The Effects of Data Compression on SAR Change Detection

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Abstract

The performance of coherent and non-coherent change detection algorithms is evaluated using complex SAR data that have been processed with various data compression approaches; the hope is that it may be possible to achieve higher compression ratios than could be achieved using classical image compression approaches such as BAQ (block adaptive quantization). BAQ compression is typically applied to raw (I,Q) SAR phase-history data, and our studies show that to obtain reasonably good coherent change detection (CCD) performance from a baseline CCD algorithm, BAQ compression requires at least 4-bit quantization for each of the I and Q phase-history data samples; since our original full-precision data is 8-bits I and 8-bits Q, the best compression ratio (CR) that could be achieved using BAQ compression was a factor of 2. Our goal is to increase the amount of compression while achieving the same quality of change detection using more sophisticated wavelet-based approaches such as “compressive sensing” or “set partitioning” (SPIHT). This paper demonstrates a wavelet-based compressive sensing approach that gives CR = 3 with comparable CCD performance; we also demonstrate a wavelet-based SPIHT approach that gives CR = 4 with comparable CCD performance.

1. Introduction

Figure 1 shows a typical SAR image gathered by the General Dynamics Data Collection System (DCS). The image size is 4096x4096 pixels and the resolution of the data is 1ft by 1ft. The red box superimposed on the image shows a region of interest containing two interesting change detection scenes that will be studied in this paper. Non-coherent change detection studies focus on a scene containing parked vehicles (the “vehicle scene”); coherent change detection studies focus on a scene containing subtle man-made disturbances due to people walking in a grassy area (the “racetrack scene”).

Figure 1: Typical SAR image gathered by the General Dynamics Data Collection System (DCS).
Figure 2 shows the 1024x1024 region of interest containing these change detection scenes. Figures 3 and 4 show the CCD and NCD change images obtained from comparisons of a test image and a previously gathered reference image; several detected changes are pointed out on the NCD and CCD images. Note that only coherent change detection has detected the “racetrack” in the grass area — and although the change in amplitude between the reference and test images is too small to be detected, the change in phase (i.e., the “coherence”) between the reference and test images is sufficient to detect this subtle change.

Figure 2: Region of interest containing a grass area and an area containing vehicles; these areas contain interesting change detection objects used in these coherent (and non-coherent) studies.

Figure 3: CCD image of region of interest; Vehicle arrivals and departures are easily detected; Note that the “racetrack” is detected in the grass area.

Figure 4: NCD (amplitude ratio) image of region of interest; Vehicle arrivals and departures are easily detected, but the “racetrack” is not detected.
2. Review of Baseline Block Adaptive Quantizer (BAQ) Compression Performance

This section demonstrates compression performance achieved with the BAQ compression approach using bit-depths of 8-bits, 6-bits, 4-bits, 3-bits, and 2-bits. At each of these quantization levels we evaluate coherent change detection performance using test and reference imagery of the “racetrack scene” and we determine the smallest number of bits that provide reasonably good CCD performance for this scene. Figure 5 shows a 128x128 pixel image of the “racetrack” CCD image, generated from full-precision 8-bit phase-history data samples. A binary mask of the racetrack (Figure 6) was constructed by appropriately thresholding the CCD image.

Figure 5: CCD image of the “racetrack scene” generated using 8-bit phase-history data samples. The average coherence of this CCD image is 0.9145.

Figure 6: Binary mask constructed by thresholding the CCD image shown in Figure 5 at coherence level of 0.7. The pixels in red and blue correspond to “target” and “clutter”.

We constructed CCD images corresponding to the various bit-depths of interest (8-bits, 6-bits, ..., 2-bits) and determined the number of pixels inside the “target” area that were less than 0.7 (these pixels are correctly detected changes); we also determined the number of pixels in the “clutter” area that were less than 0.7 (these pixels are falsely detected changes). Figure 7 presents the results of this study. As the figure shows, the false alarm probability begins to increase rapidly using fewer than 4-bits. Figure 8 shows the corresponding CCD images for 6-bit, 4-bit, 3-bit, and 2-bit quantization.

Figure 7: Plot showing correct and false detected changes in the “racetrack scene” versus bit-depth using images formed from BAQ compressed phase-history data. For bit-depths below 4-bits, the number of false changes increases very rapidly.
3. Wavelet Compression of Phase-History Data

Figure 9 shows a simplified block diagram of the approach used to obtain an equivalent wavelet representation of the complex phase-history data. The inphase (Iph) and quadrature (Qph) data are transformed into corresponding wavelet data arrays through a matrix-transformation, Tph_to_wav. BAQ quantization is applied to the wavelets, reducing the bit-depth of the data linked to the ground station. The reduced bit-depth wavelets are transformed in the ground station through the matrix-transformation Twav_to_img, producing the complex SAR image.
Figure 10 shows a comparison of CCD images of the racetrack image for various levels of bit-depth used in BAQ-quantizing the complex wavelet data. The average coherence for the SAR image obtained from the original unquantized (8-bits I, 8-bits Q) wavelet data gives the “ideal” coherence value of 0.9145, and this CCD image is identical to the SAR image obtained from the original phase-history data. As illustrated in the figure, compression of the wavelets at the 4-bit level gives almost no discernible loss in visual quality of the corresponding CCD image – and the average coherence = 0.9071. The figure also shows that compression of the wavelets at the 3-bit level yields very good CCD image quality, with its average coherence = 0.8901. Significant degradation in CCD performance is observed when the wavelets are compressed at the 2-bit level.

The CCD change images shown in Figure 10 support that claim that 3-bit wavelet compression (CR = 8/3) provides CCD performance comparable to 4-bit BAQ phase-history compression (CR = 8/4). We will show later in the paper that setting small wavelet coefficients to zero, resulting in a “sparse” wavelet array — and applying compressive sensing approaches can provide additional compression gain.
4. Analysis Results for the “Vehicle” scene

This section gives a summary of our change detection studies using SAR imagery of the vehicle scene. Figure 11 shows an image containing a single vehicle parked in the lower left portion of the image; this image, denoted image #1, is the “reference image” in these change detection studies. A second image, gathered at a later time, is used as the “test image” in these change detection studies; this second image, denoted image #2, is shown in Figure 12. During the time interval between the gathering of image #1 and image #2, a second vehicle entered the scene and parked next to vehicle #1; image #2 shows both vehicles quite clearly, and it is interesting to note that the image of vehicle #1 has been somewhat modified due to the close proximity of vehicle #2 to vehicle #1. This change in the appearance of vehicle #1 is demonstrated in the NCD and CCD images obtained in these studies.

Figure 11: SAR image #1, showing a parked vehicle (denoted vehicle #1) in Bottom left section of the image.

Figure 12: SAR image #2, showing an additional vehicle (denoted vehicle #2) has arrived next to vehicle #1.
Figures 13 and 14 show side-by-side comparisons of the NCD image and CCD image for 8-bit wavelet processing and 4-bit wavelet processing. The images shown in these figures illustrate that comparable NCD (and CCD) performance is achieved using Wavelets quantized at 4-bits. In both Figures 13 and 14, the arrival vehicle #2 is clearly shown in blue (left image); also, note the red blob corresponding to a change within the area occupied by vehicle #1 – this most likely is from a scatterer on vehicle #1 that has been blocked from radar view by vehicle #2. The CCD images (right images) are self-similar, indicating negligible degradations with 4-bit Wavelet processing. The walkway located near the parked vehicles is not detected in the NCD change images but is detected in the CCD images due to the low clutter-to-noise ratio of the radar return from the walkway.

Figure 13: Comparison of NCD (left) and CCD (right) images generated from the uncompressed (8-bit) images shown in Figures 11 and 12. The arrival vehicle (vehicle #2) is reliably detected and is shown in blue (left image). Also, note the red blob corresponding to a departure-change within the area occupied by vehicle #1 – this is most likely due to a scatterer on vehicle #1 being blocked from radar view by vehicle #2.

Figure 14: Comparison of NCD and CCD images obtained from 4-bit wavelet-compressed complex images.
Figures 15 and 16 show side-by-side comparisons of NCD and CCD images formed from 3-bit wavelets and 2-bit wavelets. The change images in Figure 15 illustrate that good CCD and NCD performance is obtained using images formed from 3-bit quantized wavelets. Figure 16 illustrates that the images formed from 2-bit quantized wavelets resulted in significantly degraded CCD performance, but reasonable NCD performance was obtained.

Figure 15: Comparison of NCD and CCD images obtained from 3-bit wavelet-compressed complex images.

Figure 16: Comparison of NCD and CCD images obtained from 2-bit wavelet-compressed complex images.
Section 5: Implementation of CS Compression

The previous section of this paper summarized studies of an approach for achieving compression of SAR data using wavelets; the goal of those studies was to quantify the amount of compression achievable by reducing the bit-depth of the wavelets used in reconstructing an image. We hope to achieve additional gains in compression ratio using a wavelet-based Compressive Sensing approach by first using minimum bit-depth wavelets, next converting these wavelets into a sparse representation, and finally followed by taking a minimum number of random projections of the sparse wavelet data — these measurements (ie, random projections) are transmitted to the ground where SAR change detection exploitation is performed. In the ground station, the sparse-wavelet dataset is reconstructed from the random projections using a convex programming algorithm such as L1-magic [3]; the corresponding complex SAR image is then formed from this reconstructed sparse-wavelet representation. The CCD-processing results presented in Section 1 of this paper support the use of wavelet bit-depths of 3 or 4 bits to obtain reliable coherent change detection. Using this finding, in this section of the paper we investigate the effects of CS-based image reconstruction on the performance of coherent change detection. We evaluate CCD performance using the “racetrack” image and the “vehicle” image.

Figure 17 shows a block diagram of the approach we implemented in these studies. As the figure shows, the phase-history data are transformed into an equivalent wavelet representation; these wavelets are then quantized (for these studies we used a bit-depth of 4-bits, corresponding to a compression ratio of 2 for the first stage of the figure). The second stage of the CS algorithm involves taking a set of random projections (measurements) of the quantized wavelet dataset, followed by reconstruction of the SAR image.

![Block diagram of CS-based data compression approach](image)

Figure 17: Block diagram of CS-based data compression approach using "M" random projections of quantized wavelets; wavelet reconstruction is performed using the L1-magic algorithm; image reconstruction is performed using an inverse wavelet transformation matrix, inv(Wmat).
Figures 18 and 19 show CCD images obtained from reconstructed imagery of the racetrack and vehicle scenes. Reference and test images were CS-processed from their 4-bit wavelet representations; the side-by-side CCD images shown in these figures illustrate CCD performance with and without CS compression applied to the data. The CS-compressed images were obtained from 2730 random projections of 4-bit wavelets. As indicated in the figures, the overall compression ratio for these CS-compressed images is the product of \((8\text{-bits}/4\text{-bits}) \times (N/M)\) where \(N = 64 \times 64\) and \(M = 2730\) projections, thus the end-to-end compression ratio \(CR = 3\) was achieved.

Figure 18: CCD images of racetrack scene. Left: CCD image obtained using 4-bit wavelets; Right: CCD image obtained using 2730 random projections of 4-bit wavelets. Total end-to-end compression ratio for right image is 3.

Figure 19: CCD images of vehicle scene. Left: CCD image obtained using 4-bit wavelets; Right: CCD image obtained using 2730 random projections of 4-bit wavelets. Total end-to-end compression ratio for right image is 3.
Section 6: Compression Results using SPIHT Wavelet Coding/Decoding

This section presents an evaluation of a state-of-the-art compression approach [5], set partitioning in hierarchical trees (SPIHT); in this evaluation we compare the performance of our CCD algorithm using a variety of available wavelet transforms. SPIHT is an image compression algorithm that exploits the similarities across sub-bands of a wavelet decomposition. The algorithm codes the most significant wavelet transform coefficients first; the coefficients can be transmitted such that an increasingly refined copy of the original image is progressively obtained. The user selects a desired average bit-rate for encoding/decoding the given image (the SAR image is represented by an equivalent Wavelet array) and the SPIHT algorithm processes the number of most significant wavelet coefficients satisfying the desired bit-rate — and the SPIHT algorithm can yield fractional bit-rates. We selected desired average bit-rates of 0.25, 0.5, 1, 2, 3, 4, 6, and 8 bps — and we evaluated CCD coherence metric results achieved using db1(Haar), db4, db10, Meyer, and bior4.4 wavelets versus the desired average bit-rates. Figure 20 presents the CCD coherence values obtained using these wavelet types with level-3 wavelets. As the figure shows, comparable performance results are obtained for all wavelet types tested, except for the Haar (db1) wavelet which gave the worst results and failed to provide finite coherence values for 0.25 and 0.5 bps. The bior4.4 appears to be the best wavelet type to use for this scene (the racetrack scene) — and at 2 bps this wavelet achieved the CCD image coherence > 0.9. We found that SPIHT compression using Bior4.4 level-3 wavelets provided the best compression performance (CR = 4) for the coherent change detection “racetrack data” used in these studies.

![Figure 20: Compression performance results for the "racetrack" data using SPIHT Wavelet compression. Curves of CCD "coherence" versus bit-rate obtained using SPIHT encoding/decoding are shown for a variety of level-3 wavelet types.](image-url)
Section 7: Summary

This paper presented a study of SAR data compression and its effect on the performance of coherent and non-coherent change detection algorithms. The goal of these studies was to determine the minimum quantization bit-depth of complex data that is to be transmitted through a data link to a ground station, where exploitation processing of the complex SAR imagery is to be performed; since exploitation of the imagery involves the detection of stationary targets using change detection algorithms, an additional goal of these studies was to minimize degradation to change detection performance. Coherent change detection was the main focus of these studies, and the effects of complex data compression on the ability of a coherence-based CCD algorithm to detect vehicle changes ("arrivals" and "departures") and subtle man-made changes such as the "racetrack" were evaluated. Non-coherent change detection was studied using a ratio-based change detector on amplitude images; the NCD algorithm was not able to detect the racetrack, but arrival and departure vehicles were easily and reliably detected. The following paragraphs provide a summary of the major results demonstrated in the paper.

Section 2 reviewed the well-established BAQ compression of SAR complex phase-history data and showed that using 4-bit quantization (4-bits I and 4-bits Q) provided very good CCD performance against subtle man-made disturbances such as depicted in the "racetrack" scene; lowering the bit-depth below 4-bits caused a rapid increase in false changes detected in the undisturbed high-coherence neighboring grass areas; this result was demonstrated in Figures 6 and 7. In Section 3, the complex phase-history data were transformed into an equivalent wavelet representation using a linear transformation, Tph_to_wav; this transformation was equivalent to processing the complex phase-history array using an unweighted 2D FFT, followed by conversion to wavelets. The goal of this study was to determine the minimum quantization bit-depth of complex wavelet data that could be transmitted through a data link to a ground station, where the compressed wavelet data is then inverse-transformed into a complex SAR image using a linear transformation, Twav_to_img. This approach showed that 3-bit quantized wavelets provided good CCD performance for the "racetrack" scene.

Section 4 presented reference and test SAR imagery of the "vehicle" scene; the reference image contains a single parked vehicle and the test image contains an additional "arrival" vehicle. NCD and CCD images of this scene using quantized wavelets were compared, side-by-side, in Figures 13,14,15, and 16. Reasonable CCD performance was obtained using 3-bit quantized wavelets with the "vehicle" scene; good NCD performance was obtained using 2-bit quantized wavelets. In Section 5, the concept of compressive sensing was introduced; the goal is to achieve additional gains in compression ratio using a wavelet-based compressive sensing with minimum bit-depth wavelets, converting these wavelets into a sparse representation, followed by taking a minimum number of random projections of the sparse wavelet data — these measurements (i.e., random projections) are transmitted to the ground station where the sparse-wavelet dataset is reconstructed from the random projections; the complex SAR image is then formed from the reconstructed sparse-wavelet representation. Example CCD images demonstrating this approach are presented in Figures 18,19 for the "racetrack" and "vehicle" scenes, respectively; compression ratios = 3 are shown in the figures. All wavelet results discussed above were obtained using level-1 Daubechies-3 wavelet transforms.

Section 6 presented compression performance using SPIHT wavelet compression. We selected desired average bit-rates of 0.25, 0.5, 1, 2, 3, 4, 6, and 8 bps – and we evaluated the CCD image coherence obtained using a variety of wavelet types and levels. Figure 20 showed the coherence versus bit-depth for the racetrack image; these results were obtained using level-3 wavelets. The curves in Figure 20 showed that SPIHT compression with Bior4.4, level-3 wavelets provided the best compression (CR = 4) for the CCD algorithm using the "racetrack" scene.

References