Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

Frequency domain raw SAR data compression for multi-mode SAR instruments

Problem area
From a commercial viewpoint, the market for satellite SAR data products is relatively immature compared to the market for satellite Electro-Optical (EO) products. To enforce commercial attractiveness it is mandatory for satellite SAR data providers to broaden the application field of new SAR satellite missions. The technical consequences are that future SAR sensors 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 techniques. The conventional compression method for application on board SAR satellites is Block Adaptive Quantisation (BAQ). However there are new methods needed with better compression performance to fulfill the requirements of upcoming satellite SAR missions.

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. Moreover, the compression performance of the ECBAQ can be substantially improved in the frequency domain. Especially when applied to multi-mode SAR instruments, the resulting compression ratio is excellent as compared to BAQ. Extensive simulations and image quality tests have been carried out to demonstrate the performance of the compression method. The feasibility of the application of FFT-ECBAQ in space is addressed. The PowerFFT, the world's fastest FFT-oriented DSP, of which the space qualification program is currently in progress, and state-of-the-art space FPGA components, make the application of the FFT-ECBAQ on-board satellites feasible.

Report no.
NLR-TP-2006-273

Author(s)
T Algra
L. Bierens

Classification report
Unclassified

Date
April 2006

Knowledge area(s)
Geomatica

Descriptor(s)
SAR
Data compression
satellite

This report is based on a presentation to be held at EUSAR 2006, 6th European Conference on Synthetic Aperture Radar, 16-18 May 2006, Dresden

Results and conclusions
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 a space-qualified version of the powerFFT ASIC.

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

Nationaal Lucht- en Ruimtevaartlaboratorium, National Aerospace Laboratory NLR

Anthony Fokkerweg 2, 1059 CM Amsterdam,
P.O. Box 90502, 1006 BM Amsterdam, The Netherlands
Telephone +31 20 511 31 13, Fax +31 20 511 32 10, Web site: www.nlr.nl

NLR-TP-2006-273

Frequency domain raw SAR data compression for multi-mode SAR instruments

T . Algra and L. Bierens[1]

[1] EONIC B.V.

This report is based on a presentation to be held at EUSAR 2006, 6th European Conference on Synthetic Aperture Radar, 16-18 May 2006, Dresden

Customer	National Aerospace Laboratory NLR
Contract number	---
Owner	National Aerospace Laboratory NLR + partner(s)
Division	Aerospace Systems & Applications
Distribution	Unlimited
Classification of title	Unclassified

Approved by:

Author	Reviewer	Managing department

Summary

This paper addresses a novel frequency-domain raw SAR data compression concept that outperforms conventional methods based on Block Adaptive Quantisation (BAQ). The results of extensive compression performance and image quality evaluations are presented. It is shown that for an advanced multi-mode satellite SAR instrument the average compression ratio can be doubled as compared to BAQ. Space borne implementation is feasible due to the advent of advanced space FPGA's and ASIC's including the powerFFT, a fast FFT-oriented DSP.

Contents

2 Tables

4 Figures

(13 pages in total)

1 Introduction

From a commercial viewpoint, the market for satellite SAR data products is relatively immature compared to the market for satellite Electro-Optical (EO) products. To enforce commercial attractiveness it is mandatory for satellite SAR data providers to broaden the application field of new SAR satellite missions. The technical consequences are that future SAR sensors 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 techniques. The conventional compression method for application on board SAR satellites (such as ENVISAT) is Block Adaptive Quantisation (BAQ). Its coding rate is at least 4 bits/sample in order to guarantee acceptable image product quality.
In section 2 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. Moreover, the compression performance of the ECBAQ can be substantially improved in the frequency domain. Especially when applied to multi-mode SAR instruments, the resulting compression ratio is excellent as compared to BAQ.
In section 3 the results of extensive simulations and image quality tests are presented demonstrating the performance of the compression method. With the PowerFFT, the world's fastest FFT-oriented DSP, of which the space qualification program is currently in progress, and state-of-the-art space FPGA's, the application of the FFT-ECBAQ [1] in space is feasible as will be described in section 4. It has been selected as the baseline compression method for the TerraSAR-L satellite [2].

2 Advanced raw SAR data compression

2.1 Entropy-Constrained BAQ

Raw SAR data samples are characterised by a Gaussian shaped probability density function, a low correlation, and a slowly varying standard deviation. In BAQ the samples are divided into blocks of M, e.g. 128, successive samples. For each block the standard deviation is calculated and the related optimum quantizer function is selected. In the case of BAQ, for each quantizer function Q_i there exists one particular input standard deviation σ_i for which the Signal to Quantisation Noise Ratio (SQNR) is maximal. Consequently in practical implementations of BAQ a large number of quantizers is used to achieve sufficient dynamic range without SQNR performance degradation, for example 256.
With ECBAQ the situation is different. Although also in this case a quantizer/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 result in lower performance. The SQNR will change, but the

actual output rate changes proportionally, over a relatively large interval. This property can be exploited by the introduction of a feedback loop to automatically control the effective quantization step size. Refer to fig. 1.

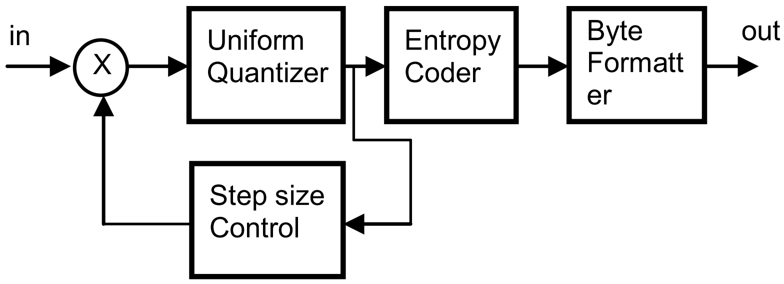

Figure 1 ECBAQ with step-size control

Before quantization the digitized input samples are multiplied with a scaling factor. At the block transitions the scaling factor can be increased or decreased by a factor D, for example 3 dB.
By continuously adjusting this scaling factor in a proper way, it is ensured that the average of the quantizer input standard deviation equals σ_{REF}.
The difference between σ and σ_{REF} can be measured by the accumulation of the lengths of the variable-length code words [4]. Another possibility is to count the number of quantized values with an absolute value smaller than σ_{REF}. The latter method is more appropriate for frequency domain operation as will be shown in section 2.2. Let C_L be the total number of such values within one block. Then

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

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:

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

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

The limits Δ1 and Δ2 are

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

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

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 rate control exceeds the SQNR of BAQ by 2.2 dB at 4 bits/sample. Moreover, ECBAQ allows non-integer bit rates. Some other advantages of this version of ECBAQ are:
1- There is no block buffer needed;
2- The instantaneous dynamic range can be large;
3- The block standard deviation values do not have to be transmitted;
4- The performance of the control loop is independent of the implemented entropy code.

2.2 Frequency domain application

During the SAR sampling and digitisation process always a certain amount of oversampling occurs. 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 smaller than the pulse repetition frequency (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 encoding with 2D-frequency dependent bit allocation. The frequency coefficients representing the oversampling regions can be encoded with a significantly lower rate than the coefficients in the signal portion of the spectrum. However, reduction of these rates to 0 b/s is not advisable (i.e. not transmitting them at all). It is necessary to apply FFT-sizes ≤128 in order to achieve sufficient throughput rate in practical implementations. However, these relatively short FFT-sizes cause cross leak noise effects if no overlap & save/add operation is performed. Especially around strong point scatterers stripes may occur in the error noise patterns in the processed SAR image. These artefacts may lead to decreased local SQNR levels in the image.
Application of overlap & save/add operation is possible, but at the expense of compression ratio. A better solution is to encode the oversampling regions with a low coding rate, depending on chirp bandwidth and on the 2D-frequency co-ordinate.
SAR image processors in the ground segment apply apodization. Hence it is possible to match the quantisation 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 two-dimensional bit allocation is a function of the azimuth and the range coefficient index of the block of FFT coefficients.

Fig. 2 presents a block diagram of the compressor .

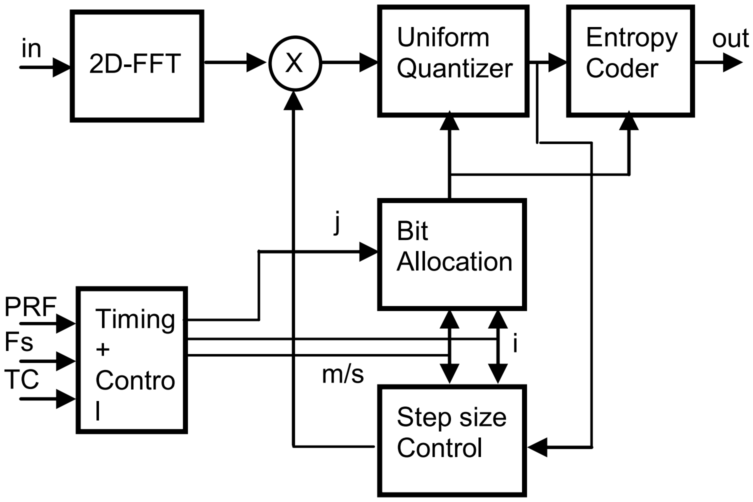

Figure 2 Compressor architecture
(without byte formatter and source packet formatter)

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. The compressor includes 8 different quantizer/entropy coder tables.

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 dynamic range of the quantizer is substantially enlarged in order to correctly encode peak values due to bright point scatterers.

The presence of the latter would cause too high step sizes resulting in locally insufficient SQNR if the rate control would be based on codeword length accumulation. But by the adoption of the rate control version described in 2.1, the influence of these large amplitudes on the control behaviour is negligible.

Fig. 3 shows an example of the bit allocation of a block of samples after 2D-FFT transformation.

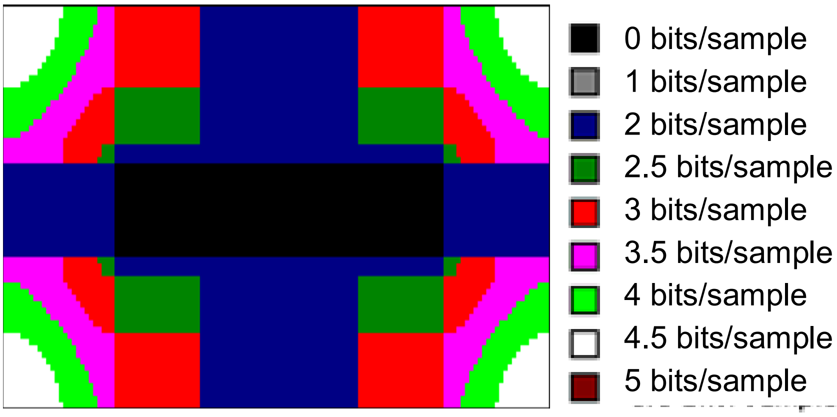

Figure 3 Example of bit allocation map (128 range x 64 azimuth complex samples)

3 Simulation results

3.1 Test approach

The FFT-ECBAQ algorithm has been extensively tested to evaluate compression ratio and image quality. The input data consisted of several real SAR data files and a number of synthetically generated files. The TerraSAR-L satellite has been used as a target mission for this evaluation.
In TerraSAR-L raw SAR data is digitized with 10 bits/sample. Currently there is no 10-bits space SAR data available. Therefore we choose to convert raw ERS data into 10 bits data according to the method described in [3]. The 5-bits ERS data samples are multiplied by 32. Subsequently noise is added to the samples in such a way that the resulting probability density function (pdf) remains Gaussian.
Three 100 x 100 km ERS scenes have been selected: i) Indonesia (sea, mountains, urban areas); ii) Yamal coast (sea-ice); iii) Netherlands (lakes, flat areas, rivers, urban areas, ESA corner reflector). Each of the scenes has been split up in two sub-scenes. Further, synthetic files have been generated for additional point target analysis and dynamic range testing. One of the files was low-pass filtered in range direction to 75% and to 50% of the original chirp bandwidth, respectively.
Both the original and the compressed/decompressed files have been processed by a SAR processor using identical processing parameters for each pair of files.

3.2 Performance results

Table 1 compares the performance results with BAQ in the Single-Look-Complex (SLC) slant range image domain. Table 2 shows an excerpt of the point target analyses. After compression, decompression and SAR processing (SLC) the images were subtracted from the original ones resulting in difference images. The difference image shows the noise due to compression. It is an important tool to check unwanted noise patterns. The difference image results with FFT-ECBAQ are equal or better than with BAQ.

Table 1 Performance results in the image domain

	BAQ (4 b/s)		FFT-ECBAQ		
Scene	SQNR (dB)	rms phase error °	SQNR (dB)	rms phase error °	Rate (bits/ sample)
1	22.2	10.5	22.1	10.6	2.95
2	22.6	11.4	22.8	11.1	2.94
3	22.7	9.7	22.1	10.2	2.92
4	22.8	9.5	22.0	10.2	2.91
5	22.4	11.0	22.1	11.1	2.94
6	22.5	11.8	22.2	12.0	2.95
7	22.6	11.2	22.7	11.0	2.94
8 50% of original chirp bandwidth			22.6	10.9	1.93
9 75% of original chirp bandwidth			22.3	11.4	2.49

Table 2 Point target analyses results

File A: real SAR data B: Synth. data		PSLR (dB)	ISLR (dB)	Resolution (3 dB, in pixels)	
				Range	Azimuth
Original	A	21.2	16.5	1.50	1.52
FFTECBAQ	A	21.2	16.5	1.50	1.52
BAQ	A	21.2	16.5	1.50	1.52
Original	B	22.6	17.3	1.39	1.55
FFTECBAQ	B	22.6	17.3	1.39	1.55
BAQ	B	22.6	17.3	1.39	1.55

3.3 Average compression ratio

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. Each of the 34 combinations of mode and swath corresponds to a PRF/chirp bandwidth pair. Hence for each combination a separate bit-allocation table can be designed.

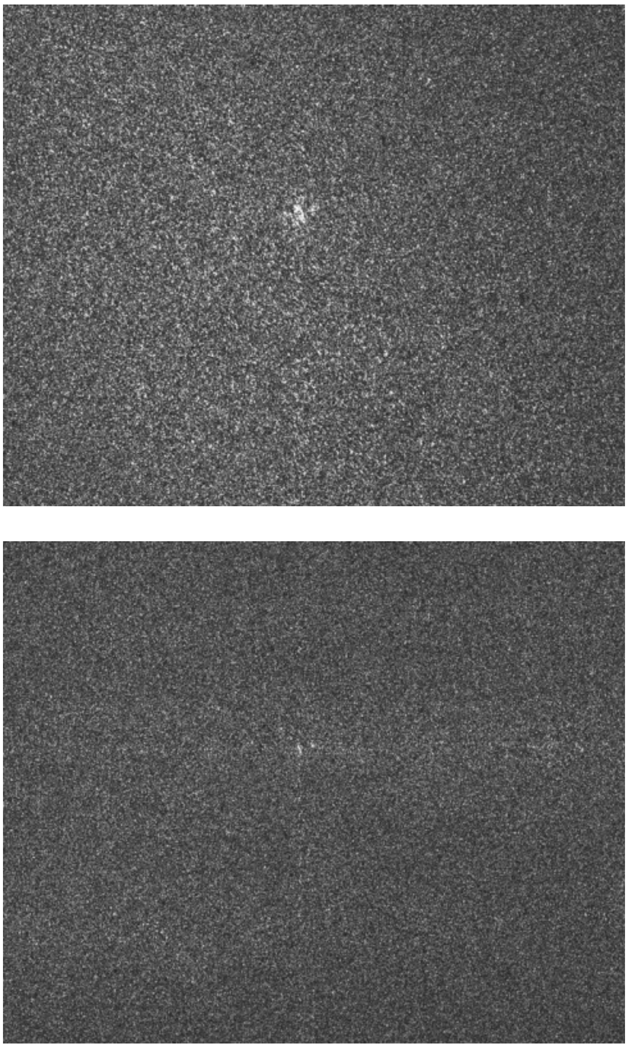

Figure 4 Difference image detail of a strong point scatterer. Top: BAQ; bottom: FFT-ECBAQ

Note that in the ScanSAR modes the option to match the bit-allocation to the processor weighting is not possible. We can extrapolate the experimental results as presented in the previous section, to each of the mode/swath combinations with the following assumptions:

1- The target quality parameters in the SLC image domain are
   - SQNR = 22 dB;
   - rms phase error = 11 degrees;
   - no artefacts in the difference image;
   - the point target analysis parameters are not influenced.

2- In the oversampling regions additional compression is obtained using runlength coding and adjusted Modified Huffman codes.

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.

4 Compression architecture

The FFT-ECBAQ Architecture (fig. 2) consists of two units: the 2D-FFT and the ECBAQ (including Byte Formatter and the Source Package Formatter, which are not shown in the figure). Based on the FFT-ECBAQ performance evaluation study [5], the optimum FFT size is 64 points in azimuth and 128 points in range. The maximum length of a range line is 33167 complex samples. The maximum effective input rate of the 2D-FFT is about 65 x 10^6 complex samples / second. Note however, that the range lines are transferred from the pre-processing to the 2D-FFT at a maximum burst sampling rate of 91.15 MHz [2]. The 2D-FFT function is executed by two cascaded PowerFFT processors [6], a programmable FFT processor which is currently being space qualified. For the ECBAQ FPGA architecture the following design constraints have been taken into account:

1- Platform independency, i.e. the design shall be flexible and upgradeable, and no vendor or platform specific blocks shall be used (dedicated multipliers, memory blocks, etc.);

2- Minimize the size of memory resources (LUTs) as much as possible to avoid the necessity of external memory components;

3- Effectively the maximum input throughput shall be up to 125 MSPS (67.5 MSPS complex), but higher throughputs shall be possible in the future.

In feasibility studies [2,5] it has been shown that the ECBAQ implementation fits in a medium sized space qualified FPGA.

5 Conclusions

For the compression of raw data from multi-mode SAR instruments, frequency-domain entropy-constrained BAQ (FFT-ECBAQ) is an attractive option. 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 fast FFT-oriented DSP ASIC, which is currently being space-qualified.

References

[1] Patent application PCT/NL2004/000479

[2] Algra, T., L. Bierens: *L-SAR data compression and filtering*, AST04_TN_0001, Issue 2.3, NIVR/ESA contract report, 2005

[3] Dutkiewicz, M., G. Kuduvalli: *SAR pre-processing on-board study: Algorithm definition*, Final report vol. 1 of 2, ESA contract report, DC-TN-50-5830, Richmond, May 1994

[4] Algra, T.: *A SAR raw data compressor using Frequency Domain Entropy-Constrained Block Adaptive Quantization*, SPIE Proc. Remote Sensing 2005, Sensors, systems and next generation satellites IX, Vol. 5978, 58; Bruges 19-22 sept 2005

[5] Algra, T., L. Bierens: *Advanced on-board SAR data compression, Final Report,* ESA contract report, NLR-CR-2006-087, Amsterdam, 2006

[6] *PowerFFT Data Sheet*, EONIC B.V., Delft