Comparison of Bit Allocation Methods for Compressing Three-Dimensional Meteorological Data after Applying KLT

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Abstract – **This paper presents the latest results of an ongoing project to assess the impact of lossy compression applied to three-dimensional meteorological data. The main innovative outcomes presented are based on different bit allocation techniques used to compress Karhunen-Loeve transformed data. The transform is applied in the z-direction (between slices) as suggested in the JPEG2000 Part 2 standard. New results using these bit allocation techniques are presented on two data sets. The performance results are presented in terms of SNR, root-mean squared error (RMSE), and the maximum absolute error (MAE) for the entire cube of data.**

I. INTRODUCTION

This paper presents the most recent results obtained since [1] for compressing two different sets of meteorological data. One of the data sets is obtained from the Battlescale Forecast Model (BFM), which has been used in other works such as [2] and [3]. The variables available for this data set were pressure (PR), temperature (THET), water vapor (WVAP), U, V, and W wind components. The other data set is from the Naval Operational Global Atmospheric Prediction System (NOGAPS), which is in Gridded Binary (GRIB) format. The variables used from this data set were geo potential height (GP_H), temperature (TEMP), dew point (DP), U and V wind components. Some of our initial work on compressing these data was presented in [1]. Others' work on compressing meteorological data include [4] and [5]. The dimensions of the BFM data are 129x129 with 64 slices in the z-direction. On the other hand, the NOGAPS data used in this study are comprised of 20 slices, which have a size of 181x360. It should be noted that the NOGAPS data is obtained from a global model while the BFM data comes from a mesoscale model. Both data sets are in floating point format. A 16-bit quantizer was used to convert the data into integers in order to use the JJ2000 implementation of JPEG2000 Part 1.

For this study, the data sets were compressed using two approaches. The first approach was to treat each slice as an independent image going into JPEG2000. We refer to this technique as the 2-dimensional (2D) approach, and it is considered to be the baseline. The other approach was to apply the KLT in the slice direction. We refer to this technique as the pseudo 3D approach, which complies with JPEG2000 Part 2. For this method of compressing the meteorological data, bit allocation techniques are needed in order to take advantage of the energy compaction obtained from the KLT. The two methods used in this study for bit allocation are described in Section II. The results obtained for both data sets using the two approaches are presented in Section III. The compression results were obtained using CompressMD©, a software tool for compression of multiple slices of data developed by co-author A. Aguirre. Among other things, this package makes it easier to run the simulations for compressing 3-D data in compliance with JPEG2000 Part 2. A snapshot of a typical window of CompressMD© is shown in Figure 1.

II. BIT ALLOCATION TECHNIQUES

In this section, the different bit allocation techniques used on the KLT slices are described. The first technique discussed is the traditional log-variance. One of the shortcomings of this bit allocation scheme is that negative bit rates are generally assigned. Different methods used to deal with this problem are described. The second technique described is based on the interior-point optimization method, which incorporates the non-negativity constraint as part of the problem.

A. Traditional Log-Variance

The traditional log-variance bit allocation scheme is well known in the literature [6]. This technique is the solution to the following problem

$$\min \left\{ f(x) = \sum_{i=1}^{M} \sigma_i^2 2^{-2R_i} \right\} \quad (1)$$

$$\textit{subject to} \quad \left\{ \frac{1}{M}\left(\sum_{i=1}^{M} R_i \right) - R = 0 \right\}$$

In our study, M is the number of slices, x is the vector of M bit rates, σ_i^2 is the variance associated with slice i, and R is the

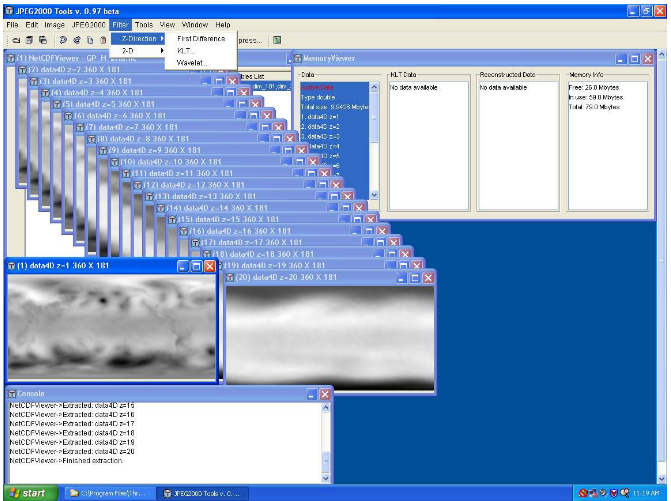

Figure 1. Screenshot of CompressMD© Software

average target bit rate. Solution to this problem can be achieved by using the standard optimization technique of Lagrange multipliers. The solution to this problem is expressed by the following equation:

$$R_k = R + \frac{1}{2}\log_2 \frac{\sigma_k^2}{\prod_{i=1}^{M}\left(\sigma_i^2\right)^{1/M}} \tag{2}$$

As mentioned before, this approach to allocating bit rates often yields negative values. Three different procedures to deal with negative bit rates were implemented. The first procedure is referred to as log-variance with offset. For this procedure, the following steps are followed:

1. Calculate the bit rates using (2).
2. Find the minimum value from the R_i's calculated in the previous step.
3. Add the absolute value of the minimum value obtained in Step 2 to the R_i's calculated in Step 1.
4. Scale the values obtained in Step 3 in order to achieve the original average target bit rate (R).

The procedure guarantees that no negative bit rates are achieved, but it is sensitive to scaling of the original data. Furthermore, the inherent characteristic of this procedure is that M-1 KLT slices are always assigned non-zero bit rates, thus, only one slice is discarded.

The second procedure used to deal with negative bit rates is called truncated log-variance. The description of this procedure is as follows:

1. Use (2) in order to calculate the bit rates.
2. From the bit rates computed in Step 1, find the ones that are negative.
3. Set bit rates found in Step 2 to zero (discard KLT slices associated with these bit rates).
4. Scale the remaining bit rates in order to maintain the average target bit rate.

This is a simple procedure employed to handle the negative bit rates. Unlike the log-variance with offset procedure, this technique is not sensitive to any scaling of the original data.

Iterative log-variance is the name given to the third procedure used to process the negative bit rates. The steps used to implement this procedure are:

1. Use (2) in order to find the bit rate allocation for M slices.
2. Test to see if any negative bit rates were assigned in Step 1. If yes, go to Step 3, otherwise return this answer.
3. Set negative bit rates to zero (KLT slices associated with those bit rates will be discarded) and adjust M to be the new number of remaining slices.
4. Go to Step 1.

This procedure is referred to as iterative log-variance since it iterates on (2) until no negative bit rates are computed. This procedure is also invariant to scaling of the original data. Bit rate allocations obtained from all three procedures will be presented in Section III.

B. *Interior-Point Method*

The interior-point optimization technique is the other method used in this study to allocate the bit rates. A summary description of this scheme is included. For further details, the reader is referred to [7]. For this technique, the problem can be expressed as follows:

$$\min\left\{ f(x) = \sum_{i=1}^{M} \sigma_i^2 2^{-2R_i} \right\}$$

$$\textit{subject to} \quad \left\{ \frac{1}{M}\left(\sum_{i=1}^{M} R_i\right) - R = 0 \quad ; \quad R_i \ge 0 \right\} \tag{3}$$

This problem is similar to the one described in (1), but the non-negativity constraint has been added. The following steps describe how to solve this problem using the interior-point scheme:

1. Solve the following system

$$\begin{bmatrix} H & A^T & -I \\ A & 0 & 0 \\ Z & 0 & X \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta y \\ \Delta z \end{bmatrix} = -\begin{bmatrix} \nabla_x \ell \\ h(x) \\ XZe - \mu e \end{bmatrix}$$

$$\textit{where} \quad \begin{aligned} \ell &= f(x) + h(x)^T y - x^T z \\ h(x) &= \frac{1}{M}\left(\sum_{i=1}^{M} R_i\right) - R \\ A^T &= \nabla h(x) \\ H &= \nabla^2 f(x) \end{aligned} \tag{4}$$

2. Force positivity.
3. Update point (x, y, z) using a step length.
4. Test for convergence. Iterate with the new point until the stopping criteria is met (tolerance is met or number of iterations desired is encountered).

The bit allocations obtained using this method will be presented in Section III.

III. RESULTS

In this section, the results obtained for the four previously described bit rate allocation methods are presented. Figure 2 shows how bits were allocated for BFM pressure data. The number of the KLT slice is on the x-axis, and the value of the number of bits allocated is on the y-axis. Similarly, the bit rate allocation for BFM U and W wind components is shown in Figures 3 and 4 respectively.

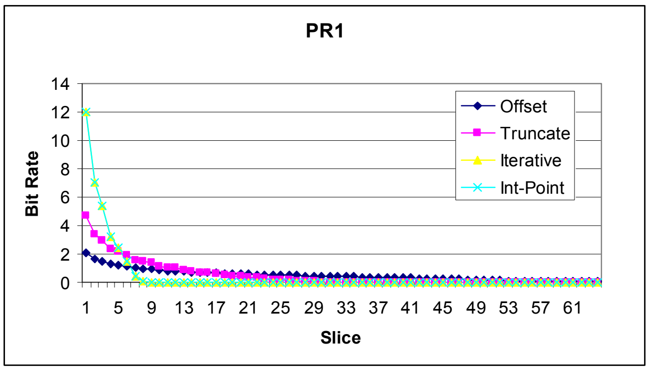

Figure 2. Bit allocation for BFM pressure

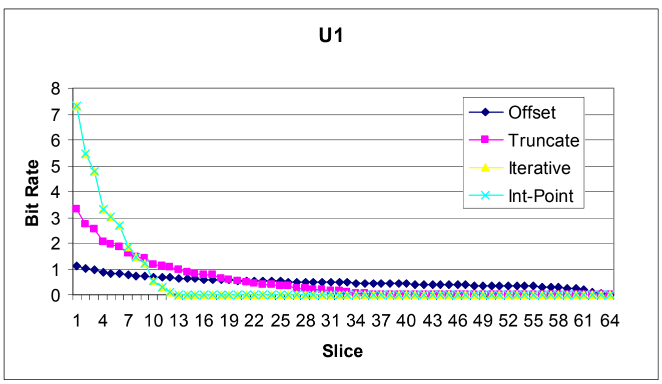

Figure 3. Bit allocation for BFM U wind component

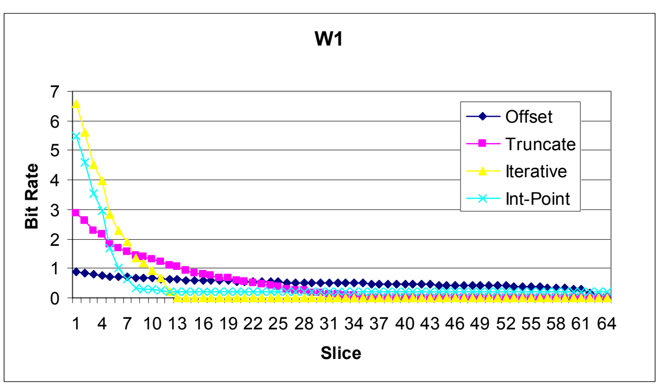

Figure 4. Bit allocation for BFM W wind component

The following tables show the performance of the bit allocation schemes shown in Figures 2, 3, and 4 in terms of signal-to-noise ratio (SNR), root mean-squared error (RMSE), and maximum absolute error (MAE). These values are computed when comparing the original data versus the recovered data after decoding the JPEG 2000 files and applying inverse KLT. The results from the 2D approach have also been included. An average target bit rate of 0.5 was used for all cases.

TABLE I
RESULT COMPARISON FOR BFM PRESSURE

Bit Allocation Scheme	SNR (dB)	RMSE	MAE
2D Approach	51.2094	1.977	18.6245
Log-variance with offset	60.3554	0.6898	4.3725
Log-variance truncated	74.5652	0.1343	0.8064
Log-variance iterative	95.4026	0.0122	0.1013
Interior-point method	95.4026	0.0122	0.1013

TABLE II
RESULT COMPARISON FOR BFM U WIND COMPONENT

Bit Allocation Scheme	SNR (dB)	RMSE	MAE
2D Approach	48.9276	0.0294	0.3925
Log-variance with offset	50.4966	0.0245	0.292
Log-variance truncated	53.4742	0.0174	0.4224
Log-variance iterative	40.3776	0.0786	1.6017
Interior-point method	40.3776	0.0786	1.6017

TABLE III
RESULT COMPARISON FOR BFM W WIND COMPONENT

Bit Allocation Scheme	SNR (dB)	RMSE	MAE
2D Approach	10.6511	0.0087	0.0857
Log-variance with offset	13.057	0.0066	0.051
Log-variance truncated	22.8	0.0022	0.0133
Log-variance iterative	32.7569	0.0007	0.0162
Interior-point method	29.6084	0.001	0.0143

It can be observed that the range of the results is significant. The difference in SNR between the 2D approach and the best technique for pseudo 3D ranges between 4.5466 and 44.1932 dB. Results for the NOGAPS data set follow. Figure 5 shows the bit allocation obtained for NOGAPS GP_H using the techniques described in Section II. On the other hand, Figure 6 shows the bit allocation achieved for NOGAPS TEMP. Finally, the bit allocation for NOGAPS DP is shown in Figure 7. Tables IV through VI display the performance of the different techniques for allocating the bits for these data sets. Once again, the performance of the 2D approach has been included for comparison purposes.

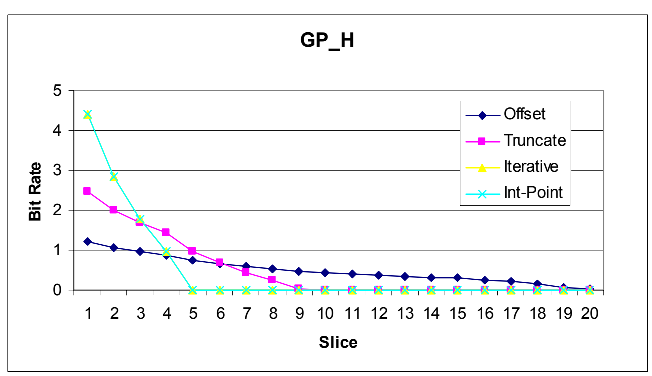

Figure 5. Bit allocation for NOGAPS geo potential height

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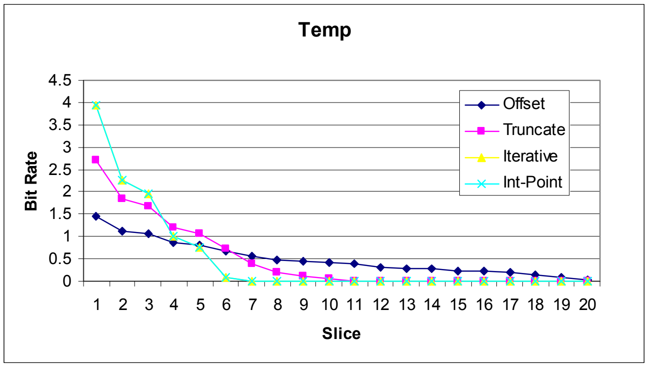

Figure 6. Bit allocation for NOGAPS temperature

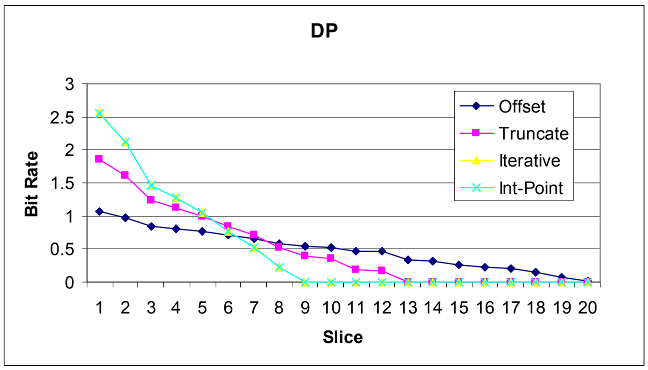

Figure 7. Bit allocation for NOGAPS dew point

TABLE IV
RESULT COMPARISON FOR NOGAPS GP_H

Bit Allocation Scheme	SNR (dB)	RMSE	MAE
2D Approach	86.944	0.6189	7.5191
Log-variance with offset	91.3554	0.3725	3.2843
Log-variance truncated	76.8096	1.9878	17.5145
Log-variance iterative	60.1434	13.5418	85.576
Interior-point method	60.1434	13.5418	85.576

TABLE V
RESULT COMPARISON FOR NOGAPS TEMP

Bit Allocation Scheme	SNR (dB)	RMSE	MAE
2D Approach	59.1839	0.2709	3.4782
Log-variance with offset	60.1539	0.2423	6.872
Log-variance truncated	52.6654	0.5738	10.9332
Log-variance iterative	48.5284	0.9239	13.148
Interior-point method	48.5284	0.9239	13.148

TABLE VI
RESULT COMPARISON FOR NOGAPS DP

Bit Allocation Scheme	SNR (dB)	RMSE	MAE
2D Approach	24.9671	1.0862	20.5347
Log-variance with offset	26.237	0.9385	18.3351
Log-variance truncated	24.619	1.1307	22.5267
Log-variance iterative	21.2407	1.6682	25.7201
Interior-point method	21.2402	1.6683	25.7201

For this data set, the difference in SNR between the 2D approach and the best pseudo 3D technique ranges only between 0.97 and 4.4114 dB. It should be noted that for both data sets, the best performance in SNR is not always associated with the best performance in MAE.

IV. CONCLUSIONS

Description and performance of different bit allocation techniques for KLT slice compression have been presented. Some of the salient results are that for NOGAPS data, the log-variance with offset method yields the best performance in SNR for all variables used in this study. Another observation is that through our experimentation, the iterative log-variance method and the interior-point method yielded the same bit allocation. Nonetheless, the latter can be improved by improving the objective function described in (3). Furthermore, more constraints could be added in order to try to improve the performance of this algorithm. All of these items are being considered in our future work. Additional items for future work include error distribution and location analysis. The main incentive for this analysis would be the implementation of different methods to guarantee a maximum absolute error. Data analysis is also being done in search of a parameter that can help determine which bit allocation will generate the best results before any actual compression is performed.

ACKNOWLEDGMENT

Aldo Lucero would like to thank the Texas Space Grant Consortium and the GEM Consortium for all their support. Miguel Argaez was supported in part by the U.S. Department of the Army Grant No. DAAD19-01-1-0741. This work was also supported by NSF Grant EIA-0080940 and ARL Contract DATM05-02-C-0046.

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