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Executive summary

Advanced on-board SAR data compressor

Problem area
Future SAR sensors on-board satellites require higher bandwidths, better sensitivity, multiple modes, etc. The resulting increase of payload data rates automatically leads to a need for better on-board compression techniques of the raw SAR data than the conventional Block Adaptive Quantization (BAQ) method.

Description of work
In this report a novel approach to the on-board compression of raw SAR data is presented, the so-called Entropy-Constrained BAQ (ECBAQ). It is more efficient than the BAQ with respect to the resulting coding rate. It is shown that, especially with multi-mode SAR instruments, a significant improvement of the compression factor is possible due the property that the coding rate can be accurately tuned to any 2-D bandwidth.
Moreover, the compression performance of the ECBAQ can be further improved when it is applied in the frequency domain. The feasibility of the application of FFT-ECBAQ in space is briefly addressed. Due to the space-qualification program of the PowerFFT, the world's fastest FFT-oriented DSP, the application of FFT-ECBAQ on-board satellites is feasible.

Results and conclusions
For the compression of raw data from multi-mode SAR instruments, Entropy Constrained Block Adaptive Quantization is an attractive option. In the time domain the compression results exceed that of BAQ by more than 20%. Moreover, in a frequency-domain configuration, the average compression ratio is more than twice that of BAQ with the same image quality. The implementation on-board satellites is feasible due to the availability of the PowerFFT, a very fast FFT-oriented DSP ASIC, which is currently being space-qualified.

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This report is based on a presentation to be held at IGARSS 2006, IEEE Intern Geoscience and Remote Sensing Symposium, 31 July – 4 Aug. 2006, Denver

Applicability
The presented compression method is an attractive compression method for application on all future SAR satellites.

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Advanced on-board SAR data compressor

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Summary

This paper presents a new on-board SAR data compressor which outperforms the conventionally used Block Adaptive Quantization (BAQ) compressor. For a multi-mode SAR instrument the compression ratio can be doubled when frequency-domain Entropy-Constrained Block Adaptive Quantization is applied.

Keywords-SAR; data compression; satellite

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Abstract—**This paper presents a new on-board SAR data compressor which outperforms the conventionally used Block Adaptive Quantization (BAQ) compressor. For a multi-mode SAR instrument the compression ratio can be doubled when frequency-domain Entropy-Constrained Block Adaptive Quantization is applied.**

Keywords-SAR; data compression; satellite

1 Introduction

We present a novel technique for on-board compression of raw SAR data, the so-called Entropy-Constrained Block Adaptive Quantization (ECBAQ)[1]. This algorithm has been developed recently for next generation remote sensing satellites with multi-mode SAR instruments. Such advanced SAR sensors generate significantly higher payload data rates due to their improved spatial resolutions, higher sensitivity, and extended duty cycles, which lead to a need for better on-board compression techniques of the raw SAR data than the conventional techniques based on Block Adaptive Quantization (BAQ).

In general, raw SAR data compression is not lossless. The digitization and coding process introduce additional noise and effects on the SAR images to be processed. Two important quality parameters are the Signal to Quantization Noise Ratio (SQNR) and the rms Phase Noise, as apparent in the processed image. For example, with ENVISAT in practice a BAQ-based compression ratio of 2 is used, resulting in SQNR ~ 22 dB and rms Phase Noise ~ 11° in the Single Look Complex image [1]. Simulations have shown that ECBAQ-based compression on raw SAR data would result in an improved compression ratio of ~ 4 to 5 while maintaining excellent image quality (similar to BAQ), especially when it is applied in the frequency domain.

ECBAQ has been described in [2] and [3]. Recently in [4] a new version of ECBAQ has been presented using a rate control loop which is optimized for frequency domain applications. Furthermore, in [5] we have shown that the algorithm can be efficiently implemented using advanced space-qualified devices.

Section II gives a brief introduction to this ECBAQ variant. In Section III we present how ECBAQ can be applied in the time domain in the case of a multi-mode SAR. Section IV explains how the compression ratio

[1] Patent Application PCT/NL2004/000479

can be further improved by operation in the frequency domain. The method has been selected as the baseline compression method for the TerraSAR-L satellite [5].

2 Entropy-Constrained Block Adaptive Quantization

ECBAQ divides the input data into blocks of, for example, 128 samples, which is similar to BAQ. The digital numbers are multiplied by a scaling factor and then uniformly quantized. The stepsize is smaller than in the case of BAQ and the range is larger. After quantization, a variable-length encoder, for example a Modified Huffman encoder, compresses the data, after which a byte forming function is used to convert the data into a byte format. After each block the rate control updates the scaling factor. It is possible to accumulate the encoded word lengths and calculate the average coding rate of the completed block. This actual coding rate is compared with the required rate. Dependent of the result, the scaling factor can be increased, decreased, or left unchanged.

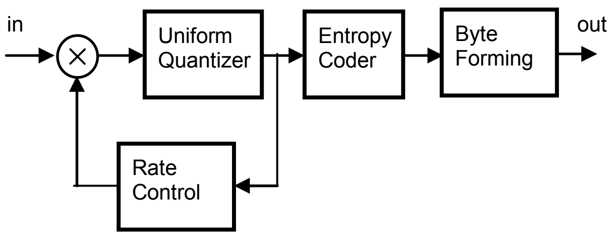

Figure 1. Block diagram of ECBAQ encoder

In [4] an improved version of ECBAQ has been presented with another rate control loop mechanism. Instead of the average coding rate, now the counted number of samples with amplitude smaller than the reference standard deviation (σ_{REF}) is used. It is assumed that the clutter signal has a Gaussian probability density function. Hence the counted number of samples with absolute value < σ_{REF} is related to the actual standard deviation. Based on this comparison the scaling factor is updated at each block transition. The advantage of this method is that the rate control is less dependent on signal peaks which are caused by bright scatterers. Refer to figure 1.

Let C_L be the total number of absolute values < σ_{REF} within one block. Then

$$\overline{C_L} = M \int_0^{\sigma_{REF}} \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-0.5(x/\sigma)^2\right] dx$$

with M = number of samples/block.
At the block transition moment, C_L is compared with a lower and an upper limit to decide whether the step size S has to be increased or decreased:

$$S_{k+1} = S_k / D \qquad if\ C_L / M > \Delta_1$$

$$S_{k+1} = S_k * D \qquad if\ C_L / M < \Delta_2$$

D is a constant. $D = 1.41$ (3 dB) gives good performance results. The limits Δ_1 and Δ_2 correspond to distributions with $\sigma = \sigma_{REF}$ +1.5 dB and $\sigma = \sigma_{REF}$ -1.5 dB , respectively,

$$\Delta_1 = \int_0^{\sigma_{REF}} \frac{1}{\sigma_{REF}\sqrt{2\pi / D}} \exp(-0.5(\frac{x\sqrt{D}}{\sigma_{REF}})^2)dx$$

$$\Delta_2 = \int_0^{\sigma_{REF}} \frac{1}{\sigma_{REF}\sqrt{2\pi D}} \exp(-0.5(\frac{x}{\sigma_{REF}\sqrt{D}})^2)dx$$

Note that the step size changes are derived from the quantized values. Hence the decoder can perform the same operation and it is not necessary to multiplex the standard deviation codes into the codeword stream as is done with BAQ.

The SQNR of ECBAQ with such a rate control loop exceeds the SQNR of BAQ by 2.2 dB at 4 bits/sample [6]. Moreover, ECBAQ allows non-integer bit rates [2]. Some other advantages of this version of ECBAQ are: there is no block buffer needed; the instantaneous dynamic range can be large; the performance of the control loop is independent of the implemented entropy code.

3 ECBAQ in the Time Domain

In this section we will explain how ECBAQ can be applied in the time domain in the case of a multi-mode SAR.

For ECBAQ, the SQNR in the time domain can be approximated by

$$SQNR_{TD} \approx 6 * R - 1.6 \quad dB$$

where R can be any non-integer coding rate (bits/sample).

For BAQ, in practice only a rate of 4 bits/sample is used resulting in $SQNR_{TD}$ ~20 dB.

In advanced SAR systems the effective chirp bandwidth is tuned to the current swath for optimal performance and can be significantly smaller than the 0.5 sample rate. Furthermore the bandwidth of the Doppler signal that is processed on ground is usually smaller than the Pulse Repetition Frequency (*PRF*) to avoid high azimuth ambiguity levels. The TerraSAR-L SAR instrument is able to operate in six different modes. Two ScanSAR and three high-resolution modes use 6 different swaths. The Wave mode uses 4 swaths. In total there are 34 combinations of mode and swath, each corresponding to a different PRF/chirp bandwidth pair.

Hence during SAR image formation processing a bandwidth reduction is effectuated which results in a reduced quantization noise level. In other words the SQNR in the image domain exceeds the SQNR in the time domain. Assuming the quantization noise is white, the noise reduction is proportional to the factor

$$NR = \frac{B_D}{PRF} * \frac{B_{CH}}{F_S}$$

where B_D = Doppler Processing Bandwidth; PRF = Pulse Repetition Frequency; B_{CH} = Chirp bandwidth, F_S = Sample Frequency. However the signal power level is also affected by the SAR processing and this reduction ratio can be expressed by the factor

$$SR = \frac{\int_{-0.5B_D}^{0.5B_D} g(f)df}{\int_{-0.5PRF}^{0.5PRF} g(f)df}$$

where g(*f*) is the antenna weighting factor stemming from the PRF-sampled azimuth antenna pattern

$$g(f) = \sum_{k=-\infty}^{k=\infty} \left[\frac{\sin\left(\pi \frac{f + k * PRF}{B_{D,pz}}\right)}{\left(\pi \frac{f + k * PRF}{B_{D,pz}}\right)} \right]^4$$

with $B_{D,pz}$ = the peak-to-first-zero point Doppler Bandwidth.
To reduce undesired sidelobes, usually, an apodization function h(*f*) will be applied in the processing. The recommended function is a raised cosine weighting function with Hamming factor = 0.75.

$$h(f) = \left[0.75 + 0.25\cos(2\pi f / B_D)\right]^2$$

Hence this changes SR and NR into, respectively,

$$SR = \frac{\int_{-0.5B_D}^{0.5B_D} g(f)h(f)df}{\int_{-0.5PRF}^{0.5PRF} g(f)df} \qquad NR = \frac{B_{CH}}{F_S}\frac{1}{PRF}\int_{-0.5B_D}^{0.5B_D} h(f)df$$

Using the above equations we are able to calculate the difference of the SQNR in the image domain and the time domain.

$$\Delta_{SQNR} = \frac{SR}{NR} = \frac{SQNR_{ID}}{SQNR_{TD}}$$

Using ECBAQ's non-integer rate capability, now for every mode/swath combination we can tune the coding rate such that the $SQNR_{ID}$ ~22 dB which corresponds to an acceptable level of image quality [1]. On the average this leads to considerable data reduction.
In a practical implementation the number of coding tables has to be limited to a feasible amount. Therefore we will assume that the available coding rates are multiples of 0.1 bits/sample.

Calculating the resulting coding rates for all the 34 mode/swath combinations of TerraSAR-L, the resulting average coding rate is 3.1 bits/sample. This is a reduction of ~22% as compared to BAQ. Figure 2 shows a diagram with the coding rate results as a function of the mode/swath index.

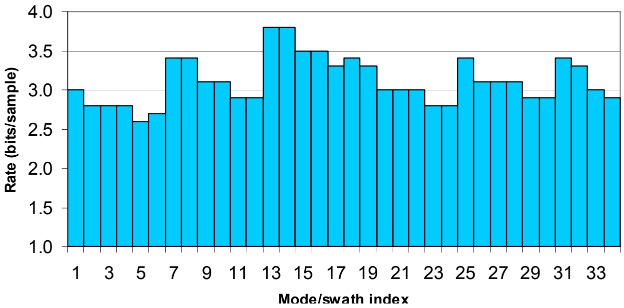

Figure 2. Time-domain ECBAQ coding rates for TerraSAR-L's 34 mode/swath combinations

4 ECBAQ in the Frequency Domain

More data reduction can be achieved when the ECBAQ operates in the frequency domain, the so-called FFT-ECBAQ.
After conversion of the raw complex data into the frequency domain by a two-dimensional FFT device, the above-described ECBAQ can be extended to perform compression based on 2D-frequency dependent bit allocation. The frequency coefficients representing the oversampling regions are encoded with a lower rate than the coefficients in the signal portion of the spectrum. For implementation reasons the data is transformed into the frequency domain based on the application of a relatively short FFT applied on adjacent non-overlapping blocks (FFT size << chirp size). This prevents the application of zero coding rates in the oversampling regions because of cross leak noise effects.
The fact that SAR image processors in the ground segment apply apodization functions can be exploited by this type of compression. It is possible to match the quantization noise in the frequency domain to these weighting functions by variable bit allocation in order to optimize the resulting SQNR in the image domain. The resulting two-dimensional bit allocation is a function of the azimuth and the range coefficient index of the matrix of FFT coefficients. For every possible mode/swath combination a different optimized bit allocation matrix is used. The compressor includes 8 different quantizer/entropy coder tables. Figure 3 presents a block diagram of the compressor . Figure 4 shows an example of a bit allocation matrix.
Since the probability density function of the frequency domain signal is not exactly Gaussian-shaped as is the case in the time domain, the ECBAQ design is slightly different from a time domain version. The dynamic range of the quantizer is substantially enlarged in order to correctly encode peak values. Note that if the rate control would be based on codeword length accumulation, the presence of large peak values would cause too high step sizes resulting in locally insufficient SQNR levels. The adoption of the rate control version as described in Section II has the advantage that the influence of these large amplitudes on the control behaviour is negligible.
The FFT-ECBAQ algorithm has been extensively tested with real and synthetic SAR data to evaluate compression ratio and image quality [6]. The TerraSAR-L satellite has been used as a target mission for this evaluation. Each of the 34 combinations of mode and swath specified for TerraSAR-L corresponds to a PRF/chirp bandwidth pair. Hence for each combination a separate bit-allocation table can be designed. Note that in the ScanSAR modes the option to match the bit-allocation to the processor weighting is not possible. Averaging over all the mode/swath combinations, the resulting coding rate is 1.82 bits/sample.

Compared to BAQ this is a reduction of 55%. The average of the most frequently used mode, the interferometric wideswath mode, is 1.76 bits/sample. Figure 5 shows a diagram with the coding rate results as a function of the mode/swath index.
A compactly design fitting on a half-size euro-board is feasible [6], using a state-of-the-art space FPGA for the ECBAQ algorithm and two PowerFFT ASICs for the 2-dimensional FFT conversion. The PowerFFT is the world's fastest FFT-oriented digital signal processor and it's space qualification program is currently in progress [7]. The design is flexible and can be easily adapted to other frequencies, bandwidths and modes, i.e. other SAR instruments. The data throughput can be as high as 180 Msamples/s in the most simple configuration. Higher throughputs can be achieved by adding more PowerFFT ASICs.

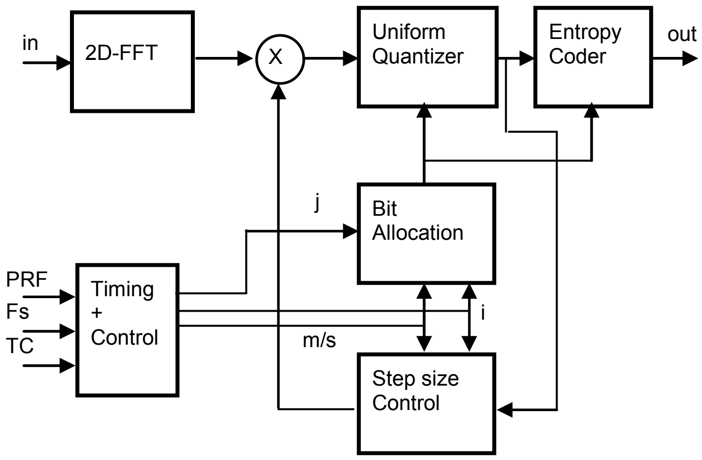

Figure 3. FFT-ECBAQ encoder

Figure 4. Example of bit-allocation matrix, consisting of 128 (range) x 64 (azimuth) elements

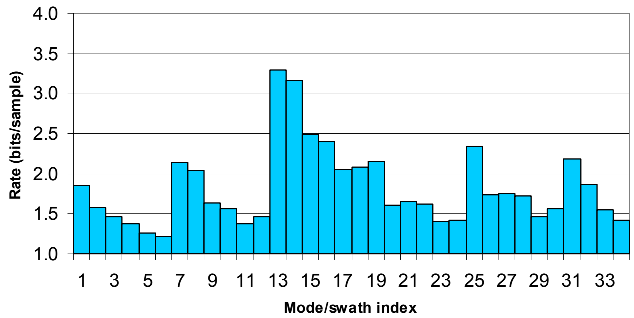

Figure 5. Frequency-domain ECBAQ coding rates for TerraSAR-L's 34 mode/swath combinations

5 Conclusions

For the compression of raw data from multi-mode SAR instruments, Entropy Constrained Block Adaptive Quantization is an attractive option. In the time domain the compression results exceed that of BAQ by more than 20%. Moreover, in a frequency-domain configuration, the average compression ratio is more than twice that of BAQ with the same image quality. The implementation on-board satellites is feasible due to the availability of the PowerFFT, a very fast FFT-oriented DSP ASIC, which is currently being space-qualified.

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