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IMPACT OF DATA COMPRESSION ON QUALITY RADAR IMAGES

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ABSTRACT- *Synthetic Aperture Radar (SAR) systems generate large data volumes that complicate onboard processing and transmission. This paper investigates the impact of several lossy SAR data compression techniques on radar image synthesis quality, including block adaptive quantization in quadrature and polar formats, vector quantization, and Daubechies D4 wavelet-based compression. The quantization signal-to-noise ratio (SQNR) is used as the main evaluation criterion. Simulation models were developed using ERS SAR data with 8-bit in-phase and quadrature components. Results show that for compression ratios of four or higher, the considered algorithms provide comparable performance and preserve the visual quality of synthesized images, while block adaptive quantization and vector quantization achieve higher SQNR at lower compression ratios. These findings confirm that efficient lossy compression can significantly reduce SAR data volume while maintaining acceptable image quality for practical applications.*

Keywords *- Synthetic aperture radars (SAR), vector quantization (VC), block adaptive quantization (BAQ)*

1. Introduction

Synthetic aperture radars (SAR) are effective means of obtaining operational and long-term information about the state and dynamics of objects and regions of the globe, regardless of meteorological conditions and time of day [1]. With the growth of requirements for the quality of information received by RSA, the volume of processed information flows increases. In modern SAR, data streams from grids reach volumes of 4 Gbit/s or more, which complicates the processes of further processing, storage, and transmission of data to Earth. The incoming information contains statistical and visual redundancy, which can be eliminated using SAR data compression algorithms. Lossless data compression algorithms eliminate statistical redundancy and achieve data compression ratios up to 1.4 times. 8-bit ADCs are used in in-phase and quadrature channels) and are of greater practical interest [2]. This article discusses the impact of various approaches to partial lossy SAR data compression on the quality of radar image synthesis, including an algorithm based on the D4 wavelet transform. Next to the quantitative compression criteria, the corresponding results of the synthesis of radar images are given. During the study, the statistical properties of the signal samples were shown, the criteria for the quality of the compression algorithms were determined, various approaches to data compression were selected for consideration, models of the selected compression algorithms were created, which made it possible to obtain quantitative estimates of the criteria and analyze the results.

2.DEFINITION OF QUALITY CRITERIA FOR COMPRESSION ALGORITHMS

To assess the accuracy of restoring samples of the original signal, we define the criteria for the quality of work of SAR data compression algorithms. Consider the statistical properties of the signal samples at the input of the compressor used to minimize the error that appears in the process of compression/decompression. The received signal is a superposition of responses of elementary reflectors [3]:

$$S = \sum_{k=1}^{K} a_k e^{i\theta_k}$$

where a_k amplitude, θ_i phase delays. Amplitude a_k and phase θ_i are statistically independent of each other and of the amplitudes and phases of other elementary reflectors random variables [4-5]. It follows from the central limit theorem that the distribution of values of the received SAR signal, which is the sum of independent random variables, tends to Gaussian at K→∞. The instantaneous values of the in-phase and quadrature components of the signal S have a normal distribution with zero mean. The signal amplitudes are distributed according to Rayleigh, the phases are evenly distributed over the interval [-π, π).

It is important for a radar image synthesis application to restore the samples of the original signal subjected to compression/decompression as accurately as possible. The main criterion for the quality of signal recovery is the signal-to-noise ratio of quantization [6]:

$$\mathrm{SQNR} = 10\log\left[\frac{\sum_{m=0}^{M-1}\sum_{n=0}^{N-1} s_{m,n}^2}{\sum_{m=0}^{M-1}\sum_{n=0}^{N-1}(s_{m,n} - \hat{s}_{m,n})^2}\right]$$

Where $s_{m,n}$ is the initial reading of the digitized signal, $\hat{s}_{m,n}$ restored after compression, the signal count.

The main characteristic of the algorithm is the data compression ratio, calculated as the ratio of the number of bits per sample before and after compression.

3.Approaches to SAR Data Compression

Various approaches to SAR data compression were chosen for the study block adaptive quantization (TANK)in trigonometric(quadrature)format, LHC in polar format, vector quantization (VC), wavelet-based compression-transformations (VP) D4 (Daubechies wavelet).

The operating principle of the block adaptive quantization algorithm is based on splitting the signal sample stream into blocks, for each of which the threshold values of the Max quantizer are calculated and compression is performed [7].Block sizes choose, assuming, so that the statistics of the data in each is close to the normal distribution, And, in the same time, the scene being filmed was fairly homogeneous. For the LHC algorithm in trigonometric(quadrature)format, signal samples are presented as in-phase and quadrature components. When calculating the threshold values choose the Max quantizer coefficients for the normal distribution and the corresponding compression factor [8]. In the case when the readings represent the amplitude and phase of the signal (LHC in polar format), the Max coefficients corresponding to the Rayleigh distribution are chosen for the amplitude, and for the phase - a uniform distribution.

Another approach to compression is vector quantization, which consists of two stages. The purpose of the first stage is to minimize the quantization error of the stream of samples; for this, a code book is compiled. Codebook compilation is an iterative process, described in detail in [9]. The codebook needs to be updated periodically. At the second stage of the algorithm, quantization is performed, and each incoming sample is assigned the number of the vector from the code book for which the quantization error is minimal. To restore the data, the code book that is relevant for this part of the stream is used, while each incoming count-number is assigned a vector in the code book.Compression based on the Daubechies D4 wavelet transform is applied to data samples presented in polar format [10]. The D4 wavelet transform separates the data into low-frequency and high-frequency components, eliminating identical and linearly growing components. The transformation is carried out by multiplying the transformation matrix by the column vector of amplitude readings in the polar format and, then, is performed for the low-frequency component until the number of low-frequency components becomes equal to two (less than the number of D4 coefficients) [11]. The high-frequency components are normalized to the standard deviation of their absolute values and quantized. The inverse wavelet transform for D4 is equivalent to multiplying the received data by the transposed matrix of the original transform. The phase component is quantized uniformly.

4.Simulation of PCA data compression

To study the effect of SAR data compression on the quality of radar image synthesis, SAR data compression/decompression models were created in the Matlab environment. When simulating the operation of compression algorithms, complex ERS SAR readings [12] with 8-bit in-phase and quadrature components were used.

B In the process of operation, the data compression device model, using the LHC algorithm with quadrature components, splits the initial array of complex samples into blocks of 512 (32x16) samples in size of each of the quadratures.

The method described in the article was used to estimate the standard deviation of the quadrature components of the readings. This method uses a one-to-one correspondence between the mean of the absolute values of the samples of a data block and the standard deviation of the samples of the same data block. Pre-calculated RMS values are stored in memory, the address of which is the average of the absolute values of quadrature readings. To calculate the RMS, you only need the average of the absolute values of the readings, which is easier to calculate when implemented in hardware. The RMS value of the sample amplitudes of the i-th data block and the Max coefficients for the normal distribution were used in calculating the threshold values for quantization of the samples of the (i+1)-th data block. RMS of the i-th block and compressed data of the (i+1)-th data block were fed to the compressed data recovery scheme,

The results of modeling the LHC algorithm with a quadrature sample format (LHC sq.) for data compression to 1, 2, 3, 4-bits per quadrature sample (compression ratios 8/1, 8/2, 8/3, 8/4) are presented in figure 1.

Images synthesized from the data obtained because of compression/decompression by the LHC algorithm with a quadrature representation of samples are shown in Figure 2. Figure 3 also shows images obtained from the original data and from those restored after compression.

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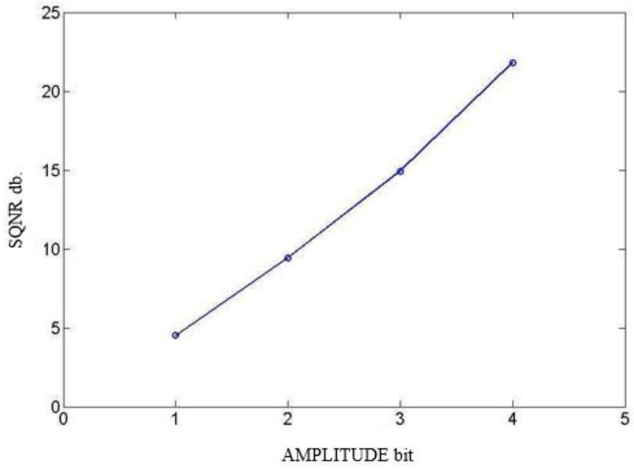

Figure 1. LHC SQNR with quadrature representation of samples.

When compressed to 4 bits per sample (SQNR = 21.8 dB) of quadrature (compression ratio is 2), the image synthesized from the reconstructed data does not visually differ from the image synthesized from the original data. An image synthesized after compression to 3 bits per sample (compression ratios 8/3) differs from that compressed to 4 bits per sample by the appearance of subtle noise at the boundaries of objects. When compressed to 2 bits per sample (compression ratio 4), the noise becomes visually more distinct, but most objects are distinguishable. As a result of compression to 1 bit per sample (compression ratio 8), noise is observed in the image, which makes it possible to distinguish only contrasting and large objects. Thus, data with quantization signal-to-noise ratios of the order of 14-15 dB and higher can be used for the same purposes as the original image.

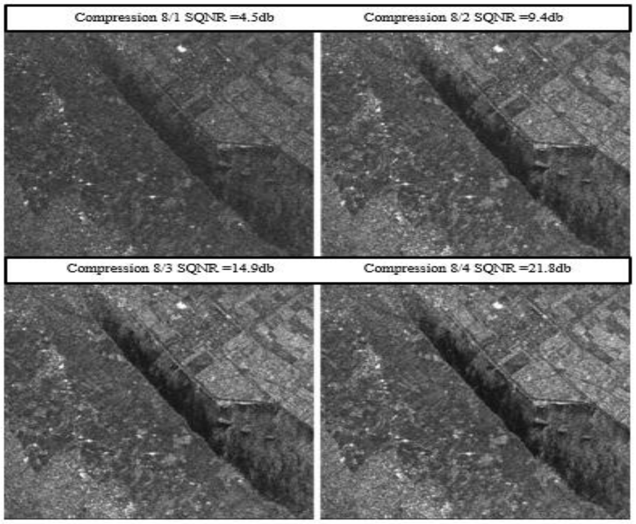

Figure 2. Synthesized images after LHC data recovery.

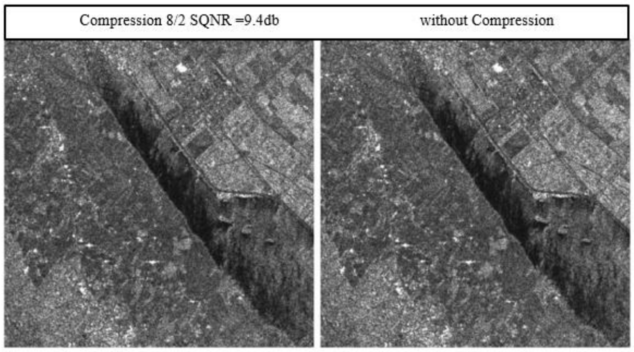

Figure 3. Image synthesis based on the LHC data and on the original data.

To test the operation of the LHC algorithm in the polar data format, the amplitude and phase of each sample were calculated:

$$A_i = round(2^{k1}\sqrt{I_i^2 + Q_i^2}\ /2^{k1}$$

$$Q_i = round(2^{k1}\arg\,(I_i^2, Q_i^2\ )/\pi/2^{k1}$$

where A_i , Q_i are the amplitude and phase of the i-th sample, I_i and Q_i original samples in quadrature representation, round(a) - rounded to the nearest integer a, k1 - number of bits in the binary representation of the amplitude, k2 - number of bits in the binary representation of the phase, the function arg (a) - calculates the argument of the complex number $a_i = I_i + j * Q_i$ on the interval [-π, π).

The following parameters were chosen for modeling:

k1 = 12, (8 bits is the integer part of the number and 4 bits is the fractional part);

k2 = 8, the phase is normalized to π so that the phase values of the i-th sample are in the range [-1, 1).

The standard deviation of the amplitudes of the samples of the i-th block was used to calculate the threshold values of the Max quantizer (Rayleigh distribution) and to compress the samples of the amplitudes of the (i + 1)-th data block. The coefficients of the Max quantizer for uniform were used as threshold values for the complex samples normalized to π phases. RMS amplitudes of the i-th data block and compressed data of the amplitudes and phases of the data samples of the (i+1)-th data block were fed to the data recovery circuit. To restore the amplitudes of the readings, the standard deviation was multiplied by the Max coefficient corresponding to the reading for the Rayleigh distribution. Each phase reading was associated with the Max coefficient for uniform distribution.

The results of modeling the LHC algorithm with a polar sample format (LHC square) for compressing the signal amplitude to 1-4 bits and the phase to 2-5 bits are shown in Figure 4.

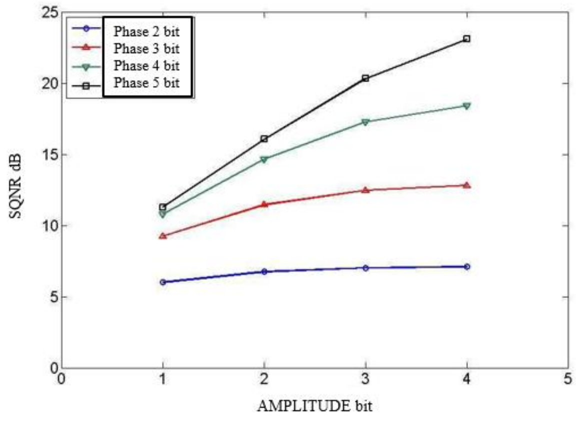

Figure 4. LHC SQNR in polar format.

Figure 4 shows that data compression by the LHC algorithm in polar format to 2 bits of amplitude and 4 bits of phase (data compression ratio 8/3) makes it possible to achieve a quantization signal-to-noise ratio SQNR = 14.6 dB. An image synthesized from data compressed with the above characteristics will be visually almost indistinguishable from the original. By using fewer bits to represent amplitude and phase, the synthesized image will exhibit noise and visual differences from the original, similar to those shown in Figure 2 with the corresponding characteristics.

In the created model of data compression by the method of vector quantization for the construction of the code book, the amplitudes of the in-phase and quadrature components were used as samples of the test sequence. The length of the test sequence N = 65536 samples. Minimum error increment value 10-3.

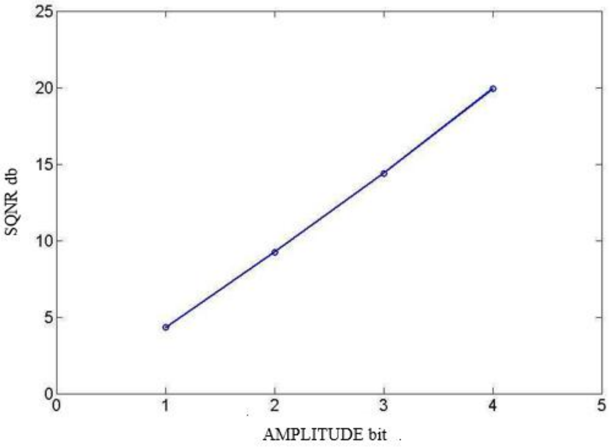

Figure 5. SQNR for vector quantization.

The results of modeling the vector quantization (VC) algorithm for a codebook of size 2, 4, 8, 16 vectors (encoded respectively 1, 2, 3,4 bits) are shown in Figure 5.

Figure 5 shows that the VC has SQNR indicators comparable to the LHC in the quadrature format. Thus, images obtained from data recovered after compression by the VC method up to 3 (SQNR = 14.4 dB) and up to 4 bits (SQNR = 19.9 dB) per quadrature sample are suitable for use in the same tasks as the original image. But unlike the LHC, the VC has a more complex implementation, requires periodic use of a test sequence to calibrate the codebook vectors, and, in addition to transmitting the numbers of vectors in the codebook, also transmits the codebook itself.

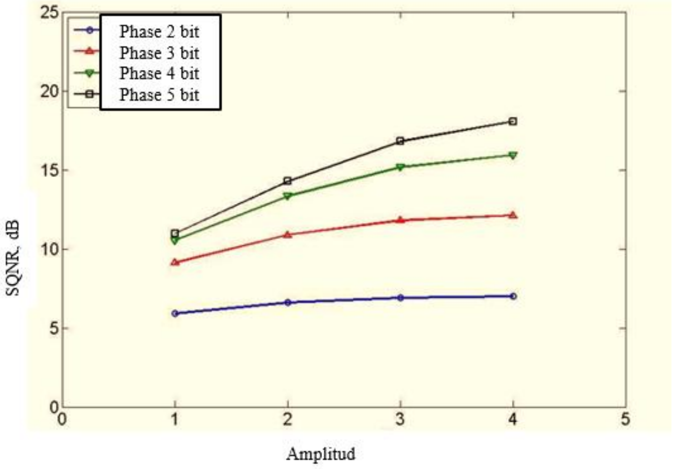

Figure 6. SQNR for compression based on the D4 VI.

In the compression model using the wavelet transform (WT D4), the complex data were reduced to the polar format by the same algorithm as for the LHC in the polar format. The signal amplitude was subjected to compression based on the wavelet transform. Sample block size amplitudes was chosen equal to 2048, because after the D4 conversion, two low-frequency components with a size of 12 bits remain, the remaining components are normalized to the RMS and quantized.

The simulation results for signal amplitude compression to 1-4 bits and phase to 2-5 bits by the D4 wavelet transform method (D4 WT) are shown in Figure 6.

This figure shows that data compression by the Daubechies D4 wavelet transform has comparable SQNR characteristics with the LHC algorithm in polar format at compression ratios of 4 or more (1-2 bits per amplitude sample, 2-3 bits per phase sample). At compression ratios less than 4, D4 IP compression has an SQNR 2-5 dB less than LHC and vector quantization. Images synthesized after compression of the amplitude to 2 bits and phase to 5 bits (SQNR = 14.3 dB) and at large SQNRs are practically indistinguishable from the original. To increase the SQNR and more accurately restore the amplitude values while maintaining the compression ratio, wavelets are required that eliminate high-order moments, but this complicates practical implementation.

The results of ERS data compression modeling for all considered algorithms are presented in Table 1.

The use of SAR data obtained as a result of compression / restoration by LHC algorithms in quadrature format and VC up to 3-4 bits per quadrature sample makes it possible to obtain an image that is visually almost indistinguishable from the original one with quantization signal-to-noise ratios (SQNR) of the order of 14-15 dB and 19-22 dB. Similar results are achieved when compressed by the LHC algorithm in the polar format of amplitude up to 2-4 bits per sample, phase up to 4-5 bits per sample, SQNR over 14 dB. For the D4 VI algorithm, similar results are achieved for 3-4 bits per amplitude sample and 4-5 bits per phase sample.

Table 1. Characteristics of SAR data compression algorithms.

Compression algorithm	Coefficient compression times	SQNR, dB
LHC quadrature 1I+1Q	8	4.5
TANK quadrature 2I+2Q	4	9.4
LHC quadrature 3I+3Q	8/3	14.9
TANK quadrature 4I+4Q	2	21.8
TANK polar 1A+2F	16/3	6.0
TANK polar 1A+3F	4	9.2
TANK polar 1A+4F	16/5	10.8
TANK polar 1A+5F	8/3	11.3
VK 1I+1Q	8	4.3
VK 2I+2Q	4	9.2
VK 3I+3Q	8/3	14.4
VK 4I+4Q	2	19.9
VP D4 1A+2Φ	16/3	5.9
VP D4 1A+3Φ	4	9.1
VP D4 1A+4Φ	16/5	10.5
VP D4 1A+5Φ	8/3	11.0

5.Conclusion

In this work, we investigated the impact of data compression in space-based SAR on an image synthesis application.

In the work defines a criterion for the quality of data compression algorithms, which makes it possible to evaluate the accuracy of data recovery after compression,

relative to the original data: quantization signal-to-noise ratio (SQNR). The description of approaches to the implementation of models

compression/decompression of SAR data based on block adaptive quantization (BAQ) algorithms in quadrature format, LHA in polar

format, vector quantization (VC), Daubechies D4 wavelet transform (WP D4), which made it possible to obtain quantitative characteristics of the algorithms used for further analysis.

In the article presents the characteristics of compression algorithms obtained by modeling, by which the possibility of using various approaches to data compression in the problem of synthesizing radar images is estimated, an example of synthesizing a radar image from data subjected to compression / decompression is shown.

Simulation results using SAR ERS data show that all the considered algorithms, with compression ratios of 4 more times, have similar characteristics. In this case, noise is observed on the synthesized image, the brightest and most contrasting objects are clearly distinguishable. The image synthesized from the reconstructed data with compression less than 4 times visually practically does not differ from the image synthesized from the original data. At the same time, LHC algorithms in both formats and VK allow achieving quantization signal-to-noise ratios larger by 2-5 dB, compared with compression by the D4 IP method. LHC with quadrature representation of samples is the simplest of the considered algorithms in terms of practical implementation.

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