N95-14590

p. 15

Synthetic Aperture Radar Signal Data Compression Using Block Adaptive Quantization

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Abstract

This paper describes the design and testing of an on-board SAR signal data compression algorithm for ESA's ENVISAT satellite. The Block Adaptive Quantization (BAQ) algorithm was selected, and optimized for the various operational modes of the ASAR instrument. A flexible BAQ scheme was developed which allows a selection of compression ratio/image quality trade-offs. Test results show the high quality of the SAR images processed from the reconstructed signal data, and the feasibility of on-board implementation using a single ASIC.

1 Introduction

Because of the growing volume of data collected in remote sensing satellites, the need for on-board data compression is increasing. This is particularly true of synthetic aperture radar (SAR) sensors, where swath widths and resolutions are limited by the on-board data handling capacity and the downlink bandwidth. Little use has been made of on-board data compression to date, because of the unavailability of signal processing capacity, power and weight constraints, reliability considerations, and the reluctance of users to accept any form of data degradation. However, the experience with the Magellan mission, and the progress of electronic technology has set the stage for the use of data compression in future operational SAR satellites.

Pioneering work on SAR data compression was done by JPL, and an algorithm called Block Adaptive Quantization (BAQ) was developed for the encoding of SAR signal (raw) data [1, 2]. The algorithm was first implemented on the Magellan mission to Venus [1], and later on the SIR-C mission. Following this, engineering studies were carried out by MacDonald Dettwiler for ESA, evaluating the Block Adaptive Quantization (BAQ), Vector Quantization (VQ) and Discrete Cosine Transform (DCT, JPEG version) data compression algorithms. Each algorithm had its advantages and its preferred application, and in the case of on-board compression of SAR signal data, BAQ was preferred, primarily because of its simplicity [3, 4]. There have been a number of other studies on SAR data compression in this period [5, 6, 7].

Following the initial demonstrations of feasibility, ESA funded a second project to design an ASIC for the next generation of European SAR satellites. The next planned SAR sensor after ERS-2 is the ASAR, to be flown on ENVISAT in the 1998 time frame. ASAR is to have a number of operating modes, each with its own engineering and application requirements. The modes varied from a 400 km wide-swath survey mode to a 100 Km precision imaging and calibration mode.

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These different requirements pointed to the need for flexibility in data compression algorithms, where users could decide between the widest swath at moderate image quality and the highest precision with narrower swath widths.

Detailed requirements were placed on the encoder's signal/quantization noise ratio, preservation of statistics, radiometric linearity, phase error, spectral fidelity, discrete target accuracy and visual image quality. Additional requirements were placed on simplicity, reliability, scene-independence and real-time operation.

This paper describes the design and testing of a flexible BAQ SAR signal data compression algorithm to satisfy the above requirements. Section 2 summarizes the characteristics of SAR data, and the metrics selected to evaluate the effects of encoding. In Section 3, the selection and design of a flexible BAQ algorithm, including theoretical and experimental evaluation of several variants of the basic algorithm, is detailed. The hardware implementation of the algorithm in an ASIC is described in Section 4, and conclusions are given in Section 5.

2 SAR Data Characteristics and Evaluation Metrics

2.1 SAR Data Characteristics

SAR signal data is acquired by measuring the reflections of linear FM chirps transmitted and received with a SAR antenna. Thus SAR signal data consists of a two-dimensional convolution of the reflectances of a number of targets spread over the width of the linear FM chirp along range, and the SAR antenna beam width along the azimuth. Typically, this convolution operator is of the order of a few hundred samples in both range and azimuth directions [2]. The signal data are acquired in the complex domain by measuring both the in-phase and quadrature phase (I/Q) components of the received signal.

The convolution operation implicit in the acquisition of the SAR signal data results in a slow variation of the rms value of the signal in both range and azimuth directions. Further, this convolution operation results in a distribution of the received signal data that tends to be Gaussian [8, 9]. Thus SAR signal data can be modeled as Gaussian distributed random variable with a slowly varying rms value, and with little or no correlation between adjacent samples [1, 2]. Further, SAR signal data typically has a low signal to noise ratio — of the order of 10 to 15 dB. These characteristics govern the choice of a suitable algorithm for the compression of SAR signal data.

2.2 Evaluation Metrics

SAR data encoding takes place in the raw or signal data domain, whereas all the applications of SAR data are in the image domain. A convolution operator (matched filter) is used to transform the SAR signal data to the image domain. A consequence of the convolutional operator used to create the image is that there is no simple relationship between the properties of the data in the two domains. Thus to fully quantify and understand the effects of encoding, evaluation should take place in both the signal *and* image domains. In this way, one can gain insight into the cause, nature and severity of the signal domain error; into how the error is propagated into the image domain;

and, finally, into how the error might affect applications using the data. Evaluation metrics were chosen in order to:

- understand the *manner* in which the encoding error manifests itself,
- quantify the *severity* of the encoding error,
- understand the *mechanism* by which the encoding error is introduced.

The methods of evaluation which have been selected to meet these goals are [4]:

- **in the signal domain**: measurement of signal to quantization noise ratio (SQNR); analysis of effects of encoding on data statistics, data histograms, phase statistics and phase histograms,
- **in the image domain**: all the metrics used in the signal domain in addition to the analysis of effect of encoding on point target characteristics and spectral characteristics; measurement of radiometric linearity of encoding[1]; and measurement of global and local mis-registration effects.

3 Algorithm definition

3.1 Selection of candidate algorithms

Data compression algorithms generally exploit the correlation between samples of data to reduce the redundancy, and then apply a suitable quantization scheme to encode the resulting data. SAR signal data is best modeled as a Gaussian random variable with very low correlation between samples. Hence, the choice of a compression algorithm for SAR signal data reduces to that of selection of a suitable quantizer. The fundamental idea behind the block adaptive quantization (BAQ) is to adaptively vary the step sizes of a non-uniform quantizer based on the estimated variance of a block of samples [1, 2]. This achieves a wider overall dynamic range at the quantizer output, for the same number of quantization levels, than simple uniform quantization of the data. Several variants of this basic idea are possible, based on the choice of the quantizer.

In this study, the design of a compression algorithm with flexible compression ratios was approached in two stages. The first stage of the study was to select the best form of the BAQ algorithm, identify important parameters and determine their optimum values using experimental evaluation with actual SAR signal data. The second stage of the study was to extend the selected version of the algorithm for flexible compression ratios, evaluate the algorithm at different encoding rates, and fully specify the design of the algorithm for an ASIC implementation.

The variants of the BAQ algorithm selected as potential candidates for implementation are described in the following subsections.

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1. Radiometric linearity is a measure of how well the algorithm preserves the intensity levels of homogeneous regions within the image. Linearity is determined by plotting mean intensity of homogeneous regions (ranging from dark to very bright) in the decoded image versus mean intensity of the same regions in the original image. Perfect linearity would give an exact fit to a straight line with slope of 1.0 and zero offset.

3.1.1 Block Adaptive Quantization (BAQ):

This scheme is based on JPL's BAQ implementation for the Magellan mission [1]. The absolute values of I and Q are compared with a threshold derived from a block of input signal data samples, and encoded with 1 bit. The sign bit of the I and Q samples constitute the second bit. The threshold and reconstruction levels are chosen to result in minimum mean square quantization error for 2-bit quantization of a Gaussian random variable with a variance equal to the sample variance of the block.

This idea can be extended to provide greater compression accuracy by increasing the number of thresholds and allowing more bits per codeword. Three-bit BAQ requires 3 thresholds, and 4-bit BAQ requires 7 thresholds. The quantizer for 3 and 4 bits consist of successively comparing the absolute values of I and Q with the set of thresholds computed from a block of samples, and encoding the result of comparison with a 2 or 3-bit codes; the sign bit constitutes the additional bit.

3.1.2 Block Adaptive Magnitude Phase Quantization (BMPQ):

In BMPQ, the input I/Q values are transformed to magnitude-phase representation. The phase component is uniformly distributed and the magnitude is Rayleigh distributed. The quantization thresholds and reconstruction levels are determined for each component to minimize the mean square quantization error for the respective distributions. The number of bits allocated to the magnitude and phase components for quantization are varied to achieve the best overall performance. Table 3-1 gives the theoretical performance of the quantizer for different bit allocations to magnitude and phase.

Table 3-1 SQNR performance of BMPQ for different bit allocations

Number of bits/sample for encoding the magnitude	Number of bits/sample allocated for encoding phase				
	1	2	3	4	5
0				6.48	6.63
1			9.19	10.70	11.19
2		6.63	11.41	14.57	15.93
3	1.38	6.89	12.44	17.21	20.22
4	1.38	6.98	12.79	18.40	23.11
5	1.39	7.00	12.89	18.78	24.38

The cross diagonals of Table 3-1 represent the SQNR for a constant encoding rate or compression ratio. The shaded cells highlight the bit allocation combination which results in the best performance for the given number of bits per sample. For example, at 2 bits/sample (i.e., 4 bits per complex sample) the highest SQNR is expected with 1 bit allocated to magnitude and 3 bits for phase.

3.1.3 Block Adaptive Histogram Equalization Quantization (BHEQ):

BHEQ consists of transforming the I/Q samples from Gaussian distribution to uniform distribution using the block rms value. This operation is recognized as the classical histogram equalization, with the added feature that the histogram is known a-priori. The transformation consists of computing the cumulative distribution function of the Gaussian distribution, and can be performed using look-up tables. The resulting 8-bit transformed I/Q values can be quantized to the required number of bits simply by truncation.

BHEQ minimizes the quantization error in the histogram-equalized domain. This is *not* equivalent to minimizing the quantization error in the original signal with Gaussian distribution. Thus BHEQ results in lower SQNR than BAQ at all encoding rates. The main reason for studying this type of quantizer is that the quantizer is essentially identical for different compression ratios.

3.1.4 Block Adaptive Complex Quantization (BACQ):

BACQ consists of treating a pair of I and Q values as a complex sample, and designing a generalized complex quantizer using quantization boundaries and reconstruction levels in the two-dimensional (2-D) space. Straight forward implementation of 2-D quantizers using look-up tables require large amount of memory and precludes on-board hardware implementation. However, the approach used in the case of BHEQ can be used to bring down the size of the look-up tables to more manageable levels. The I/Q samples are converted to uniform distribution, as in the case of BHEQ, using look-up tables. A second look-up table is used to quantize the transformed I/Q values into a single complex quantizer code.

A possible selection of quantizer reconstruction levels and the corresponding optimal quantization boundaries in the 2-D space is shown in Figure 3-1.

3.2 Evaluation of BAQ Variants

Table 3-2 gives the theoretical (signal domain) SQNR performance of the four variants of the BAQ algorithm. Previous studies have shown that the SQNR is the most significant signal domain parameter that affects the image domain performance of a quantizer for SAR signal data compression [3]. Table 3-2 shows that the expected SQNR performance of the four candidate algorithms are very close to one another, with BAQ outperforming the other algorithms by a slight margin. (The shaded cells highlight the best performing algorithm at each encoding rate.) Simulations showed that all the four variants maintain these performance levels over a dynamic range of 40 dB, for 8-bit data [10].

Analysis showed that the best signal domain *phase* performance is achieved by BMPQ and BACQ. This is because BMPQ and BACQ have more reconstruction levels for phase for a given number

Figure 3-1 Quantizer reconstruction levels and quantization boundaries for a 2-D quantizer

Table 3-2 SQNR performance of the variants of BAQ

bits/sample	SQNR in dB			
	BAQ	BMPQ	BHEQ	BACQ
2	9.30	9.19	9.15	9.15
3	14.62	14.57	14.34	N/E[a]
4	20.22	20.22	19.94	N/E[a]

a. Not evaluated

of bits for encoding. However, whether this could result in any improvement in the performance in the processed image domain could only be verified with experimental evaluation.

Compression at 2 bits/sample was selected as a baseline for comparison of the performance of the variants of the BAQ algorithm using simulations with actual SAR signal data. Experimental evaluation of the four BAQ variants at 2-bits per sample showed that:

- The SQNR performance of the four variants was within 0.7 dB of each other, with BAQ giving the best performance of the four variants. For the *detected image*, an average SQNR of about 14 dB was achieved in all cases.
- It had been conjectured that using M/P representation might result in improvement in encoding performance. The results showed, however, that although BMPQ did have the best phase performance in the signal domain, the lower signal domain SQNR of the individual I and Q components prevented this result from being propagated into the image domain. Among the various bit allocation possibilities for BMPQ, only BMPQ(1,3) — i.e. 1 bit

allocated to magnitude, 3 bits to phase — was comparable in performance to the other three variants.

- All the variants showed very good visual image quality, good fidelity in preserving data magnitude and phase distributions, and produced no mis-registration effects.
- The spectra of the detected images were virtually indistinguishable from that of the original image for all variants.
- Apart from a small loss in total peak energy, the point target characteristics for all variants were very well preserved, with negligible distortion in peak phase, 3 dB widths in range and azimuth, peak or integrated sidelobe ratios for all variants.
- Radiometric linearity was perturbed least by BAQ and most by BACQ.
- The phase performance of all the four variants, when encoding to 2-bits/sample, were found to be below acceptable levels for certain specialized applications. An rms phase error of about 30^o was found in the reconstructed processed image data. The rms value of phase error weighted by the magnitude was about 15^o. This is thought to be outside the limits of acceptability in applications such as SAR interferometry — an rms weighted phase error of less than 10^o is desired for such applications.

3.3 Flexible BAQ algorithm (FBAQ)

The intial study of different variants of BAQ established that the overall performance in both the complex image domain and the detected image domain was very similar for all the four variants. BAQ performed slightly better in terms of SQNR. In the case of BMPQ and BACQ, although somewhat better signal domain phase performance was observed, it did not translate to an improved image domain SQNR or phase performance.

For hardware implementation with flexible compression ratios, BHEQ is the most straight forward since it involves no additional hardware for extension from single compression ratio to flexible compression ratios. However, BHEQ requires a large amount of memory to implement the look-up table for the histogram equalizing transformation. Further, the look-up table has to be accessed once for every I or Q sample for encoding. This is a serious limitation for on-board implementation at high data rates.

BAQ requires a total of 11 different look-up tables to achieve flexible compression ratios at 2, 3, and 4 bits/sample. Further, the encoder requires a successive comparator which is a little more complex than the simple truncation involved in the case of BHEQ. However, the look-up tables need to be accessed only once for every block, thus simplifying the design of the look-up tables and their addressing in hardware.

BMPQ, which involves rectangular to polar conversion in hardware, requires higher hardware complexity than both BAQ and BHEQ. The 2-D quantizer for BACQ is inherently limited to low bit rate encoding.

With these considerations, BAQ was selected as the most appropriate variant for implementation as an on-board SAR data encoding algorithm with flexible compression ratios. We have called this extension of the BAQ algorithm to incorporate flexible compression ratios the Flexible BAQ algorithm (FBAQ).

3.4 Optimal of Selection of Implementation Parameters

A number of parameters were identified for the optimal implementation of the FBAQ algorithm for on-board use. Experimental evaluations were performed at 2 bits/sample, since the optimal selection of these parameters were deemed independent of the compression ratio selected.

- The size and shape of the block of samples from which to estimate the optimal thresholds for encoding depends upon the nature of variation the rms value of the SAR signal data along the range and azimuth directions. Experiments showed that the BAQ algorithm is not sensitive to the changes in the block size in the range of ~64 to ~512 samples. Further, the use of two-dimensional blocks did not result in any significant improvement in the performance of the algorithm. For hardware simplicity, and to limit encoding delay, a one-dimensional block oriented along range is preferred.
- Sub-sampling of the block, and using thresholds computed from the statistics of the previous block were considered to simplify the on-board implementation. It was however observed that both these options result in a small degradation of performance of the algorithm. Preliminary hardware analysis showed that these simplifications were not required.
- Independent encoding of I and Q channels was considered to reduce the effect of gain and offset imbalance between channels in the on-board sensor. The effect of this imbalance on the performance of the quantizers was found to be minimal. It was concluded that the effective doubling of complexity of the hardware required for the independent encoding of I and Q channels is not desirable.

Based on the results of these experimental evaluation, the final the set of the parameters for on-board implementation of FBAQ were chosen as shown in Table 3-3.

Table 3-3 FBAQ implementation parameters

encoded bits/sample	Block size along range (Block size along azimuth=1)	LUT size
2 bits	126 pairs of I/Q samples	64x1, 7-bit thresholds
3 bits	84 pairs of I/Q samples	64x3, 7-bit thresholds
4 bits	63 pairs of I/Q samples	256x7, 7-bit thresholds

Note that if the quantizers are linearly spaced across the dynamic range for 8-bit data, the optimum number of entries per threshold look-up table (LUT) is 256. For address space considerations in the on-board implementation, a total look-up table size of 2K entries was preferred. As a result, a slightly sub-optimal size of look-up table is used for encoding at 2 and 3 bits/sample[1]. However, this does not affect the performance significantly.

The thresholds for each block were determined by estimating the rms value using from all samples in the current block, as opposed to a subset of the samples, as was used in the Magellan BAQ implementation [1]. This requires that all the samples of each block have to be stored in a buffer memory until the thresholds for that block become available. This additional memory was determined to result in negligible increase in hardware complexity.

3.5 Evaluation of FBAQ algorithm

A complete performance evaluation of the FBAQ algorithm was conducted by running end-to-end tests at each of the three available bit rates. Each end-to-end test consisted of the following steps:

- raw data encoding and decoding,
- signal domain evaluation,
- SAR processing of original and decoded data sets,
- processed image domain evaluation.

Three data sets with a variety of scene content were used during the test campaign — an agricultural scene from Flevoland, Holland, which included coastline, inland sea, fields and SAR transponders; a mountainous region of Sardegna, Italy; and a suburban region of Flevoland, Holland, which included an airfield and buildings. The latter data set was taken at far range, and was included to test the algorithm under low scene SNR conditions.

Table 3-4 SQNR and Phase Performance Ranges of FBAQ Algorithm

Parameter	2 bits	3 bits	4 bits
Signal domain SQNR, magnitude (dB)	11.10 - 11.64	15.55 - 16.84	21.65 - 22.89
rms phase error (deg)	18.09 - 18.11	11.20 - 11.42	6.92 - 7.00
mean abs. phase error (deg)	14.03 - 14.08	7.87 - 8.05	4.47 - 4.50
Image domain SQNR, magnitude (dB)	14.14 - 14.68	19.29 - 20.16	25.12 - 25.96
rms phase error (deg)	29.78 - 34.61	17.56 - 21.71	10.00 - 12.48
rms weighted phase error (deg)	14.06 - 17.18	7.27 - 9.37	3.60 - 4.49

Table 3-4 shows the range of performance results for the FBAQ algorithm obtained using the three data sets at all three bit rates. The results of the evaluation showed that:

- the images from compressed data had excellent visual quality at all three bit rates, being virtually indistinguishable from the original image, except for a slight increase in background noise at 2-bits/sample. Figure 3-2 and Figure 3-3 show the Original, reconstructed and error images for the Flevoland data set. Note that the error images have been multiplied by a factor of 10 - no structure is visible at x1 magnification.

1. It should be noted that if the number of quantizers is reduced, log spacing gives better performance at low powers and linear spacing gives better performance at high powers. Log spacing does however considerably increase the addressing complexity.

- rms weighted phase error is in the range 14^o - 17^o at 2-bits/sample, 7^o - 9^o at 3-bits/sample and of the order of 4^o at 4-bits/sample. An rms weighted phase error of 10^o or less should be acceptable for SAR applications requiring high phase integrity, encoding at both 3- or 4-bits/sample meets this requirement.
- the statistical moments are slightly degraded at the lowest bit-rate (2-bits/sample) but no significant degradation was observed at either 3- and 4-bits/sample,
- image data and phase distributions are well reproduced at all bit rates,
- point target characteristics are well reproduced at all bit rates, with the only noticeable effect being a small loss in total peak energy at 2-bits/sample,
- the spectra of the detected images were virtually indistinguishable form those of the original image for all bit rates.
- no mis-registration was observed at any of the bit-rates,
- radiometric linearity was slightly degraded at 2-bits/sample, but excellent at 3- and 4-bits/sample,
- the algorithm performance is relatively insensitive to scene content and hence no reprogramming of threshold look-up tables is required for the algorithm as the characteristics of the scene under view changes,
- the algorithm is effective on far- as well as near-range data, with only a slight increase in SQNR and phase error observed at far range.

Thus this algorithm has been found to result in images which meet the requirements of applications dependent on visual properties of the image at all three bit-rates - with the lowest bit-rate giving the additional benefit of allowing wider swath width coverage for the same transmission bit-rate - and to meet the requirements of applications requiring good radiometric and phase performance at 3- and 4-bits/sample.

4 Implementation for On-Board Use

The preliminary designs of the ASAR on-board data handling system were studied, and it was determined that the data compression scheme could be implemented by a single ASIC placed between the A/D converter and the main data handling memory. In addition to the selection of 2, 3 or 4-bits per sample, the ASIC could be programmed to pass 8-bit data through without encoding to perform built-in self tests.

A block diagram of the ASIC functionality is shown in Figure 4-1. A range line of up to 6000 complex samples is divided into blocks of 63 to 126 samples and the rms value of each block is estimated by accumulating the absolute values of the I and Q portions of the complex SAR signal data. This is done with the full 8-bit precision of the A/D converter. The rms estimate is used to select a set of thresholds, depending upon whether 2, 3 or 4-bits per sample are selected. The thresholds are used to quantize the samples in the same data block as the estimate was taken. A successive comparator approach was selected as the most efficient for the ASIC implementation. The index of the selected threshold is multiplexed into the encoded data block.

The threshold values are stored in a PROM outside of the encoder chip. Although these can be reprogrammed, in has been determined in tests that the FBAQ scheme is sufficiently general that there is no need to change threshold levels when the scene content changes.

A synthesizable VHDL model of the FBAQ algorithm has been developed using the V-system VHDL compiler and simulator running under Windows on a PC. The interfaces of the ASIC have been designed to fit into the ASAR Data Subsystem. The ASIC design has been verified using both internal test vectors and real SAR data. In the latter case, the ASIC output was compared with the output of the simulation used in the algorithm study.

ABB HAFO and Matra MHS have been selected as foundries for the chip, and the manufactured ASIC is expected to have the specifications shown in Table 4-1..

Table 4-1 Preliminary specifications of the FBAQ ASIC

Technology	0.8μm CMOS
Estimated Gate Count	< 15,000
Maximum Operating Frequency	20 MHz
Radiation Tolerance	> 30 kRad
Power Dissipation	< 1 w
Packaging	84-pin Quad Flat Pack

5 Conclusions

After assessing the user requirements for satellite SAR image quality, and the image quality/ coverage trade-offs in sensor deployment, it was concluded that an operational ASIC should have the flexibility of encoding to a user-selectable variable precision of 2, 3 and 4-bits per sample. The project objectives were to design the algorithm, to evaluate the accuracy and to design the ASIC for such a requirement. The desired results were obtained in that the 3-bit case was found to yield very good image quality and was deemed suitable for most users. However, users who wanted a very large swath width with reduced emphasis on image quality could choose the 2-bit option, and users who had very precise < image quality requirements could select the 4-bit option (which gives image quality almost identical to the full 8-bit case).

Thus the project has shown that a flexible on-board data compression scheme can be designed for SAR signal data which gives significant compression ratios without an appreciable degradation in image quality. The scheme has been implemented in a single ASIC, whose simplicity, reliability, flexibility and low power consumption make it suitable for use on-board a remote sensing satellite. A prototype ASIC is now being manufactured for the ASAR breadboard with the intent of incorporating it in the ENVISAT data handling system.

Looking beyond the ENVISAT program, the FBAQ encoder is expected to yield additional satellite SAR system improvements. One example is increased range bandwidth, which will give a direct improvement in SAR image quality. Once additional power is available to drive the SAR power amplifiers, the FBAQ algorithm will allow a doubling of range bandwidth, keeping the swath width and data rates the same as on current missions.

6 Acknowledgments

The research work was carried out under contract to the European Space Agency, with Mr. J.-L. Marchand and Mr. D. Chaturvedi as Technical Officers. The detailed ASIC design and testing was performed by Mr. Peter Roos of Saab Ericsson Space, Gothenburg, Sweden.

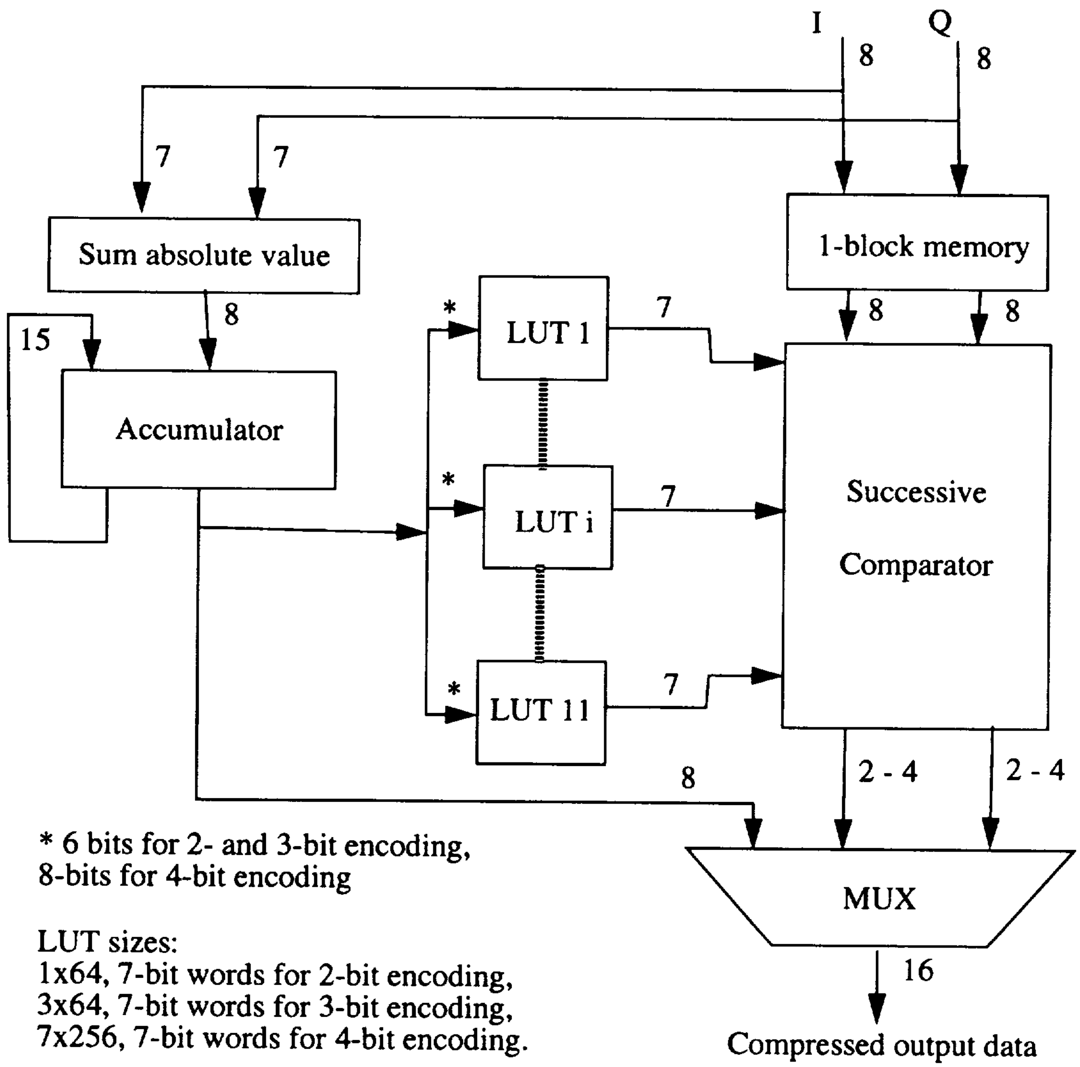

Figure 4-1 Schematic Diagram of FBAQ Encoder with Table Sizes and Word Lengths

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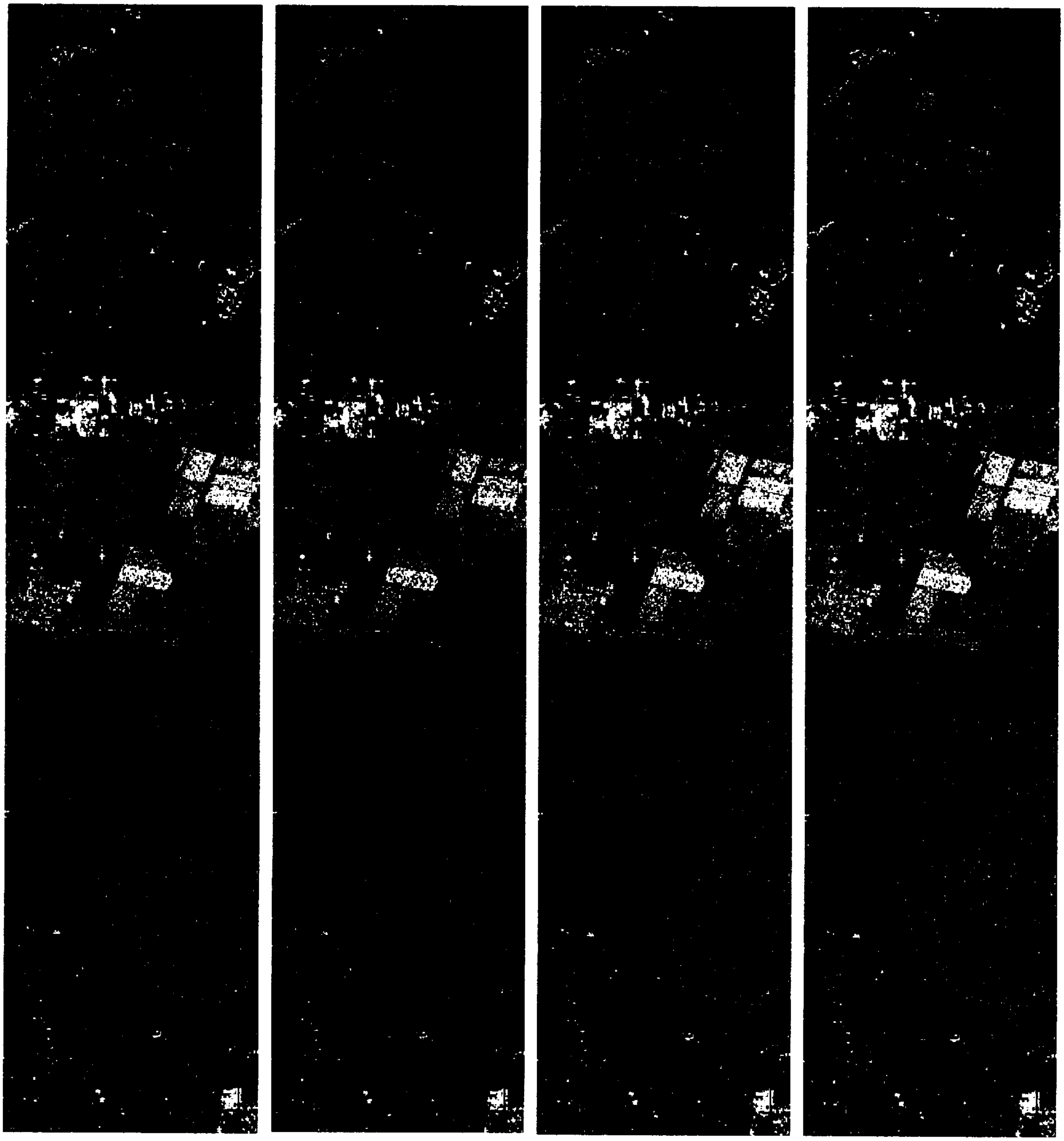
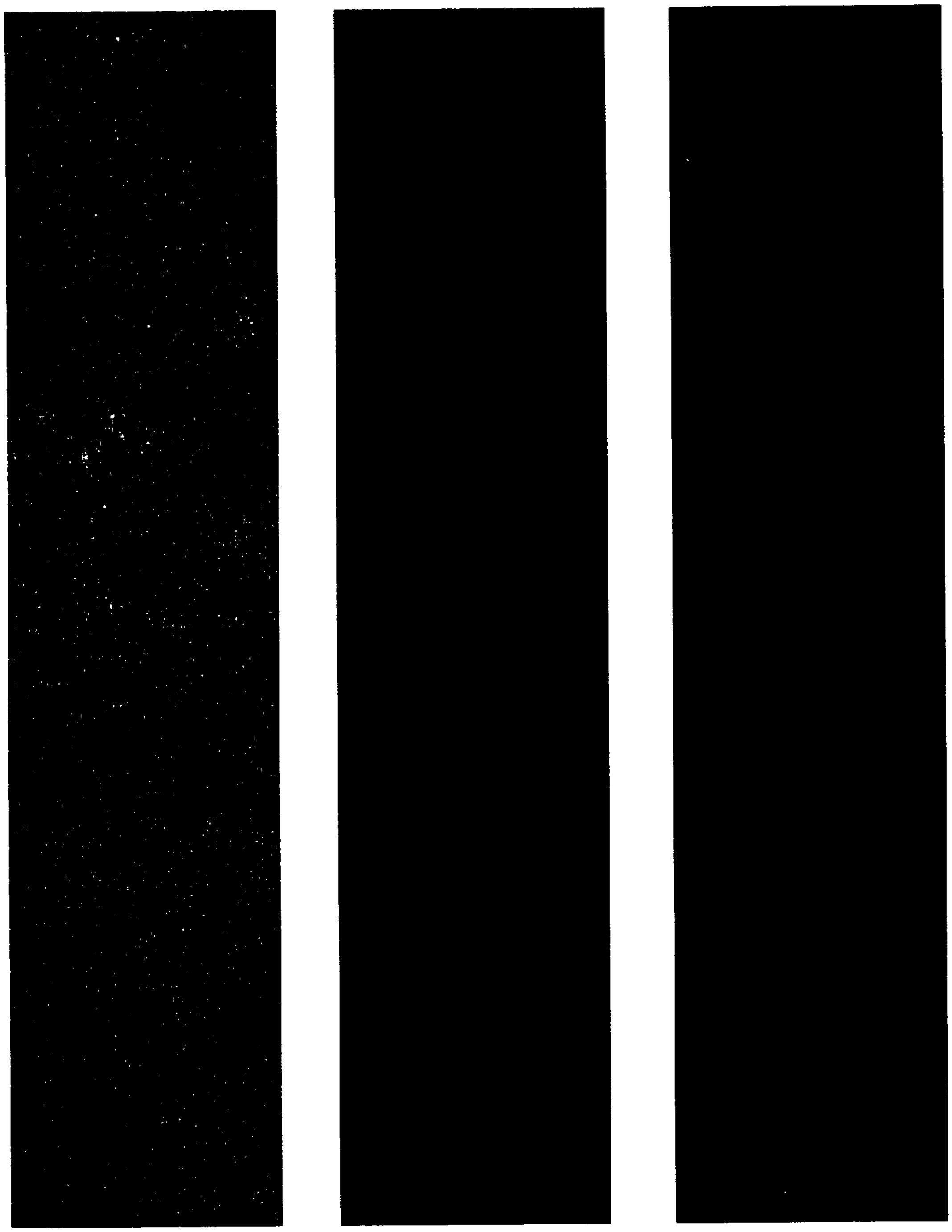


Original 2-bits/sample 3-bits/sample 4-bits/sample

Flevoland Images for Original and Decoded Data



2-bits/sample | 3-bits/sample | 4-bits/sample

Flevoland Difference Images x10