ADAPTIVE SAR IMAGE COMPRESSION IN WAVELET DOMAIN

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ABSTRACT

Synthetic Aperture Radar (SAR) provides valuable information for the remote sensing community. Polarimetry and interferometry are most important applications. They require amplitude and phase information of complex SAR data. Here, we propose a flexible phase preserving algorithm (FLECS) to compress these complex SAR data. Flexibility allows adjustment of compression ratio to the application's requirements. Adaptability of the algorithm ensures a signal-to-distortion-noise ratio and a phase error, which is nearly independent from image contents. The algorithm uses wavelet transform for energy packing and linear quantization for lossy compression in transform domain. In case of separately performed phase compression vector quantization is applied.

1 INTRODUCTION

Polarimetry and interferometry are most important remote sensing applications of SAR systems. They allow detailed extraction of information and the derivation of precise digital elevation models. A disadvantage is the huge data rate associated with those applications. Instead of one single data set, two, four or even eight channels of complex data have to be transmitted. Data compression becomes mandatory.

Performance of data compression can be measured according to two different strategies: 1) Application independent: No disadvantages for any application are given due to data compression. 2) Application dependent:
No disadvantages for a certain application are given. Any drawbacks for other applications are not considered.

Here, the first strategy is followed. Lossless compression would be ideal, but it is not efficient for SAR data with high entropy. Thus, lossy algorithms have to be used and a trade-off between compression ratio and performance is performed. There are various approaches, which focus either on high compression ratio or on high reconstruction quality. In wavelet domain very high compression ratios still allow visual detection of main objects. High quality data compression of fully polarimetric complex data is usually applied on the scattering matrix itself [9]. A reduced data rate dr = 20 bits per complex sample causes a signal-to-distortion noise ratio SDNR ³ 40 dB and a standard deviation of phase error: $stdev(\hat{j}) < 1^\circ$. Another promising approach compresses the trigonometric functions of copolar and polar phase to simultaneously reduce speckle [7]. However, both algorithms are not applicable for interferometric data sets.
We present a flexible approach for SAR image compression, applicable on complex SAR data or on SAR intensity images. The algorithm operates over a wide range of compression ratios with high performance.
In standard mode this data compression algorithm is very suitable for SAR data compression with respect to class A and class B products [1]. *Adaptability to image contents* (see chapter 3) is introduced to achieve an uniform SDNR and to reduce varying phase errors. 1) Areas with very high dynamic are treated separately, so that they can be accurately reconstructed and do not disturb surrounding neighborhood. 2) Edges are detected and compressed with a lower compression ratio. This ensures enhanced edge preservation.

2 ALGORITHM DESIGN

We propose a new *phase preserving* SAR image data compression algorithm suitable for class A and class B SAR products. Dependent on the desired application and the memory or channel requirements an applicable compression mode, compression ratio or reconstruction quality are selected.

2.1 SELECTION OF COMPRESSION MODE

Our approach is applied to complex SAR data either in polar or in cartesian format. The selected format depends on several parameters.

Polar mode is chosen,

- if the phase information has to be perfectly reconstructed and no phase compression is allowed (Class A products with extremely high reconstruction requirements);
- if no phase information is required and all phase information is omitted (Class B products);
- if both, amplitude compression and phase compression, are required together with a large compression ratio (Class A products with reduced reconstruction requirements).

Cartesian mode is applied,

- if only a small compression ratio ($cr < 10$ for compression of E-SAR data) is allowed;
- if high reconstruction quality is desired (Class A products).

2.2 ALGORITHM IMPLEMENTATION

2.2.1 Phase Compression in Polar Mode

If *phase data* are to be compressed separately, *learning vector quantization in time domain* is used. Two samples in azimuth and range are combined to one vector exploiting the correlation between those neighbored samples. A codebook with 2^14 codevectors is used, thus a compression ratio $cr = 4 \times 32/14 = 9.14$ is achieved. The performance of the applied vector quantizer [6] is dependent on the initial codebook. We achieved best results, if all initial codevectors are equally spaced on the diagonal in the four-dimensional cube. Ongoing studies will consider other learning strategies, e.g. FCM or FLVQ [3], which lead to an enhanced independence of the initial codebook. However, they have larger computational requirements for training.

2.2.2 Wavelet Based Compression in Polar and Cartesian Mode

Our wavelet-based approach is applied on *amplitude data in polar mode* and on *real and imaginary part in cartesian mode.*

We apply a Daubechies wavelet transform on slightly overlapping data blocks of 1024 by 1024 samples in azimuth and range direction. Overlapping is necessary to avoid invalid data. The amount of overlapping pixels corresponds to the number of wavelet coefficients. One iteration of the wavelet transform is performed. The transform coefficients in each wavelet subband are quantized using a block adaptive linear quantizer. The wavelet subbands are divided into N quantization blocks $q_i, i \le 1 \le N$. To ensure approximately constant statistic within one block q_i, the block size is small, e.g. 8 by 8 samples. The quantizer is adapted to the dynamic range d_i of each block q_i: $d_i = \max(q_i) - \min(q_i)$ with $\max(q_i)$ and $\min(q_i)$ maximum and minimum value within quantization block q_i, respectively. Dynamic range d_i is divided into equally spaced intervals I_m, $I_m, m \le 1 \le M_i$. The number M_i is given by the available bit number b_i for quantization of block q_i: $M_i = 2^{b_i}$.

In *standard mode* all quantization blocks q_i within one wavelet subband are quantized using the same bit number. The four bit numbers $b_{LL}, b_{HH}, b_{LH}, b_{HL}$ for the four wavelet-subbands LL, HH, LH and HL form a bit mask *B*.

The bit mask *B* is evaluated based on the ac energy distribution within the subbands (the higher the subband's ac energy the higher is the subband's bit number) and optimized in an iterative process to gain minimum quantization distortion. During the optimization process the average bit number $b = (b_{LL} + b_{HH} + b_{LH} + b_{HL})/4$ is fixed to ensure a desired compression ratio.

Decompression requires transmission of header information: Bit mask *B* and for each quantization block maximum $\max(q_i)$ and minimum $\min(q_i)$. Decompression starts with inverse quantization. Afterwards, the inverse wavelet transform is performed to retrieve the reconstructed SAR image data. In case of polar mode with transmitted phase information, the data are re-converted into cartesian format to get their original representation.

The proposed SAR data compression algorithm is very suitable for compression considering class A and class B products. The phase of class A products are preserved very well. With respect to interferometric and polarimetric applications where usually multi-looking [8] is used prior to phase calculations, we estimate the phase error also after averaging the data by a small 3 by 3 window. Table 1 shows both, the rms phase error without averaging the phase and after averaging the phase data.

	SDNR	rms phase error	rms phase error (averaged)	cr	dr
class A product	65 dB	0.2°	0.1°	3	21.3
	60 dB	0.3°	0.1°	3.2	20
	30 dB	5°	1.9°	8	8
class B product	13 dB	-		64	1

***Table 1**: Compression performance on E-SAR data for representative class A and class B products; rms phase error is measured after and without averaging phase data. (cr: compression ratio, dr: data rate in bits/sample)*

There is nearly no change in coherency between the channels, point target localization and geometric resolution due to data compression. These good results are valid for all four polarimetric channels and the two interferometric channels. Only small differences are measured for different sensor types (e.g. E-SAR and X-SAR).

The algorithm's minimum data rate *dr* equals one bit/sample. This is a suitable mode for Class B products. Phase information is omitted, but intensity data are still retrieved to a high degree. Statistics of the data are preserved very well. Thus, automatic classification based on distribution comparison is efficient for both, the original and the decompressed data.

We tested the algorithm on a polarimetric L-band SAR data set. Considered classes were urban, forest, medium vegetation, low vegetation and smooth surface. For classification of SAR data Fuzzy Interactive Analysis was used [2]. For both data sets, original and decompressed we get 95% overall accuracy. Most errors occurred assigning the class urban. The performance (product of user's and producer's accuracy) was slightly increased by the compression (64 % to 70%) due to the denoising effect of the compression algorithm.

3 ADAPTABILITY TO IMAGE CONTENTS

The foregoing sections describe the algorithm in its standard design without adaptability to image contents. Size and form of quantization blocks q_i and bitnumber b_i do not depend on the image contents. A very good performance is achieved for homogeneous regions. However, problems occur if one single block q_i contains very high and very small coefficients. If the quantizer is adapted to the high coefficients this leads to significant errors on the smaller ones and causes a small signal-to-noise ratio SDNR and an increased phase error $\hat{j}$ for block q_i. This distortion, which is dependent on the local image contents, can be detected in SNDR maps and phase error maps, where SDNR and phase error $\hat{j}$ are visualized for each pixel. Obviously, most distorted regions are edges and background around point targets. Therefore, compression has to be adapted for two major categories of quantization blocks: 1) Blocks containing strong backscatter of point targets and simultaneously very small backscatter from background and 2) blocks containing sharp edges. These blocks are characterized by a mixed statistic. Performance of the proposed data compression algorithm is decreased compared to blocks with pure statistic, because the linear quantizer is no longer adapted to the statistic.

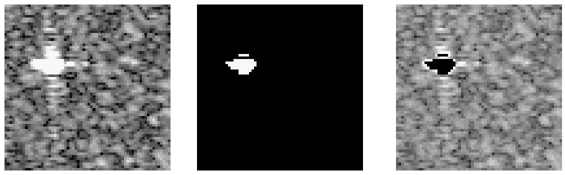
Improvements are possible, if 1) the few high coefficients are separated and 2) blocks q_i with mixed statistic are split into smaller blocks q_i' with approximately pure statistic. Prior to this separation from homogenous regions, these blocks q_i with disturbed statistics have to be identified. We describe improved compression of 1) environment of point targets and 2) edges.

3.1 ENHANCED PRESERVATION OF POINT TARGET NEIGHBORHOOD

Backscatter from point targets is very strong and leads to high wavelet coefficients in all subbands. A linear quantizer adapted to these coefficients deteriorates the adjacent small coefficients. Due to those high and small coefficients in one single block, the quantization intervals I_m are very large and only few quantization levels are assigned to the small coefficients. This results in bad SDNR of those blocks q_i and a minor reconstruction quality for pixels adjacent to point targets.

To detect those blocks with very high dynamic we analyze each subband's dynamic. Based on this dynamic thresholds are chosen to decide between very high coefficients and smaller ones. The locations of these coefficients are stored in a map, which is an additional input into the header. This map is used to quantize block q_i. High coefficients within the block are quantized with an increased number of bits or remain even uncompressed whereas the other coefficients are quantized with b_{XY} the usual bitnumber of wavelet subband *XY*.

Thus, the high dynamic can be maintained. A perfect reconstruction of point targets is possible, which is especially helpful for exact calibration of SAR images. Compression performance on the adjacent pixels is equal to the performance of the algorithm on homogeneous areas.



a) b) c)

Fig. 1: *Separation of high coefficients and background: (a) Quantization block q_i (here, 64 by 64 pixels), (b) Corresponding point target map (c) Adjacent background*

3.2 ENHANCED EDGE PRESERVATION

If quantization block q_i contains edges this depicts a more complicated case to get a homogeneous reconstruction quality. It is not only sufficient to separate edge pixels from those blocks but to use the edges to distinguish between several regions of different statistics. All edges themselves must be considered as extra region. All regions are compressed separately. We recommend spending more bits on edge regions, because adaptation to their mixed statistic by non-linear quantization is difficult.

We employ a fuzzy edge detection algorithm [4] on the data set to localize edges in quantization blocks. A pixel p(x,y) is assigned to be an edge pixel e(x,y), if the dissimilarity D between the mean of the pixel's neighborhoods exceeds a certain threshold. As neighborhoods two symmetrical 7 by 7 windows are chosen. The resulting crisp edge map is downsampled to match the sampling rate of the wavelet subbands. Whenever a block q_i contains edge pixels the block is split into several regions of probably different statistics. Each region and the edge line itself are to be compressed separately. Therefore adaptive compression control needs this region map or the related edge map as input. The edge map is added to the header.

3.3 ADDITIONAL EXPENSES COMPARED TO STANDARD MODE

These improvements in reconstruction qualities of edges and in environments of point targets require the creation of a corresponding point target map and of a region map. The bitnumber is no longer constant within one wavelet subband and additional min-max pairs have to be evaluated and stored in the header. These requirements result in *more computation time and increased header information for the adaptive mode*. However, computation time is only increased for data compression. Data decompression is not effected. The point target map (indicating single high coefficients by 1 and other coefficients by 0) is a sparsely filled binary map, which can be compressed with standard loss-less compression techniques. The same is valid for the edge map. By compressing an edge map with the standard ZIP algorithm (loss-less), we gained a compression ratio of 40, for example. The number of additional min-max pairs is small, because only few blocks are affected and usually contain not more than 2 regions.

4 EXPERIMENTAL RESULTS

The enhanced preservation of environments around point targets is yet fully integrated into our algorithm. It can be switched on or off by setting a certain flag. We compressed SLC E-SAR images and a detected ScanSAR image [5]. In all cases, we gain great improvements in the algorithm performance. By preserving the environments of point targets, not only all pixels are preserved much better but also *block effects* caused by point targets are minimized. Using a compression ratio of 4 we increase the minimum SDNR from 35 dB to more than 50 dB. (compare fig. 5).

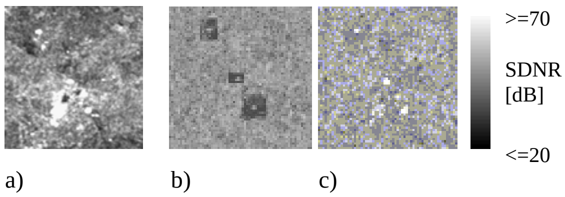


Fig. 2: a) Part of a detected ScanSAR image (64x64 pixels) including three major point targets, b) SDNR map without and (c) after adaptive compression with less block effects and increased image quality.

We tested the *enhanced edge preservation* on a SLC E-SAR image. The problem, here, is to find an accurate fitting edge map which is able to separate pixels of different statistics precisely. Up to now this mode needs some manual interaction for appropriate edge linking.

Enhanced edge preservation improves the overall SDNR only slightly, but leads to a more homogeneous error distribution across the SLC image.

Figure 3 compares the standard operation mode with additionally applying EEP. Performance loss happening in standard mode (white values in Figure 3a) disappeared more or less in Figure 3b. Similar to the magnitudes of SLC images, we observe more homogeneous phase error maps and a much smaller overall standard deviation of the phase error. The standard deviation of the phase error decreased from 3.4° to 2.0° whereas compression ratio was only reduced from 3.76 in standard mode to 3.63 in adaptive mode including all header information.

5 DISCUSSION

The standard mode of FLECS achieves good results for most regions in the image. A compression ratio cr = 3 promises a nearly perfect reconstruction, a compression ratio cr = 8 has still only minor impacts on polarimetric and interferometric applications. Even a data rate of 1 bit/pixel does not deteriorate automatic classification. *The enhanced mode* increases the homogeneity of quantization error distribution and leads to further improved image reconstruction. The overall compression ratio is not much decreased by the additional header information and - most important - decompression is hardly more expensive than in standard mode. Compression performance is determined by the performance of edge detection and the localization of blocks with high dynamic. Future studies will consider the optimization of the synergy between these modules and data compression.

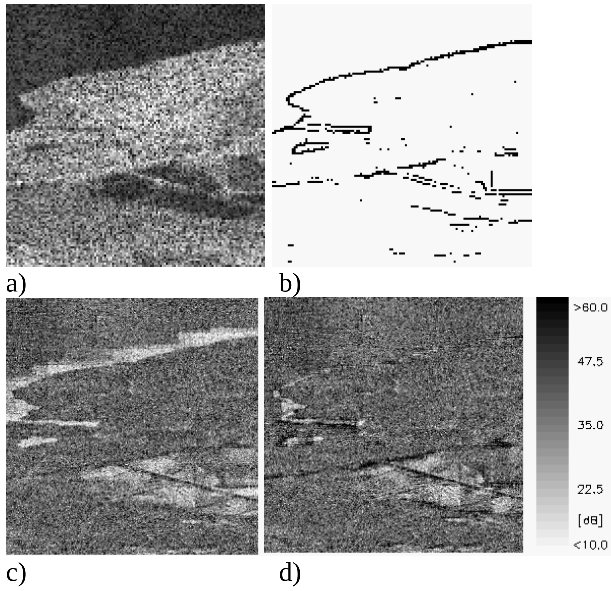


Fig. 3: Enhanced edge preservation: a) SAR image, b) edge map, c) SDNR map without and d) after adaptive compression

6 REFERENCES

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