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SESSION 1

Data Compression

Interaction of On-Board Transform-Based Lossy Compression Algorithms with EO/IR Focal Plane Nonuniformity Correction Techniques

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ABSTRACT

This paper describes the effect of using lossy transform-based compression on infrared framing sensor data with and without sensor anomaly pre-processing. Significant image degradation persists when ground-based non-uniformity correction processing is implemented after the sensor imagery has been compressed and reconstructed. Various techniques for non-uniformity correction, from low to high processing complexity (i.e., standard two-point gain/offset correction, two-point with bad-pixel replacement, adaptive temporal high pass filtering, adaptive neural net non-uniformity correction, etc.), are applied before and after lossy compression at varying compression ratios. Results using both DCT and Wavelet transform-based compression techniques indicate that on-board real-time compression algorithms and nonuniformity correction must be jointly optimized and that direct application of lossy compression without preprocessing for sensor anomalies reduces not only the compression efficiency and image fidelity, but also the performance of subsequent ground-based nonuniformity correction.

KEY WORDS

Compression, Nonuniformity Correction, Pre-Processing, EO/IR, Image Quality

1.0 INTRODUCTION

Electro-optic/infrared (EO/IR) imagery is increasingly being used in many military and commercial scientific applications. Typical tactical operation of airborne sensors used to obtain this imagery requires that the data be transmitted over buses, between platforms, and/or stored for on-board or non-real time ground processing. Currently, many lower rate airborne EO/IR sensor systems store raw image data on-board or transmit it uncompressed to a ground station where the raw data is processed to correct for sensor anomalies, noise, and other nonuniformities. The corrected data is then used for target detection, image exploitation, or other applications. The demand for faster rate and higher resolution EO/IR imagery is continually increasing and it is apparent that the amount data that can be obtained from airborne sensors in real-time is limited by the bandwidth of available communication channels and recording devices.

Data compression techniques can be used to reduce the volume of data generated by higher rate single- or multi-color EO/IR sensors. Although the use of lossless compression is desirable to maintain data fidelity, many applications require lossy techniques in order to obtain compression ratios greater than 2-3:1. In these applications, significant degradation can occur when ground-based anomaly processing is implemented after the data has been compressed using on-board lossy compression. This paper shows that the residual image artifacts that are a result

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of lossy compression are amplified by sensor noise and focal plane anomalies. Not only is the resulting data quality and compression efficiency reduced, but the effectiveness of subsequent ground-based anomaly processing and image exploitation/target detection are inhibited. *Pre-processing* must be performed to correct the sensor data before it is compressed and sent to a ground station. For platforms with limited processing capability, the processing resources must be shared between the pre-processing and the compression algorithm.

This paper focuses on the reduced performance of ground-based sensor anomaly correction using raw imagery that has been compressed on-board with lossy transform-based compression algorithms (DCT and wavelet techniques). Combinations of three non-uniformity correction techniques, from low to high processing complexity, are applied before and after lossy compression at varying compression ratios. Results using the transform-based compression techniques indicate that some degree of sensor nonuniformity correction is required prior to on-board lossy compression. The amount of non-uniformity preprocessing required is generally sensor specific and depends on the type of data being collected, its intended use, and the quality of the collection device, e.g. imagery from a high quality visible CCD requires much less pre-processing than from an experimental high resolution infrared focal plane proposed for reconnaissance target detection. Although the imagery used for this paper is from a single-band mid-wave infrared focal plane array (IRFPA), the results are applicable to imagery from any sensor with focal plane and read-out nonuniformities in any spectral band range.

1.1 Bandwidth Limitation of Communication Channels and Recording Devices

The Naval Research Laboratory, sponsored by the Defense Airborne Reconnaissance Office (DARO), is developing large-format framing visible (~10k x 10k pixels) and infrared (~ 2k x 2k pixels) reconnaissance camera systems. As seen in Figure 1, the volume of data generated by these emerging *single* color sensors exceed the available bandwidths in both transmission and real-time storage devices. This bandwidth limitation becomes more restrictive with multispectral systems which can have tens to thousands of spectral bands. Assuming use of existing communication channels, there are four apparent options to deal with this large data volume, increase the number of on-board storage devices and progressively transmit data in near-real time, upgrade to developing higher speed real-time storage devices, selectively discard spatial/spectral information, or use appropriate image compression techniques.

For most tactical airborne platforms, the use of additional storage is not an option because aircraft have space, power, and weight limitations. If additional devices could be installed, the effective reduction in the per device data rate is only linearly proportional to the number of additional devices. In these applications, it is highly unlikely that an airborne platform could support forty such devices assuming 40:1 compression is required.

In general, selectively discarding information, whether spectral or spatial, is also a highly undesirable option, although some believe that selectively discarding spectral bands in many hyperspectral sensor applications can be done without significant loss in information. In these cases, the loss is generally minimized since the received spectrum is oversampled resulting in many bands with near unity interband correlations. (Note: For certain applications spectral bands with near unity interband correlations *are* required and for these applications discarding spectral bands or losing *any* spectral fidelity is not an option). Since the purpose of developing large-format high resolution focal planes is to obtain high spatial resolution imagery (without the platform line jitter commonly found in imagery obtained with scanning sensors), subsampling or discarding spatial information to reduce the data rate is also a suboptimal solution. Greater compression performance and better image quality can be achieved by using spatial compression techniques over selectively subsampling and interpolating an image. Although it could be argued that visual quality can still be maintained using subsampling/interpolation, autonomous applications that require analysis of high spatial frequencies can not violate Nyquist sampling without a performance loss. Despite the fact that most spatial compression algorithms filter out high frequencies in order to achieve high compression, intelligent quantization can be implemented and the resulting loss is almost always less than directly subsampling an image[1]. For applications that require retention of all data frames and spectral bands, use of efficient and fast compression techniques (spatial or multispectral) that provide high compression ratios and high data fidelity is often the only viable option.

Single Color Camera, 2 Frames/Sec, 12 Bits/Pixel

Pixels/Frame- (Megapixels)	25	100 (5" film equiv.)	Communication Links	DCRSi (recording)	CDL
Data Rate (Megabits/Sec)	600	2400	**Bandwidth** (Megabits/Sec)	240	274

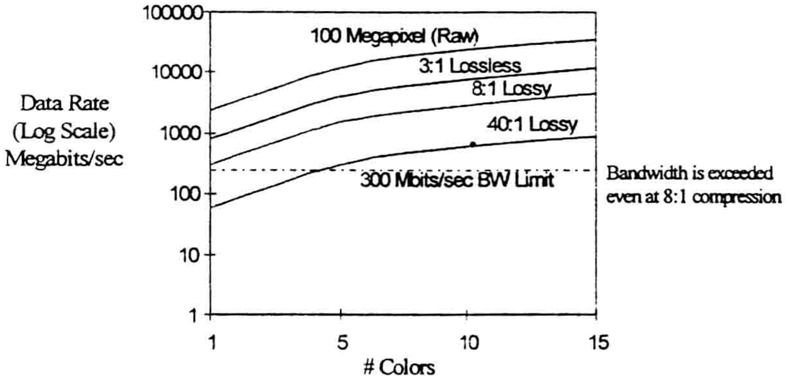


FIGURE 1 Volume of Raw Multispectral Data Generated by Emerging EO-IR Sensors as the Number of Colors Increases

1.2 Image Compression For EO/IR

Compression systems can be classified into two categories, lossless and lossy. Lossless compression systems reconstruct images that are bit-wise identical to the original. For typical single-band 8-bit imagery, the average lossless compression ratio is on the order of 2:1 (~3:1 for lossless *multispectral* compression), but depending on the specific image statistics and digital pre-processing, the peak compression ratio could be higher (or lower). Although it may be desirable to use lossless compression, many applications require higher compression ratios. Lossy compression systems can attain much higher compression ratios by allowing some loss in the image fidelity. A trade-off exists between the compression ratio and the data fidelity required. Many lossy compression systems, sometimes referred to as "near lossless" or "visually lossless", produce images that have "imperceptible" differences in the visual quality as compared to the original. The imagery generated by near and visually lossless compression systems are in fact lossy and are only "visually lossless" for *certain* applications; many factors influence the perception or lack of lossy artifacts (i.e. viewing distance, desired spatial frequencies, local image contrasts, etc.[2]). Care must be taken when visually lossless imagery is used for scientific/military analysis or machine-based detection algorithms because even though inherent distortions may be visually imperceptible at a given viewing distance, the data fidelity is in fact corrupted and may degrade the performance of the desired application.

Operational system requirements can vary widely with respect to the desired image quality and compression ratio. Compression systems must be adaptable and robust in order to satisfy these changing mission needs. The selection of the appropriate compression technique (e.g. adaptive differential pulse code modulation (ADPCM), discrete cosine transform (DCT), predictive vector quantization (PVQ), wavelets) depends on several application specific criterion: the desired compression ratio, the resulting image quality, image robustness, and the many system implementation issues (e.g. processing speed, power and memory requirements, etc.). Wavelets has shown great promise in maintaining high quality imagery at both low *and* high compression ratios and is robust enough to efficiently compress different image classes without altering algorithms or updating codebooks[3,4,5]. Older techniques such as ADPCM and standard baseline DCT can not achieve comparable image quality levels at high compression ratios (>15:1). Because of the loss in data fidelity that generally occurs at higher compression ratios with older techniques, the use of lossy compression techniques with EO/IR data has primarily been used for quick-view, browsing, or post-transmission archiving applications. Since the demand for high fidelity EO/IR imagery with higher spatial and spectral resolution is increasing, improved lossy compression algorithms are being developed and standardized (e.g. JPEG 2000) for applications other than browsing and low compression applications[6,7]. (Note: Proponents of the DCT maintain that good image quality at high compression ratios can be achieved through human visual system quantization and post-processing de-blocking, although the November 97 ISO JPEG 2000 compression evaluations proved that advanced wavelet algorithms can outperform DCT both in objective and subjective metrics.)

Even after the selection and adoption of the competitive JPEG 2000 compression algorithm standard, *direct* application of compression on EO/IR airborne sensor platforms without including appropriate anomaly preprocessing will produce imagery with less than optimal image quality. What is required is an integrated preprocessing/compression system as shown in Figure 2.

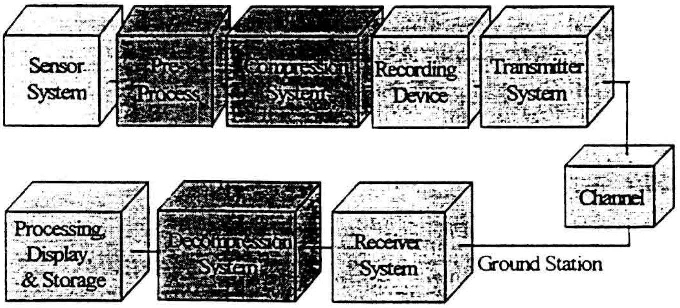


FIGURE 2 Block Diagram of an Integrated Pre-processing/Compression System for Real-time Airborne Compression and Transmission of EO/IR Imagery

2.0 INTEGRATED SYSTEM SIMULATION

The purpose of this work is to quantify the interaction of transform-based lossy compression and nonuniformity correction in order to determine the optimal combination of both processes in an integrated airborne system. There are many sources of nonuniformity in sensor systems ranging from sensor design specific issues to non-design specific issues such as geometric distortion (spatial skewing and multispectral misregistration), radiometric distortion (atmospheric conditions, focal plane anomalies, scene illumination, and viewing geometry) and inherent sensor noise[8]. It is the focal plane anomalies and sensor noise which is of interest in this work. Sensor noise can be generated by many system components including the focal plane itself (interpixel nonuniformities, bad pixels/columns, blinkers, runners, etc.), the A/D converters, and the sensor readout electronics. Other noise sources not considered in this paper include recording medium and transmission channel errors.

Imagery from IRFPAs is typically processed using nonuniformity correction to remove stationary noise in neighboring detector pixels before the image is displayed or processed[9]. Since it is common for the IRFPA levels to drift and for the background flux level to change, the effectiveness of pre-imaging nonuniformity correction decreases during sensor operation. In applications where the imagery is recorded uncompressed or compressed losslessly, residual nonuniformities can be removed successfully with post-processing at a later time. When lossy compression is added to the sensor system, it is shown that adaptively correcting nonuniformities at the sensor prior to compression becomes necessary in order to preserve image quality and retain the effectiveness of the compression. In sensor platforms with limited processing capabilities, the nonuniformity correction and compression processes must appropriately share system resources. Figure 3 outlines several integrated nonuniformity/compression designs with various "on-board" processing requirements ranging from high to low computational complexity. All paths were simulated to determine the combined effect of nonuniformities and lossy compression on the performance of subsequent nonuniformity correction techniques.

2.1 *Nonuniformity Correction*

The nonuniformity approaches include Two-Point Gain/Offset Correction (GOC), Bad Pixel Replacement (BPR), Adaptive Temporal High Pass Filtering (NUC), and Adaptive Neural Network Nonuniformity Correction (ANUC). The GOC processing is a standard pre-imaging technique used to calibrate each detector pixel using reference hot and cold temperature sources. BPR is an adaptive thresholding technique which replaces bad pixels (dead or saturated) with valid neighboring pixels. The NUC process removes drift and fixed pattern noise through adaptive temporal high-pass filtering while the ANUC performs a similar function using adaptive neural network techniques [9]. The processing requirements for these techniques (GOC...ANUC) range from low to high, respectively.

2.2 *Transform-based Image Compression*

Three compression algorithms were used in this study including the baseline DCT-based JPEG Still Image Compression Standard [10,11](JPEG), the SPIHT Wavelet-based algorithm by Said and Pearlman [3], and the Wavelet-based Trellis Coded Quantization algorithm by Marcellin [4] (Wavelet). Due to similarities in the performance of the two wavelet algorithms (both are competing technologies for the future ISO JPEG 2000 compression standard), the presented wavelet results are averaged from SPIHT and TCQ and compared relative to the current DCT-based JPEG standard. Although non-transform-based compression techniques (i.e. Vector Quantization) can produce good results with sensor specific codebook training, transform-based JPEG and Wavelets were used to remain consistent with projected future image and transmission format standards [6-7].

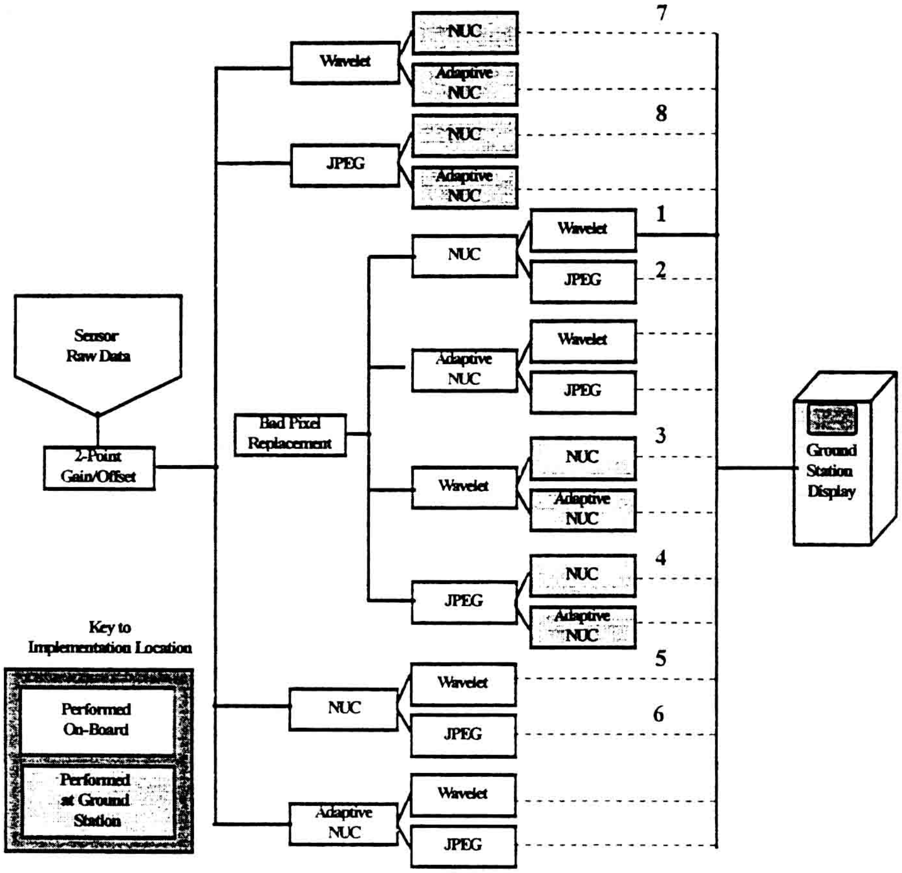


FIGURE 3 Many different combinations of nonuniformity pre-processing and compression are possible by sequentially choosing each of the many paths. All combinations were simulated and results of the indicated eight are shown in Table 2.

3.0 Simulation Results

The data used in the simulations consist of 4650 frames of 128 x 128 12-bit midwave infrared (MWIR) imagery. The quality factor (q) used in the JPEG compression was adjusted to obtain compression ratios as near to 10:1 and 40:1 as possible for the entire frame sequence. The wavelet compression bits/pixel rate for both SPIHT and WTCQ was then selected in order to match the file sizes of the JPEG compressed files. This ensured that comparisons between JPEG and Wavelet compressed imagery were based on identical file sizes. Since there is no way to determine the exact original "clean" image from the sensor, all image quality comparisons assume that the images produced from the GOC-BPR-NUC/ANUC (no compression but sensor noise removed) paths are the desired images.

TABLE 1 Image Statistics for IR Test Imagery and Entropy Changes Caused by Nonuniformity Correction Processing

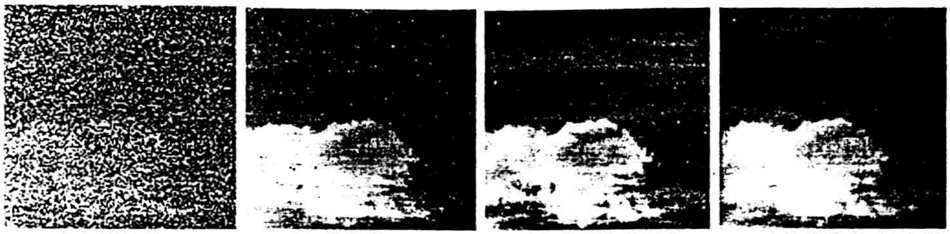
Image #875	Pixel Correlation	1st Order Entropy	2nd Order Entropy
RAW	0.26	10.57	10.86
GOC	0.88	9.61	7.73
GOC-BPR	0.88	9.61	7.72
GOC-NUC	0.91	8.98	6.36
GOC-ANUC	0.99	9.75	6.52

Table 1 shows typical correlation and entropy statistics of the imagery. These parameters aid in determining the information content of the data from an information theory point of view and give an estimate of the theoretically achievable lossless compression ratio. Generally, continuous-tone gray-scale imagery of natural scenes have a high interpixel (nearest neighbor) correlation (~0.9 Markov Model). Because of the inherent nonuniformities, the raw imagery has far less interpixel correlation. With application of the nonuniformity correction algorithms, the corrected imagery is consistent with the expected model. In addition, the first and second order entropies[12], which give an indication of the uncorrelated and correlated symbol information content (i.e. bits/symbol, where a symbol in this case is a pixel), show that the raw imagery has a broad dynamic range and fully utilizes most of the allocated 12-bits (~10/12). The second order entropy statistics show the cumulative loss in entropy of the imagery as the data is processed by the listed nonuniformity techniques. Except for the raw uncorrected data, the expected drop in the second order entropy that occurs with high interpixel correlation is observed. The relatively large second order entropy of the raw imagery indicates the spatially uncorrelated nature of the nonuniformities.

TABLE 2 Mean Absolute Error and Maximum Absolute Error for Different Nonuniformity Correction/Compression (10:1) Combinations

Path #	Data Path (10:1 Compression Ratio)	AVG |Error|	Max |Error|
1	GOC-BPR-NUC-Wavelet	7.4	56
2	GOC-BPR-NUC-JPEG	13.8	236
3	GOC-BPR-Wavelet-NUC	13.1	101
4	GOC-BPR-JPEG-NUC	17.0	242
5	GOC-NUC-Wavelet	17.1	4095
6	GOC-NUC-JPEG	22.2	4093
7	GOC-Wavelet-NUC	22.8	4095
8	GOC-JPEG-NUC	25.9	4091
-	RAW-JPEG-GOC vs GOC	104.2	4095

Table 2 shows the mean absolute error and maximum absolute error between the GOC-BPR-NUC images (desired image) and the images processed by the listed data path name as illustrated in Figure 3. The first two rows show the error results when all nonuniformity correction is done "on-board" prior to compression and basically indicate the amount of degradation caused by nominal 10:1 compression implemented by the Wavelet techniques and JPEG, respectively. As expected, the highest performance occurs when compression is applied to the cleanest image. The next six rows show results from other combinations of nonuniformity correction and compression. Very notable is the impact of not using BPR. Comparing GOC-Wavelet-NUC (almost direct implementation of lossy compression) to GOC-BPR-Wavelet-NUC, the average error and maximum error are 21.5 and 4095 compared to 16.2 and 101. With the entropy of the imagery reduced from the NUC processing, the errors shown in Table 2 result in relatively significant subjective image quality degradation. The ninth entry compares the error when the raw image is compressed prior to standard two-point gain offset correction relative to performing gain offset correction directly. These results show if no additional nonuniformity correction is performed, the average pixel degradation is over 100 gray levels in error even at a moderate compression ratio of 10:1. Results using the ANUC algorithm in place of the NUC yielded comparable objective results as the ones presented in Table 2. The image quality advantage of the ANUC compared to the NUC is more easily shown in the subjective analysis shown below.



(a) RAW (b) GOC (c) GOC-NUC (d) GOC-ANUC

(e) RAW-JPEG 10:1-GOC (f) GOC-JPEG 10:1-NUC (g) GOC-NUC-JPEG 10:1

FIGURE 4 Performance Results Comparing the Degradation of Nonuniformity Correction after Lossy Compression (10:1)

Figures 4 (a)-(d) show the visual improvement from raw imagery to imagery that has been two-point gain offset corrected and processed with NUC and ANUC. The visual advantage of ANUC relative to NUC is shown in (c) and (d). Figures (b) and (e) compare the image obtained with direct gain offset correction of the raw image (a) and the image obtained by direct 10:1 JPEG compression of the raw image followed by GOC. Note that if *lossless* compression had been used (b) and (e) would have been identical. To show the performance degradation of nonuniformity correction when used with lossy compressed imagery, Figures (c), (f), and (g) are presented. Note that in (f), even though both GOC and NUC have been applied, the image is even more degraded than the GOC image without NUC (b). This degradation occurs since the lossy compression artifacts change slightly from frame to frame and pass uncorrected through the NUC processing. In this situation, the performance of both the NUC processing and the compression are reduced. Of all the techniques, the best performance was obtained through the GOC-BPR-ANUC/NUC-Wavelet data paths. A trade-off exists between the speed of the NUC and the increased performance of the ANUC. Benchmarked on a DEC Alpha, the processing time required for all 4650 frames using ANUC, including IO file transfers, was six times as long compared to BPR-NUC processing. Although the image quality is not as high, a good nonuniformity correction processing compromise is the GOC-BPR-NUC-Wavelet path as shown in Figure 5. Results for the GOC-BPR-Wavelet-NUC path are also shown.