RAW DATA COMPRESSION EXPLOITING MODEL-BASED APPROACHES AND ARTIFICIAL INTELLIGENCE FOR PRESENT AND NEXT-GENERATION SAR SYSTEMS

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ABSTRACT

Present and next-generation synthetic aperture radar (SAR) missions require an increasing volume of onboard data, due to the employment of large bandwidths, multiple channels and polarizations, and large swath widths acquired by bi- and multi-static sensor configurations. This leads to stringent requirements in terms of onboard memory and downlink capacity, hence making the proper quantization of the SAR raw data represents an task of utmost importance, as it affects the amount of data but also the quality of the SAR and InSAR products. This paper presents novel methods for efficient SAR raw data compression, which make use of artificial intelligence for the joint optimization of bitrate allocation and the resulting performance and exploit the potential of transform and predictive coding schemes for data volume reduction in the context of multi-azimuth channel (MAC) SAR. Simulations and analyses on real data are presented, showing the suitability of the proposed methods.

***Index Terms*—** Synthetic Aperture Radar (SAR), SAR Interferometry (InSAR), Raw Data Quantization, Data Volume Reduction.

1. INTRODUCTION

Synthetic aperture radar (SAR) represents a well-recognized technique for a broad variety of remote sensing applications, as it is able to acquire high-resolution images of the Earth's surface, independently of daylight and weather conditions. Next-generation SAR systems will bring significant improvements in performance through the exploitation of digital beam forming (DBF) techniques in combination with multiple acquisition channels, bi- and multi-static sensor configurations, together with the use of large bandwidths. This will allow, among others, for overcoming the limitations imposed by conventional SAR imaging for the acquisition of wide swaths and, at the same time, of finer resolutions. Such innovative approaches are currently being widely applied in recent studies, technology developments and mission concepts by several space institutions and industries. The significant improvements that can be achieved in terms of acquisition capabilities are associated with the generation of huge volumes of data, which, in turn, set harder requirements for the onboard memory and downlink capacity of the system. Indeed, present global SAR mapping missions, such as Sentinel-1 or TanDEM-X, or future missions, such as NISAR and especially ROSE-L and Sentinel-1 Next-Generation, will acquire data over selected areas with a temporal sampling down to one week, resulting in large data volumes which need to be handled by the SAR sensor. In this scenario, the efficient digitization of the SAR raw data represents an aspect of crucial importance as, on the one hand, it directly defines the amount of on-board data volume while, on the other hand, it also affects the quality of the generated SAR products. The most widely used compression schemes for SAR raw data digitization is the Block-Adaptive Quantization (BAQ) [1]. In the last years, building on the principle of BAQ, novel acquisition-dependent compression schemes algorithms have been proposed, allowing for a finer performance and resource optimization, as in the case of the FDBAQ used on Sentinel-1 [2], or combined with the implementation of non-integer data rates [3]. In the context of the Performance-Optimized BAQ (PO-BAQ), the basic concept of the original BAQ is further extended in [4], which represents a first attempt for an optimization of the resource allocation depending on the performance requirement defined for SAR and InSAR product. Such an optimization is achieved by exploiting the a priori knowledge of the SAR backscatter statistics of the acquired scene. In the last years promising developments have been made in exploiting the use of JPEG2000 [5] as well as of complex autoencoders [6], [7] for efficient raw data compression.

Artificial Intelligence (AI) represents a promising approach in the remote sensing community, since it enables

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scalable exploration of big data bringing new insights on information retrieval solutions [8]. In this paper, we investigate the use of AI, and in particular of deep learning (DL), for onboard SAR raw data compression, with the aim of deriving an optimized and adaptive data rate allocation, fully adaptive with respect to the acquired data and the radar backscatter statistics of the scene under illumination and depending on a pre-defined SAR/InSAR performance requirement. The method was first introduced in [9], while in this paper we present more detailed results are presented in Section 2. In the context of multichannel SAR, the azimuth raw data often exhibit significant redundancy or correlation caused by specific constraints in the system design, and we propose to exploit transform and predictive coding for data volume reduction, which are elaborated in Section 3. Analyses on real and simulated data show that the proposed methods allow for a significant reduction of the data volume to be downlinked to the ground at the cost of a feasible increase of onboard computational effort and complexity. The paper is concluded in Section 4 with some outlook to future works.

2. AI-OPTIMIZED SAR RAW DATA QUANTIZATION

The quantization performance depends on the local characteristics of the illuminated scene on ground, which are, in turn, linked to the local topography, targets properties and acquisition geometry, resulting in different radar backscatter absolute levels and degrees of heterogeneity [10]. In order to achieve a joint optimization of bitrate allocation and the resulting performance degradation, we propose an AI-based data compression method whose high-level workflow is provided in Figure 1. According to it, the bitrate map (BRM) generated from the DL architecture is estimated on board for raw data quantization. The proposed DL architecture is based on a standard convolutional neural network (CNN) with three convolutional layers interleaved with max pooling operations and followed by a dense layer as final head. For the generation of the reference BRMs used for training we have acquired experimental uncompressed TanDEM-X data (i.e. quantized with 8-bit ADC), and re-quantized them using different BAQ rates (i.e., 2, 3, 4 and 6 bits/sample). The reference BRMs are then derived by considering the minimum local bitrate which satisfies a pre-defined performance requirement for the given SAR image (in the focused SAR image domain), while the bitrate estimation task is treated as a regression problem. Figure 2 depicts (a) the true (*reference*) BRM and (b) the BRM estimated by the AI-BAQ (*inference*) for a scene over the urban area of Mexico City and a target signal-to-quantization noise (SQNR) of 15 dB. For this and other examples we could verify that the error between reference and estimated bitrate maps has typically no significant bias and, considering the high degree of heterogeneity of the scene, a reduced a error standard deviation of about 0.3 bits/sample is obtained. A large variety of different land cover classes as well as acquisition geometries have been considered for the generation of the training data set, in order to properly generalize the DL model. Table 1 shows the SQNR achieved by the proposed AI-BAQ for four considered test areas, characterized by different land cover types, and AI-BAQ is able to achieve the performance aligned with the pre-defined requirements (differently from other compression scheme, such as fixed-rate BAQ and FDBAQ [2]: in most cases the mean SQNR error achieved by the AI-BAQ with respect to the requirement is below 1 dB (while for BAQ and FDBAQ we observed it above 2-3 dB in some cases) and smaller performance deviation is obtained. Also, if a 10 dB SQNR was targeted for the specific application, AI-BAQ would require up to 1 bit less than what would be needed by the FDBAQ (2.2 bps for AI-BAQ versus about 3.2 bps for FDBAQ - the bitrate selection method of the latter is simply designed with a different optimization criteria [2]), which corresponds to a data volume reduction of up to about 30%.

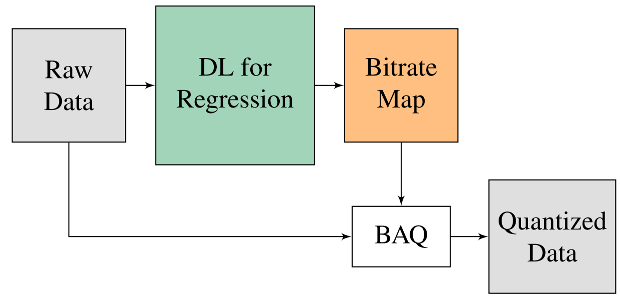
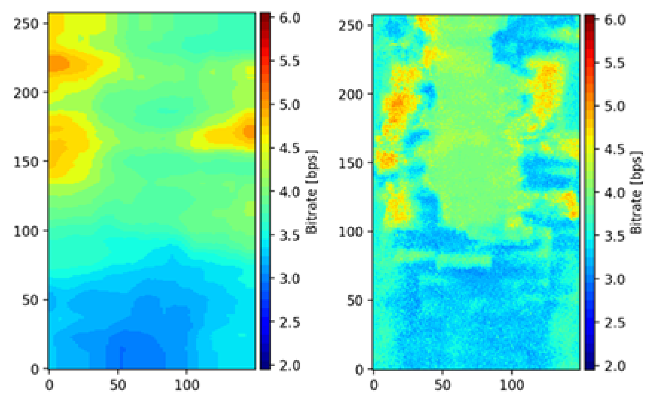


Fig. 1: Flowchart of the proposed AI-BAQ method: the raw data matrix is fed into the trained DL model which predicts the required bitrate map (BRM) to achieve the desired performance. An adaptive BAQ quantizer performs the raw data encoding with the estimated BRM.



(a) Reference BRM. (b) BRM estimated with AI-BAQ.

Fig. 2: BRM generated for an urban area of Mexico City for the target case of SQNR=15 dB. True (reference) and estimated (test, inference) BRM.

Performance target	Greenland	Uyuni	Las Vegas	Mexico City
SQNR = **10** dB	10.67 ± 0.14	10.22 ± 0.52	9.68 ± 1.27	9.60 ± 0.84
SQNR = **15** dB	15.55 ± 0.18	15.27 ± 0.64	14.68 ± 1.34	14.51 ± 0.94
SQNR = **20** dB	18.68 ± 0.57	20.45 ± 0.48	19.99 ± 1.30	19.71 ± 0.95
SQNR = **25** dB	22.52 ± 1.06	25.03 ± 0.55	23.83 ± 1.28	23.98 ± 1.06

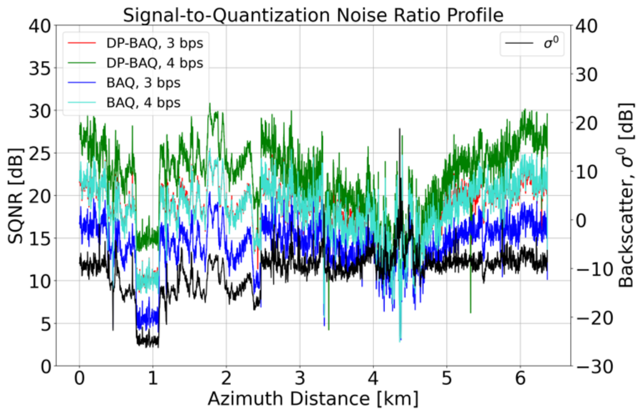
Table 1: Performance achieved by the proposed AI-BAQ for different SQNR requirements and test sites (mean +/- standard deviation, in dB). The colors indicate when the target performance was met within 1.5 dB (in green), or partially met (yellow).

Parameter	ROSE-L-like	HRWS C band	HRWS X band
Carrier frequency, f_c	1.25 GHz (L band)	5.04 GHz (C band)	9.65 GHz (X band)
Satellite height, h_{sat}	697 km	697 km	514 km
Antenna type	Planar array		
Acquisition mode	Stripmap		
Azimuth antenna length, L_{az}	11 m	12.8 m	5.04 m
Number of azimuth channels, N	5	8	[4, 8]
Pulse repetition frequency, PRF_{sys}	1364 (uniform sampling)	1188 Hz (unif.)	3017 Hz (unif.)
Target azimuth resolution, Δ_{az}	[1.5, 3, 5, 10] m	[1.5, 3, 5, 10]	[1.5, 3, 5, 10] m
Total processed bandwidth, PBW	[4510, 2255, 1353, 676] Hz	[4691, 2346, 1407, 704] Hz	[4691, 2346, 1407, 704] Hz
ADC Resolution	8 bits	8 bits	8 bits

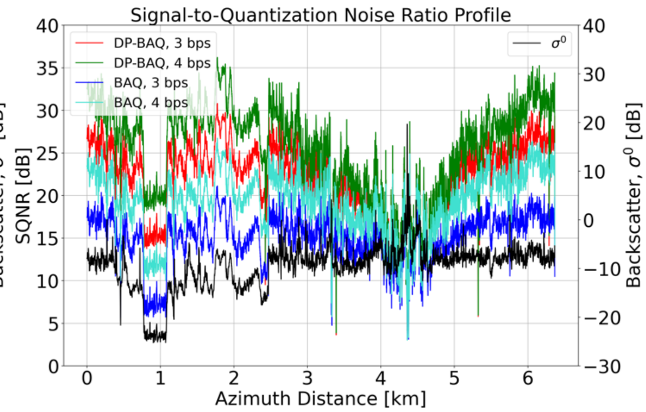
Table 2: Multichannel SAR system parameters.

3. EFFICIENT DATA VOLUME REDUCTION FOR MULTICHANNEL SAR

Multi-channel SAR allows for overcoming the inherent trade-off of conventional (single-channel) SAR systems in terms of achievable swath width and azimuth resolutions. Indeed, by exploiting multiple receiving apertures which are mutually displaced in the along-track dimension, the coherent combination of the individual received signals allows for adequate suppression of the ambiguous parts of the Doppler spectra and, in this way, high-resolution wide-swath imaging is achieved [12], [13]. The drawback for such an improvement of swath coverage and resolution is represented by a significantly larger data volume to be acquired and transmitted to the ground. In this work, three multichannel SAR system examples are investigated, and the corresponding system parameters are summarized in Table 1: in particular, different radar frequencies – L, C, and X band – are considered, and the parameters are realistic for currently investigated multichannel SAR missions, such as the ROSE-L and a Sentinel-NG-like system. To investigate potentials and limitations of data volume reduction for multichannel SAR, we have analysed the multichannel SAR raw signal characteristics, such as the autocorrelation and the Doppler power spectrum by means of simulations and generation of synthetic data as well as real TanDEM-X backscatter profiles, to identify relevant trade-offs of SAR system parameters in the context of data volume reduction. In particular, we have considered the impact of the antenna pattern shape (azimuth length, carrier frequency), the number of azimuth channels N, the PRF and more specifically the oversampling factor o_f = PRF/PBW, being PBW the the processed Doppler bandwidth. As an example, based on the oversampling and the autocorrelation properties exhibited by the HRWS X-band system (right column in Table 2), we present the potential of linear predictive coding (LPC) for efficient data volume reduction. For this, we applied the Dynamic Predictive (DP)-BAQ proposed by the authors in [11] in the context of staggered SAR systems: Figure 3 illustrates the SQNR for the case of (a) $N = 4$ and (b) $N = 8$ channels (corresponding to a $o_f = 2.6$ and $o_f = 5.2$ for the 1.5 m resolution case, respectively), evaluated for a backscatter azimuth profile of a TanDEM-X scene over the urban area of Mexico



(a) $N = 4$.



(b) $N = 8$.

Fig. 3: SQNR profiles for different quantization schemes (BAQ and DP-BAQ as in [11]) and bitrate (3 and 4 bps), depicted with different colors, for a backscatter profile over the urban area of Mexico City (shown in black). The X-band HRWS multichannel system is considered for (a) $N = 4$ and (b) $N = 8$ channels.

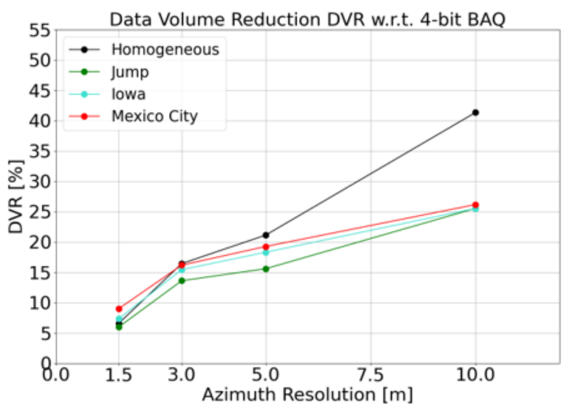


Fig. 4: Data volume reduction (DVR) in % w.r.t. the 4-bit BAQ case, for the HRWS C-band system, as function of the azimuth resolution (i.e. Doppler bandwidth) for the four considered azimuth profiles, depicted with different colours.

City (in black, right y-axis). The resulting SQNR profiles are derived for the BAQ and the proposed DP-BAQ [11] (depicted with different colors), and a consistent data volume reduction with respect to the 4-bit BAQ case of about 25% up to more than 50%, for the case (a) and (b), respectively, is achieved.

We also considered the transform-coding-based data compression method proposed in [14], referred to as multichannel (MC)-BAQ, which is based on a joint transformation in the Doppler domain of the multichannel block and adaptive bitrate allocation. Figure 4 shows the data volume reduction achievable by the HRWS C-band system, for different backscatter profiles (depicted with different colors) and azimuth resolutions, corresponding to processed bandwidth ranging from about 700 Hz to 4600 Hz, which results in a data volume reduction (w.r.t. the 4-bit BAQ case) up to 40%, hence verifying the suitability of the proposed method for data volume reduction in multi-channel SAR.

4. CONCLUSIONS AND OUTLOOK

In this paper we first investigated the potential of Deep Learning for deriving an on-board performance-optimized bitrate allocation for SAR systems. For this, we generated a proper training dataset by commanding experimental uncompressed bistatic TanDEM-X acquisitions to derive reference bitrate maps for the DL architecture. The obtained performance and results confirm the effectiveness of the proposed method. Furthermore, we analyzed further opportunities for data volume reduction in multichannel SAR. For such systems, efficient data compression strategies can be proposed, which aim at exploiting the existing correlation between subsequent azimuth samples. We assessed the statistical properties of the multichannel raw signal have been considered and, for performance assessment, we considered three multichannel SAR system architectures. Based on these, we simulated multichannel raw data using synthetic data as well as backscatter profiles from real SAR TanDEM-X. The obtained results and performance assessment are promising, highlighting the trade-off, potential and limitations of the proposed methods for data volume reduction in multichannel SAR. As next steps, we will conduct an end-to-end performance evaluation on SAR/InSAR performance (i.e. not limited to quantization degradation only), together with an assessment of the non-linear and signal-dependent impact of SAR compression on different quality measures (e.g. detection, phase), also investigating the potential of the proposed methods in the context of multistatic SAR configurations.

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