to improve upon them.

We propose a bit-rate allocation strategy based on a mixed model for the rate-distortion. The main assumption is that the relative variance of each slice $V_z \;=\; {\sigma_z}^2$ corresponds to the amount of information contained in the slice. Thus, slices with the higher variance are assigned more bits than the ones with smaller variance. The first model approximates the MSE for the case with medium and low bit rates as follows

$$MSE_L = c_1 \cdot \sum_z \; V_z \cdot \frac{1}{(R_z - R_0)^{\beta}},$$

the other approximates the case with high bit rates as

$$MSE_H = c_2 \cdot \sum_z \; V_z \cdot 2^{-2 \cdot R_z}.$$

Given the target bit rate R we want to select $R_1, \ldots, R_N$ such that the total MSE is minimized. Thus, we have a constrained minimization problem: given R, find $R_1, \ldots, R_N$ such that

$$MSE \;=\; \frac{1}{N} \;\cdot\; \sum_z \; MSE_z \; (R_z) \;\rightarrow\; min$$

under the condition $R \cdot N = \sum_z R_z$.

This problem can be converted to unconstrained minimization using a Lagrange multiplier method, that is we want to minimize $\sum_z MSE_z(R_z) + \lambda \cdot \sum_z R_z$ for some $\lambda \geq 0$. To determine appropriate parameters for both models we need to perform four compression simulations. After the parameters are computed we take derivatives of both models expressions with respect to R_z and equate them to zero. This allows us to obtain expressions for R_z as functions of λ. Also we want to take into account additional constraints that we encounter in our simulations, that is we can realistically use only bit rates $0 < \; R_z \; \leq \; R_{max} \; (z)$, where $R_{max}(z)$ is the bit rate where almost lossless results are achieved using JPEG2000 (for higher target bit rate the achieved bit rate is $R_{max}(z)$).

Therefore if the R_z computed is less than 0, we set R_z to 0, if the R_z computed is larger than $R_{max}(z)$, we set R_z to $R_{max}(z)$. The more complex rule is used to choose which of the two models is selected for the particular R_z. Using a bisection algorithm we are selecting the λ_{opt} such that $R \;=\; \frac{1}{N} \;\cdot\; \sum_z \; R_z$.

This algorithm allows us to assign bit rates in the predefined range of achievable values. In all the cases the KLT slices are ordered in decreasing variance, so that the bit rates assigned to last slices are zeros, thus those slices are not used in compression.

TABLE I

METEOROLOGICAL COMPONENTS

Component	Max	Min	Range	Units
U	32.9	-18.5	51.4	m/sec
V	25.9	-18.5	44.4	m/sec
W	0.37	-0.45	0.82	m/sec
T	333.26	270.91	62.35	deg K
WVAP	13.81	0.027	13.783	$\frac{\text{gr of water}}{\text{Kg of air}}$
P	1019.1	247	772.1	millibars

VI. RESULTS AND CONCLUSION

Our experiments described in this section show that the described bit rate allocation strategy achieves less distortion in both MSE and MAE. All the results are shown in percentages of the total amplitude range of the specific data cube. Table I

TABLE II

P, T, WV: MAE (IN %)

BR	P obr	P mbr	T obr	T mbr	WV obr	WV mbr
0.1	11.56	0.12	33.13	5.63	48.57	5.61
0.3	4.13	0.015	4.21	1.78	5.65	1.48
0.5	2.86	0.07	2.14	1.56	2.26	0.93
0.7	1.68	0.006	1.71	1.52	1.46	0.51
0.9	1.58	0.005	1.35	1.52	1.07	0.45
1.1	1.28	0.005	1.17	1.51	1.02	0.33
1.3	0.93	0.004	1.06	1.5	0.93	0.28
1.5	0.91	0.003	0.9	1.5	0.63	0.19

TABLE III

U, V, W: MAE (IN %)

BR	U obr	U mbr	V obr	V mbr	W obr	W mbr
0.1	4.54	1.86	7.75	2.98	52.87	4.85
0.3	1.5	0.99	2.83	1.28	18.76	2.16
0.5	0.65	0.61	1.57	0.95	10.53	1.43
0.7	0.52	0.32	1.17	0.68	8.84	1.06
0.9	0.38	0.22	0.88	0.46	5.7	1.03
1.1	0.31	0.17	0.61	0.31	5.04	1.01
1.3	0.23	0.14	0.5	0.27	4.65	0.98
1.5	0.21	0.11	0.43	0.18	3.54	0.97

provides this information about different meteorological variables.

Figure 2 shows achieved percent RMSE for one case, where no special bit allocation strategy is used (highest plot showing RMSE for P), and for six cases where the bit rate allocation algorithm was used. The improvement in RMSE was achieved for all six variables (results shown in the Tables IV and V). The results obtained for MAE are shown in Fig. 3 and Tables II and III. As we can see, the obtained bit allocation resulted in the improved MAE.

ACKNOWLEDGMENT

We gratefully acknowledge the input from Dr. T. Henmi of the U. S. Army Research Lab. for generating and providing the Meteorological data used in this study.

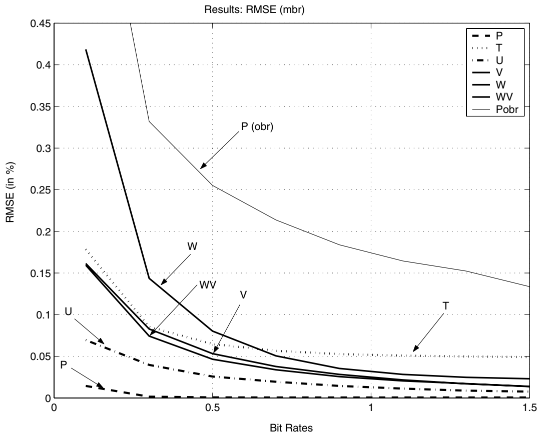

Fig. 2. RMSE in data domain for all variables using bit allocation strategy (mbr) and one case without (obr).

TABLE IV

P, T, WV: RMSE (IN %)

BR	P obr	P mbr	T obr	T mbr	WV obr	WV mbr
0.1	0.73	0.014	0.63	0.18	1.05	0.16
0.3	0.33	0.002	0.29	0.08	0.23	0.07
0.5	0.26	0.0007	0.22	0.06	0.16	0.05
0.7	0.21	0.0006	0.19	0.06	0.13	0.03
0.9	0.18	0.0006	0.16	0.05	0.10	0.03
1.1	0.17	0.0006	0.14	0.05	0.08	0.02
1.3	0.15	0.0006	0.12	0.04	0.07	0.02
1.5	0.13	0.0006	0.11	0.04	0.06	0.01

TABLE V

U, V, W: RMSE (IN %)

BR	U obr	U mbr	V obr	V mbr	W obr	W mbr
0.1	0.38	0.07	0.7	0.16	2.24	0.42
0.3	0.09	0.04	0.17	0.08	1.36	0.14
0.5	0.06	0.03	0.11	0.05	1.09	0.08
0.7	0.04	0.02	0.08	0.04	0.91	0.05
0.9	0.04	0.01	0.07	0.03	0.79	0.04
1.1	0.03	0.01	0.05	0.02	0.7	0.03
1.3	0.02	0.01	0.05	0.02	0.62	0.02
1.5	0.02	0.01	0.04	0.01	0.55	0.02

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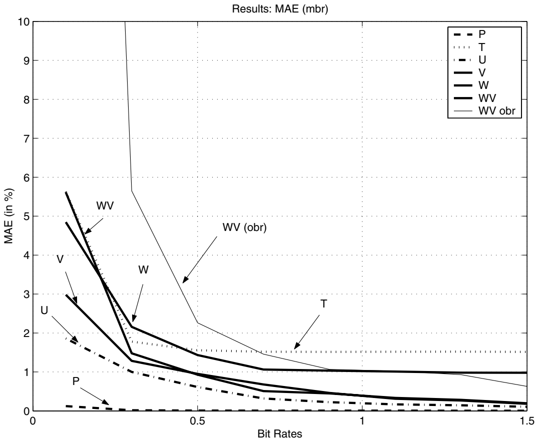

Fig. 3. MAE in data domain for all variables using bit allocation strategy (mbr) and one case without (obr).