Efficient SAR Raw Data Compression in Frequency Domain

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Abstract: SAR raw data compression is necessary to reduce the huge amount of data for downlink and the required memory on board. In view of interferometric and polarimetric applications for SAR data it becomes more and more important to pay attention to phase errors caused by data compression. Here, a detailed comparison of block adaptive quantization in time domain (BAQ) and in frequency domain (FFT-BAQ) is given. Inclusion of raw data compression in the processing chain allows an efficient use of the FFT-BAQ and makes implementation for on-board data compression feasible. The FFT-BAQ outperforms the BAQ in terms of signal-to-quantization noise ratio and phase error and allows a direct decimation of the oversampled data equivalent to FIR-filtering in time domain. Impacts on interferometric phase and coherency are also given.

SAR RAW DATA COMPRESSION

SAR raw data consist of a linear superposition of the scene backscattering in the radar field of view. Since the radar instantaneous field of view is very wide in range and azimuth the superposition consists of innumerous contributions leading to a Gaussian distributed signal with zero mean. Adjacent samples are nearly uncorrelated.

Block adaptive quantization is a very standard lossy SAR raw data compression and is based on the Gaussian statistical behavior of the SAR raw data. A bit rate of 4 bits/sample, 3 bits/sample or 2 bits/sample is usually applied.

The main module is a Max-Lloyd quantizer which is adapted to the signal statistics block by block.

The BAQ was applied in a simplified mode on several spaceborne SAR missions such as Magellan Mission to Venus [1] and on the Shuttle Radar Mission (SIR-C) in 1994.

It is also planned to use a *flexible BAQ* (FBAQ) in ENVISAT. An extensive study was performed by McLoed, Cumming and Seymour in [2] where interferometric phase errors and reduction of coherency due to block adaptive SAR raw data compression are estimated.

They concluded that only a 4 bit FBAQ can be used if DEM's are to be generated from repeat pass interferometry. An additional height error due to data compression of less than 3% is assumed.

The main advantage of using a stand alone BAQ is the very simple implementation. If a one-dimensional block size is used, as it is planned for ENVISAT, only a small memory is required. This enables the design of a single space qualified ASIC for BAQ compression.

But new hardware developments let envisage more sophisticated algorithms.

First, *entropy coding* can be considered. However, the high entropy of SAR raw data is well-known in literature. *Lossless data compression* is therefore restricted to small compression ratios. Entropy coding of BAQ coded samples is even less efficient because the data's entropy is increased by BAQ coding. Therefore, using BAQ with 4 bits/sample entropy coding leads only to an additional compression ratio of 1.06 which means an average bit rate of 3.79 bits/sample. The remaining entropy is 3.75 bits/sample. Small improvements of compression ratio (less than 0.1) are possible, if blocking is introduced. Here, neighbored data are fused to one code word. Unfortunately, header information increases significantly.

Fusing of neighbored BAQ coded samples to a vector enables an efficient lossy compression of SAR raw data. The BAVQ (*block adaptive vector quantizer*) uses the remaining correlation similar to the blocking entropy coder, but due to the lossy approach higher compression ratios are possible. Of course, in addition to the standard BAQ a codebook has to be trained and stored in memory. BAQ coding prior to vector quantization reduces training time, size of the code book and search time compared to a full vector quantizer.

BAVQ leads to a slightly improved image quality compared to BAQ, but it does not justify the additional computations. Best results are achieved if the BAQ is applied in frequency domain. WHT, DCT and FFT in fusion with a BAQ (*WHT-BAQ, DCT-BAQ, FFT-BAQ*) were applied on SAR raw data by Benz, Strodl and Moreira [3]. WHT and DCT were applied separately on inphase and quadrature channel. A linear algorithm can be assumed because of the small amount of lossy quantization. Thus, the separation is valid. All algorithms performed well. However, the best results were obtained using FFT. The compression was applied on airborne data of the experimental SAR (E-SAR) of DLR and data of the ERS-1 satellite. The methods were compared with BAVQ, BAQ and a fuzzy BAQ regarding signal-to-distortion-noise ratio, geometric resolution, peak-sidelobe-ratio (PSLR) and integrated sidelobe-ratio (ISLR), radiometric linearity and phase errors.

Considering these studies the main candidates for SAR raw data compression are the *standard block adaptive quantizer* and the *block adaptive quantizer in Fourier transform domain (FFT-BAQ)*. Up to now, FFT-BAQ was not applicable due to the higher computational requirements. But improvements in hardware design, e.g. the development of efficient FFT processors make the implementation of a FFT-BAQ possible.

DESIGN OF FFT-BAQ INCLUDING DIGITAL FILTERING

First, SAR raw data are blockwise normalized to reduce influences of the antenna pattern. Secondly, the transform is applied on large blocks of the normalized data. The transform block size is determined by the length of the correlation filter. The transform coefficients are Gaussian distributed. The variance is estimated and used by the BAQ which compresses the coefficients with a varying number of bits.

The *optimum block size* of the BAQ in transform domain should not exceed 32 x 32 samples and not be smaller than 8 x 8 samples. Larger block sizes in azimuth and/or range direction reduce image quality significantly. The statistic is no longer constant within the block. On the other hand it is necessary to have at least a certain number of samples per BAQ block to secure reliable estimations of the block's standard deviation. One-dimensional blocks in range are not recommended, because only a smaller block size can be selected due to the changing statistic in range direction. Therefore, we strongly recommend the BAQ working on two-dimensional blocks to get the largest blocks with an approximately constant statistic. This is in opposite to the ENVISAT solution where one-dimensional blocks are selected to save memory. This constraint is no more necessary for future systems.

The BAQ quantizes frequency coefficients with bit numbers which are more or less defined by the SAR system characteristics. For example, frequency coefficients which carry less energy due to the antenna pattern are quantized using less bits. Coefficients which will be neglected by low pass filtering are omitted.

Therefore, the FFT-BAQ *automatically* performs *digital filtering* of oversampled data. No additional low pass has to be implemented. This means that any required decimation of the SAR data is carried out by the FFT-BAQ without effort.

Of course, the FFT in this case needs the estimated Doppler centroid and the processed bandwidth. Thus, Doppler parameter estimation, SAR processing and data compression are closely related to each other.

COMPARISON BETWEEN FFT-BAQ AND BAQ

We performed a detailed comparison of both approaches on data sets of airborne and spaceborne sensors (E-SAR and X-SAR) for stripmap mode. The impact of compression and decompression is measured on raw and image data. The decompressed raw data are compared to low pass filtered original raw data. The bandwidth of the original data is reduced according to the bandwidth used by SAR processing. To measure the reconstructed image quality the decompressed raw data are processed in the same way as the unfiltered original raw data. Both images are used to evaluate signal-to-noise ratio and phase error.

The FFT-BAQ outperformed the BAQ for all considered compression ratios in the achieved signal-to-distortion-noise ratio as well as in phase noise. Further improvements for X-SAR compression are possible if antenna weighting in range is additionally taken into account.

Fig. 1 shows the resulting performance in terms of signal-to-distortion-noise ratio and phase error on E-SAR raw data for several blocks of data. The signal-to-distortion-noise ratio of the FFT-BAQ for n bits is similar to the BAQ using n+1 bits. The same relation is true for phase noise if bit numbers n = 2 or n = 3 are used. Compression of X-SAR data by FFT-BAQ using 0.39, 2.05 and 3.07 bits/sample leads to 6 dB, 19 dB and 24 dB, respectively, in the resulting image. Thus, the FFT-BAQ using 3 bits/sample achieves the same performance as the BAQ using 4 bits/sample does. Better reconstruction is possible if a smaller compression ratio is applied and if not only in azimuth but also in range a reduced bandwidth and a weighted antenna pattern is considered. Fig. 2 depicts the signal-to-distortion-noise ratio measured on each pixel to show dependence on image contents and Fig. 3 shows the pixel by pixel phase error. The smaller the backscatter the worse is the introduced quantization error on magnitude and phase. However, this is less severe than in case of a standard BAQ.

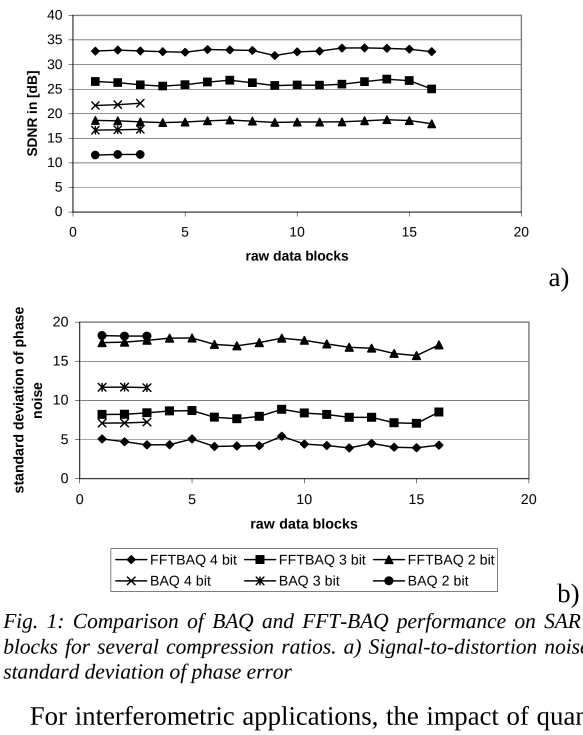

Fig. 1: Comparison of BAQ and FFT-BAQ performance on SAR raw data blocks for several compression ratios. a) Signal-to-distortion noise ratio, b) standard deviation of phase error

For interferometric applications, the impact of quantization noise on interferometric phase and coherency is of special interest.

In our recent studies for interferometric applications we measure only small degradation of coherency and interferometric phase if FFT-BAQ is applied. For a 4 bit FFT-BAQ the coherency is usually not decreased at all, at most a reduction of 0.03 is measured. The standard deviation of phase errors introduced into interferometric phase amounts 10.4 degree before smoothing (compare Fig. 4) and 4.8, 3.7 and 3.4 degree after smoothing with smoothing factors of 3, 5 and 7, respectively.

There are no severe effects if a BAQ with 4 bit is selected [2]. With FFT-BAQ phase unwrapping and reliable DEM generation should be possible with only 3 bits/sample. Follow on studies will show whether there are any impacts for phase unwrapping due to FFT-BAQ, but there should be less than in case of block adaptive quantization.

DISCUSSION

These results prove the outstanding performance of FFT-BAQ for airborne missions as well as for spaceborne missions. The FFT-BAQ achieves approximately the same performance as the BAQ does, but for one bit less. A data rate of only 3 bits/sample leads to very good reconstructed image quality. Main reason is the included digital filtering but also the weighted bit numbers in accordance to the antenna pattern.

Additionally, the signal to noise level is very homogeneous over the whole data set. No blocking occurs, because data compression is performed in transform domain and quantization errors are spread over all samples in time domain. Thus, also a high radiometric accuracy of the reconstructed data is expected.

The computational costs of the FFT-BAQ are significant, but the performance of the algorithm outperforms all other approaches. Considering the fact that there are now efficient FFT processors available, FFT-BAQ comes into consideration for SAR raw data compression for spaceborne missions. Furthermore, the first stages of chirp scaling are FFTs and they can be used for data compression as far as it will be possible to omit the normalization step in FFT-BAQ.

Considering this possible synergy with onboard processing and digital filtering, the computational costs of the FFT-BAQ are comparable to a standard BAQ.

It is an important part of the future work to investigate this synergy and study how it can be used in the data flow to reduce computational requirement and make FFT-BAQ applicable for onboard SAR raw data compression.

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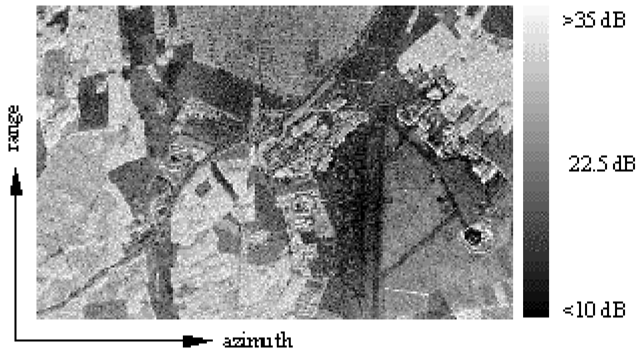

Fig. 2: SDNR map after FFT-BAQ compression (4 bits/sample)

Fig. 3: Phase error map after FFT-BAQ compression (no smoothing applied)

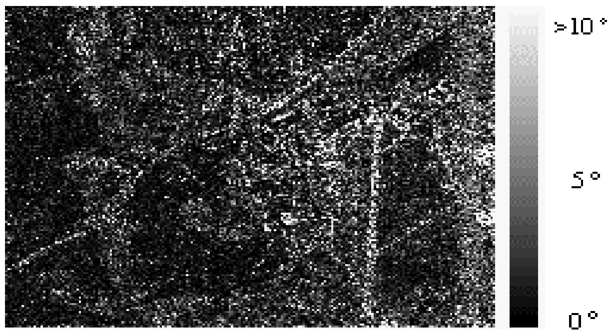

Fig. 4: Interferometric phase error after FFT-BAQ compression (no smoothing applied)