Low-Complexity Lossless Compression of Hyperspectral Imagery Via Adaptive Filtering

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More details can be found in:
[Klimesh 2005] M. Klimesh, Low-Complexity Lossless Compression of Hyperspectral Imagery Via Adaptive Filtering, to appear in *The Interplanetary Network Progress Report*, November 2005.
http://tmo.jpl.nasa.gov/progress_report/

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Summary: We have developed a low-complexity for lossless compression of multispectral or hyperspectral data.

Algorithm Overview:

- Predictive compression
- Uses the sign algorithm for prediction
  - an adaptive filtering algorithm that is a relative of the least mean square (LMS) algorithm
- Prediction residuals are encoded using Golomb power-of-2 codes
  - method is very similar to residual encoding in LOCO-I

Overview of the LMS Algorithm and the Sign Algorithm

Purpose: Estimate a desired signal d_k from an input vector $\mathbf{u}_k$ using a linear estimator that is adaptively updated from previous results.

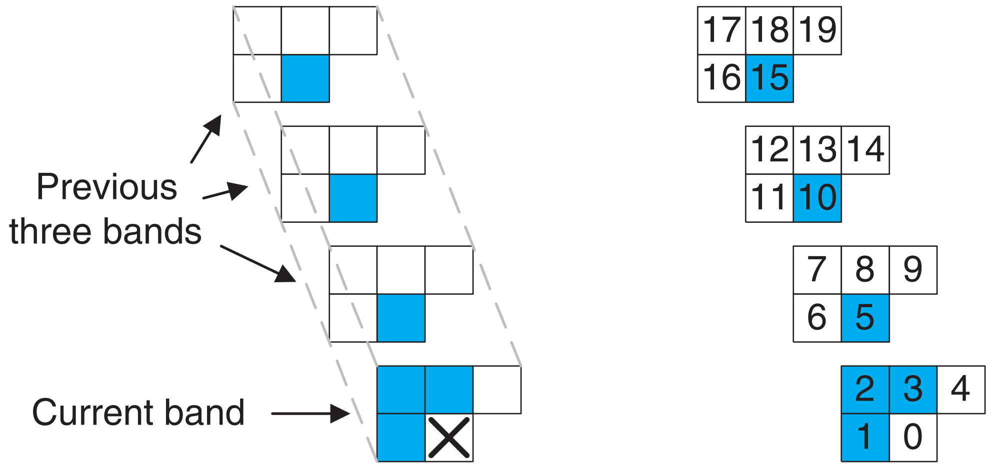
Summary:

- Form estimate: $\hat{d}_k = \mathbf{w}_k^T \mathbf{u}_k$
- Calculate estimation error: $e_k = \hat{d}_k - d_k$
  - When used as part of a predictive compression scheme, e_k is encoded in the compressed bitstream
- Update filter weights:

$$\text{LMS algorithm:} \quad \mathbf{w}_{k+1} = \mathbf{w}_k - \mu \mathbf{u}_k e_k$$

$$\text{Sign algorithm:} \quad \mathbf{w}_{k+1} = \mathbf{w}_k - \mu \mathbf{u}_k \, \mathrm{sgn}(e_k)$$

  Here μ is the "adaptation step size" parameter



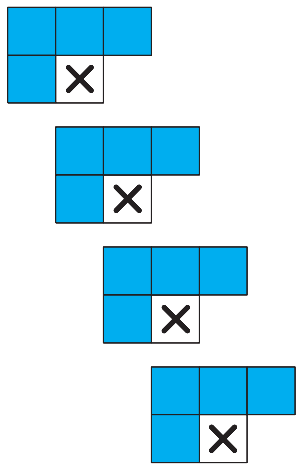
For clarity of presentation, we label the samples $s_0, \ldots, s_{19}$.

Naive approach to predictive compression using the given neighborhood:

Apply LMS or sign algorithm with $d_k = s_0$ and $\mathbf{u}_k = \begin{bmatrix} s_1 \\ s_2 \\ s_3 \\ s_5 \\ s_{10} \\ s_{15} \end{bmatrix}$

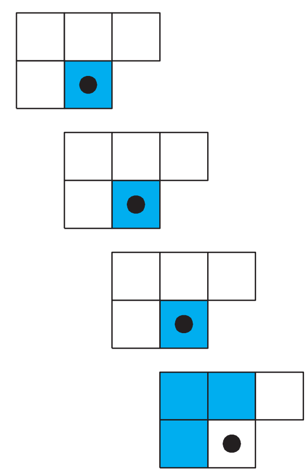
. . . however, this performs poorly!

Our solution: compute simple preliminary estimates $\tilde{s}_i$ in each band at the spatial location of the sample being predicted, and subtract from the input samples.



$$\begin{aligned}
\tilde{s}_{15} &= (s_{16} + s_{17} + s_{18} + s_{19})/4 \\
\tilde{s}_{10} &= (s_{11} + s_{12} + s_{13} + s_{14})/4 \\
\tilde{s}_{5} &= (s_{6} + s_{7} + s_{8} + s_{9})/4 \\
\tilde{s}_{0} &= (s_{1} + s_{2} + s_{3} + s_{4})/4
\end{aligned}$$

Use $\mathbf{u}_k = \begin{bmatrix} s_1 - \tilde{s}_0 \\ s_2 - \tilde{s}_0 \\ s_3 - \tilde{s}_0 \\ s_5 - \tilde{s}_5 \\ s_{10} - \tilde{s}_{10} \\ s_{15} - \tilde{s}_{15} \end{bmatrix}$ and $d_k = s_0 - \tilde{s}_0$.



Miscellaneous specifics of our implementation:

- Sign algorithm is used for weight adaptation
- Estimation error is encoded using Golomb power-of-2 codes in a manner very similar to residual encoding in LOCO-I
- Dataset is divided into 32-line parts, which are compressed independently
- Each spectral band has its own prediction weights, maintained independently of the prediction weights for other spectral bands
- For each 32-line part, the adaptation step size parameter μ is initialized to 0.00008, and multiplied by 0.75 after each of the first 10 lines

Algorithm features:

- Robust; there is no need to know in advance much about the degree of spectral or spatial correlation
  - However, the μ schedule may have to be appropriate for the dynamic range of the data

- Simple; it would be well-suited for implementation on a DSP or in an FPGA

- Low computational complexity
  - Can be implemented in such a way that the operations per sample are:
    - 6 integer multiplies
    - $\sim$ 25 integer add, subtract, or bit shift operations
    - Golomb coding operations

Compression effectiveness comparisons are given in the next four slides. Methods compared:

Fast lossless: our algorithm

ICER-3D: lossless results for ICER-3D, a 3-D-wavelet-based compressor

JPEG-LS: JPEG-LS applied to the spectral bands independently

Rice/USES: algorithm used in USES chip, with the multispectral predictor option. (Note that this can be improved on with an externally computed predictor.)

Differential JPEG-LS: JPEG-LS applied to the differences between the successive spectral bands

SLSQ and SLSQ-OPT: two versions of Spectral-oriented Least SQuares (SLSQ) [Rizzo et al., 2005]. Algorithms with complexity roughly similar to that of ours.

3-D CALIC: a nontrivial extension of the basic (2-D) CALIC algorithm to multispectral imagery

M-CALIC: multiband CALIC, another extension of CALIC to multispectral imagery

ASAP: Adaptive Selection of Adaptive Predictors [Aiazzi et al., 2001]; more computationally intensive than any of the other compressors in the tables

Bit rates achieved for compression of scenes from the uncalibrated 2001 Hawaii and 2003 Maine AVIRIS datasets. Results are given in bits/sample.

scene	fast lossless	ICER-3D	JPEG-LS (2-D)	Rice/USES multispectral
2003 Maine 1	2.92	3.38	5.00	4.02
2003 Maine 2	2.89	3.33	4.88	3.98
2003 Maine 3	2.98	3.49	5.21	4.12
2003 Maine 4	2.93	3.41	5.01	4.07
2003 Maine 5	2.86	3.27	4.70	3.93
2003 Maine 6	2.81	3.21	4.59	3.90
2003 Maine 7	2.79	3.18	4.54	3.87
2003 Maine 8	2.77	3.19	4.60	3.87
2003 Maine 9	2.84	3.28	4.75	3.95
2003 Maine 10	2.82	3.23	4.66	3.88
2003 Maine 11	2.77	3.19	4.56	3.85
2003 Maine 12	2.73	3.15	4.49	3.82
2003 Maine 13	2.80	3.24	4.68	3.89
2001 Hawaii 1	2.75	3.12	4.93	3.77
2001 Hawaii 2	2.85	3.32	5.19	4.00
2001 Hawaii 3	2.86	3.34	5.11	4.03
2001 Hawaii 4	2.79	3.17	4.70	3.89
2001 Hawaii 5	2.71	3.06	4.44	3.79
2001 Hawaii 6	2.46	2.72	3.79	3.39
average	2.81	3.23	4.73	3.89

Bit rates achieved for compression of scenes from the calibrated 1997 AVIRIS datasets. Results are given in bits/sample.

scene	fast lossless	ICER-3D	JPEG-LS (2-D)	Rice/USES multispectral	differential JPEG-LS	SLSQ	SLSQ-OPT
Cuprite 1	4.89	5.14	7.13	6.00	5.44	5.03	4.90
Cuprite 2	5.02	5.34	7.50	6.13	5.58	5.09	4.97
Cuprite 3	4.92	5.16	7.16	6.00	5.45	5.06	4.92
Cuprite 4	4.98	5.21	7.16	6.05	5.51	5.10	4.96
Jasper Ridge 1	5.04	5.41	7.72	6.17	5.62	5.06	4.95
Jasper Ridge 2	5.02	5.37	7.67	6.12	5.59	5.05	4.94
Jasper Ridge 3	5.07	5.47	7.90	6.19	5.67	5.10	4.99
Jasper Ridge 4	5.07	5.47	7.87	6.22	5.67	5.11	5.00
Jasper Ridge 5	5.02	5.39	7.75	6.14	5.60	5.06	4.94
Low Altitude 1	5.37	5.70	7.81	6.53	5.97	5.38	5.30
Low Altitude 2	5.42	5.76	7.95	6.58	6.02	5.40	5.33
Low Altitude 3	5.30	5.58	7.57	6.42	5.88	5.33	5.23
Low Altitude 4	5.32	5.58	7.53	6.42	5.89	5.37	5.26
Low Altitude 5	5.37	5.63	7.60	6.47	5.91	5.40	5.30
Low Altitude 6	5.29	5.56	7.52	6.42	5.85	5.34	5.24
Low Altitude 7	5.29	5.60	7.64	6.43	5.88	5.34	5.24
Lunar Lake 1	4.99	5.19	6.98	6.02	5.49	5.12	4.99
Lunar Lake 2	4.94	5.14	6.96	5.97	5.44	5.07	4.93
Moffett Field 1	5.12	5.48	7.78	6.24	5.70	5.15	5.03
Moffett Field 2	5.11	5.40	7.57	6.20	5.60	5.08	4.98
Moffett Field 3	4.98	5.12	7.03	5.96	5.41	4.96	4.86
average	5.12	5.41	7.51	6.22	5.68	5.17	5.06

Bit rates achieved for compression of the first half-scenes (256 lines) from four of the calibrated 1997 AVIRIS datasets. Results are given in bits/sample.

dataset	fast lossless	3D-CALIC	M-CALIC	ASAP
Cuprite	4.86	5.23	4.97	4.87
Jasper Ridge	5.02	5.20	5.05	4.83
Lunar Lake	5.02	5.17	4.88	4.76
Moffett Field	5.06	4.92	4.73	4.60
average	4.99	5.13	4.91	4.76

Bit rates achieved for compression of scenes from the calibrated 2001 Arizaro dataset. Results are given in bits/sample.

scene	fast lossless	ICER-3D	JPEG-LS (2-D)	Rice/USES multispectral
2001 Arizaro 1	4.54	4.54	5.76	5.55
2001 Arizaro 2	4.51	4.49	5.71	5.51
2001 Arizaro 3	4.49	4.46	5.65	5.48
2001 Arizaro 4	4.50	4.49	5.71	5.52
2001 Arizaro 5	4.52	4.57	5.88	5.51
2001 Arizaro 6	4.54	4.64	6.12	5.52
2001 Arizaro 7	4.61	4.62	5.91	5.60
2001 Arizaro 8	4.67	4.68	6.01	5.65
2001 Arizaro 9	4.82	4.97	6.67	5.78
2001 Arizaro 10	4.61	4.70	6.11	5.59
2001 Arizaro 11	4.56	4.60	5.98	5.55
average	4.58	4.62	5.95	5.57