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NLR-TP-2005-550

A SAR raw data compressor using Frequency Domain Entropy-Constrained Block Adaptive Quantization

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The contents of this document have been initially prepared for publication as paper in Proceedings of SPIE Volume: 5978 Sensors, Systems, and Next-Generation Satellites IX, 19-22 Sept. 2005 Brugge (ISBN 0-8194-5998-4).

Customer:	National Aerospace Laboratory NLR
Working Plan number:	A.1.I / AS.1.J
Owner:	National Aerospace Laboratory NLR
Division:	Aerospace Systems & Applications
Distribution:	Unlimited
Classification title:	Unclassified
	October 2005

Approved by:

Author	Reviewer	Managing department
15-11	15-11	

Summary

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ABSTRACT

Operational SAR satellite missions impose new requirements to on-board data compression such as a higher data reduction ratio, more flexibility, and faster data throughput. A recent approach is Entropy-Constrained Block Adaptive Quantization (ECBAQ). This method outperforms currently-used Block Adaptive Quantization with respect to Signal-to-Quantization-Noise-Ratio. The ECBAQ algorithm can be implemented using an architecture that is essentially not more complicated than that of a BAQ encoder and suitable for high-speed implementations. Moreover, the method features bit rate programmability with non-integer rates. This allows the SAR information throughput to be optimized for different types of applications. This paper presents a new ECBAQ version including a rate control loop, avoiding the need for the multiplexing of block variance levels into the compressed data stream and further reducing the complexity of the implementation. The presented method is very well suited for application with frequency domain data due to its high instantaneous dynamic range and non-integer rate capabilities. Preceded by an FFT device which transforms the data in both range and azimuth direction, more data reduction can be achieved by frequency filtering and decimation. In addition, using variable bit allocation matched to the SAR processor's weighting functions, even higher compression ratios can be achieved. Overall, the compression improvement may range over 100 % as compared to the conventional BAQ method while maintaining the same image quality. In conclusion, FFT-ECBAQ is a strong candidate for application in future SAR missions.

Keywords: SAR, satellite, data compression, FFT

I. INTRODUCTION

Raw SAR data compression has been applied for the first time in the NASA Magellan mission to Venus from 1989 to 1994 (Ref. 1). Also the ASAR data from the ENVISAT satellite is transmitted in a raw compressed format (Ref. 2). The type of compression applied in these cases has been called Block Adaptive Quantisation (BAQ). Raw SAR data compression is not lossless. The digitization and coding process introduce additional noise and effects on the SAR images to be processed. An important quality parameter is the Signal to Quantization Noise Ratio (SQNR). For example, with ENVISAT in practice a compression ratio of 2 is used, with SQNR of ~ 19-20 dB.

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Recently, due to the advent of larger and more complex ASIC and FPGA building blocks, more efficient on-board raw SAR data compression methods have become feasible. Of this new wave of compression methods, the Entropy-Constrained Block Adaptive Quantise is promising (Ref. 3) since it can be considered as a good compromise between better compression performance and improved complexity. The basic ECBAQ consists of a set of uniform quantisers cascaded with entropy coders. Each combination of quantiser and entropy coder is optimized with respect to the SQNR for a given output rate R and an input standard deviation σ. In contrast with BAQ, the rate R may be any non-integer value. The resulting performance deviates not more than 0.225 bits from the Shannon bound assuming Gaussian input. In (Ref. 4) the ECBAQ concept has been described with a view on application on-board satellites.

This paper describes two significant improvements of the ECBAQ. First, in Section II, a variant of ECBAQ is presented which includes a rate control loop. Second, in Section III, this ECBAQ version is modified in such a way that it can be applied in the frequency domain. The average resulting compression ratio can be twice as high as in the case of BAQ.

II. ECBAQ WITH RATE CONTROL LOOP

Raw SAR data samples are characterised by a Gaussian shaped probability density function, a low correlation, and a slowly varying standard deviation. In Block Adaptive Quantisation the samples are divided in blocks of M, e.g. 128, successive samples. For each block the standard deviation is calculated and the related optimum quantiser function is selected. In ECBAQ basically the same block adaptive quantisation approach is used (fig. 1).

In the case of BAQ, for each quantiser function Q_i there exists one particular σ_i for which the SQNR is maximal. If the standard deviation of the block of samples deviates from σ_i, the resulting SQNR will be lower. This means that in practical implementations of BAQ a large number of quantisers is used in order to achieve sufficient dynamic range without SQNR performance degradation, for example 256.

In the case of ECBAQ the situation is different. Although also in this case a quantiser/entropy coder combination is optimised for a certain σ_i and a given output rate, a deviation of the input standard deviation from σ_i does not lead to lower performance. The SQNR will change, but the actual output rate changes proportionally, in such a way that the distance to the Shannon bound remains the same. This means that in practical situations with real SAR data, only a few quantiser/entropy coder combinations are needed. For example with 16 combinations a dynamic range of 32 dB can be achieved without performance loss. The proportionality of SQNR and output rate can be used to control the output rate using a feedback loop, as depicted in figure 2. The block "rate control" accumulates the codeword lengths during the coding of a block. At the block transition a change of σ may take place depending on the accumulated number.

Let L_k be the length in bits of the produced codeword k in block n consisting of M samples. At the block transition the accumulated bit length is compared to an upper and an under limit leading to a possible change of σ:

$$if \ \sum_{0}^{M-1} L_k \ > \ MR + 0.5\delta \ \ then \ \ \sigma_{n+1} = \sigma_n + \delta_\sigma$$

$$if \ \sum_{0}^{M-1} L_k \ < \ MR - 0.5\delta \ \ then \ \ \sigma_{n+1} = \sigma_n - \delta_\sigma$$

wherein δ_σ is the stepsize of σ in dB. The SQNR (in dB) as a function of the rate R (in bits/sample) can be approximated for ECBAQ by

$$SQNR = 5.95R - 1.56 \ \ dB$$

From this relation the constant δ can be derived

$$\delta = \frac{\delta_\sigma M}{5.95} \ \ bits$$

Fig. 3 plots the resulting SQNR as a function of the output rate in comparison to BAQ. It shows that the SQNR of ECBAQ with rate control exceeds the SQNR of BAQ by 2.2 dB at 4 b/s.

The advantages of this version of ECBAQ as compared to the earlier published version are:

1. There is no block buffer needed
2. The number of quantisers and entropy coder tables is reduced to one for a certain coding rate (hence, this is a further reduction by a factor 16)
3. The block standard deviation values do not have to be transmitted, which results in reduced complexity and lower bit rate

III. FREQUENCY DOMAIN ECBAQ

During the SAR sampling and digitisation process always a certain amount of oversampling occurs. In practical implementations there is some margin needed between the highest signal frequency and the Nyquist rate (0.5 x sampling frequency) to avoid aliasing. Moreover, 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.

In the azimuth direction the bandwidth of the Doppler signal that is processed on ground is usually significantly smaller than the sampling rate (PRF) to avoid high azimuth ambiguity levels.

These two properties allow further data reduction. After conversion into the frequency domain by a two-dimensional FFT device, the above-described ECBAQ can be adapted to perform filtering and subsampling in both the azimuth and the range direction. On ground, this process is reversed by upsampling with zero-padding and two-dimensional inverse FFT.

SAR image processors in the ground segment apply a weighting function in the range direction as well as, for the common modes, in the azimuth direction. Hence it is possible to map the quantisation noise in the frequency domain in such a way that the resulting SQNR after image processing is maximized. This can be done by two-dimensional bit allocation as a function of the azimuth and the range coefficient index of the block of M x M FFT coefficients. Due to the large number of coefficients a sufficiently accurate tuning can be achieved with only a few different rates. For example for a target SQNR of 20 dB, only 8 rates (1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5) appear to be sufficient. Fig. 4 presents the architecture of the compressor[2]. The bit allocation block is basically a Look-Up Table (LUT) for the number of bits/sample as a function of the azimuth (i) and the range (j) coefficient indices. Obviously when this number is 0, no output is generated, which resembles the described filtering process. The compressor includes 8 different quantiser/entropy coder tables corresponding to the 8 possible bit allocations. Note that in this case "bit allocation" includes non-integer rates.

In practice the FFT size is limited in order to allow sufficiently high throughput rates. M = 128 appears to be a workable size. Consequently M is smaller than the chirp size as well as the azimuth reference function, which results in a slight performance reduction due to cross leak noise. The probability density function of the frequency domain signal is not exactly Gaussian-shaped as is the case in the time domain. Especially bright point scatterers cause large peaks. Therefore the ECBAQ design is slightly different from a time domain version.

The eventual performance improvement for a practical space SAR system with multiple swaths and SAR modes depends on the different chirp bandwidths and Pulse Repetition Frequencies (PRF) as well as the type of weighting to be applied in the ground SAR processor. Typically, averaging the resulting coding rate over all the swaths and SAR modes, a rate < 2 bits/sample is sufficient to achieve the same image quality as BAQ (with 4 bits/sample). For example in the case of ESA's TerraSAR-L satellite, for which this compression method has been selected as the baseline option, the average coding rate is ~ 1.75 bits/sample.

VII. CONCLUSIONS

For raw SAR data compression purposes Entropy-Constrained Block Adaptive Quantisation is an attractive option compared to BAQ, because

- ECBAQ outperforms BAQ with respect to the Signal to Quantisation Noise Ratio,
- ECBAQ is rate programmable (non-integer rates)

A modified version of ECBAQ has been presented with a rate feedback loop mechanism. This ECBAQ can be effectively used for Frequency domain ECBAQ.

The compression ratio improvement as compared to BAQ can be as high as 100%.

[2] Patent pending

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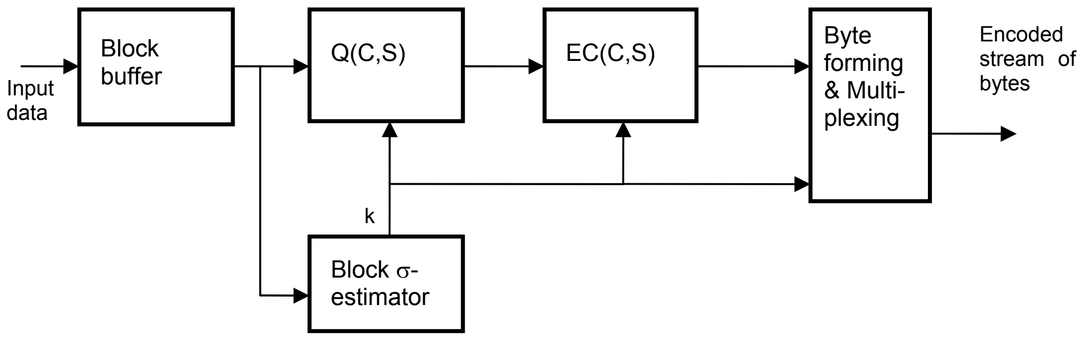

Fig. 1 Basic ECBAQ blocdiagram; Q(C,S) = uniform quantizer; EC (C,S) = entropy coder; C = number of quantizer levels; S = quantization step size

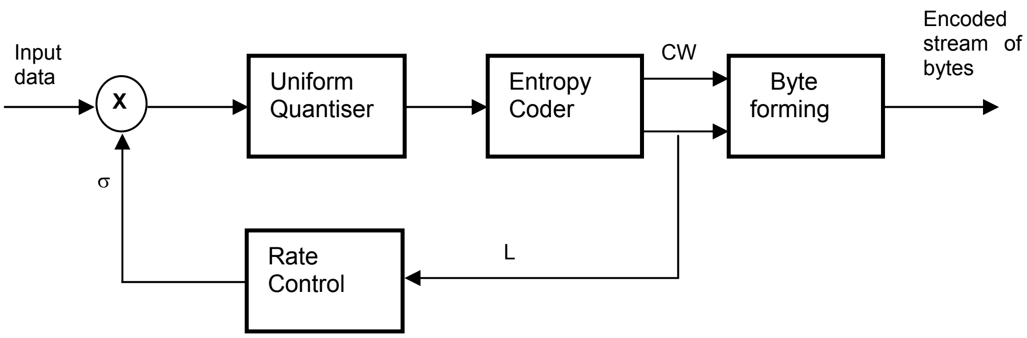

Fig. 2 ECBAQ with rate control feedback. CW= code word; L=code word length

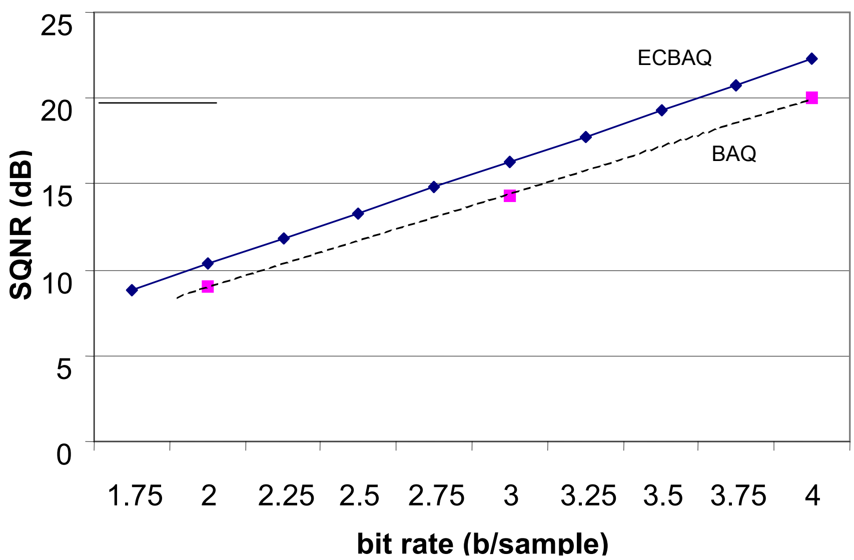

Fig. 3 SQNR performance of BAQ and ECBAQ as a function of bit rate

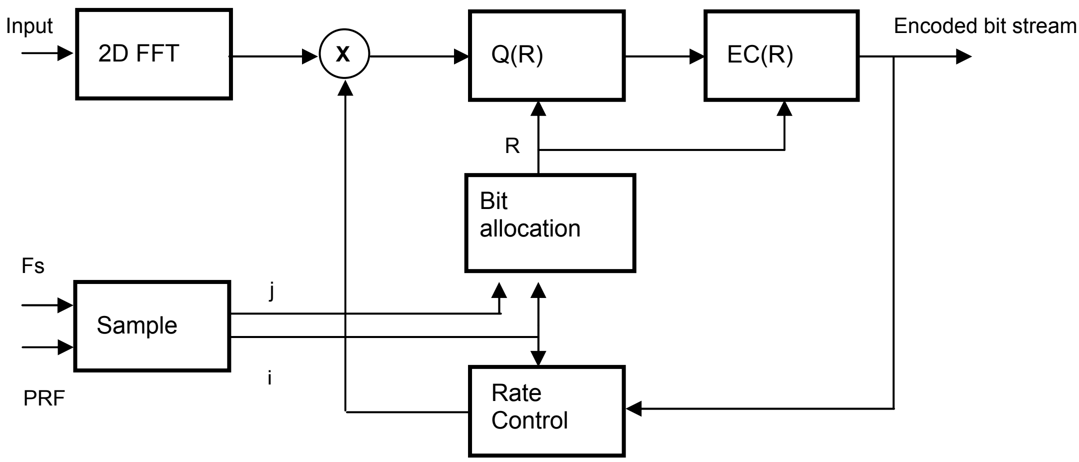

Fig. 4 Frequency Domain ECBAQ with rate control feedback (PRF = Pulse Repetition Frequency; Fs = range sample frequency; R = coding rate)