8th INTERNATIONAL WORKSHOP ON ON-BOARD PAYLOAD DATA COMPRESSION (OBPDC 2022)

28-30 SEPTEMBER 2022

EFFICIENT ON-BOARD QUANTIZATION AND DATA REDUCTION METHODS FOR PRESENT AND NEXT-GENERATION SAR SYSTEMS: RECENT ADVANCES AND FUTURE PERSPECTIVES

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INTRODUCTION

Nowadays, synthetic aperture radar (SAR) represents a well-established technique for a broad variety of remote sensing applications, being able to acquire high-resolution images of the Earth's surface, independently of daylight and weather conditions. In the last decades, innovative spaceborne radar techniques have been proposed to overcome the limitations which typically constrain the capabilities of conventional SAR for the imaging of wide swaths and, at the same time, of fine spatial resolutions. In addition to that, present and future spaceborne SAR missions are characterized by the employment of multi-static satellite architectures, large bandwidths, multiple polarizations and shorter revisit time. This inevitably leads to the acquisition of an increasing volume of on-board data, which poses hard requirements in terms of on-board memory and downlink capacity of the SAR system itself. This paper presents an overview of the efficient raw data quantization and data volume reduction methods which have been recently proposed and developed at the Microwaves and Radar Institute of the German Aerospace Center (DLR). In particular, we focus our attention on multi-azimuth channel (MAC) SAR and staggered SAR: for such systems, a pulse repetition frequency (PRF) typically higher than the processed Doppler bandwidth is selected for system design constraints. The resulting oversampling and correlation properties of the azimuth SAR raw signal can be exploited by applying an efficient encoding and digitization of the SAR raw data in order to reduce the on-board data volume. Simulation results 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 modest increase of on-board computational effort. Furthermore, we investigate opportunities for data volume reduction for Frequency Scanning (FScan), an innovative SAR acquisition mode which allows for high-resolution wide-swath imaging by implementing a frequency dependent beam pointing, which is artificially increased via the use of time delays within the array antenna. In this scenario, different solutions for on-board data volume reduction are investigated, which are based on the use of transform coding (DFT), including deramping and block-wise approaches.

The techniques introduced so far can be combined with an efficient selection of the quantization rate used during the SAR raw data acquisition. This represents an aspect of primary importance, since the utilized compression rate is directly related to the volume of data to be stored and transmitted to the ground and, at the same time, it affects the resulting SAR imaging performance. We therefore introduce the performance-optimized block-adaptive quantization (PO-BAQ), a novel approach for SAR raw data compression which aims at optimizing the resource allocation and, at the same time, the quality of the resulting SAR and InSAR products. This goal is achieved by exploiting the a priori knowledge of the local SAR backscatter statistics, which allows for the generation of high-resolution bitrate maps that can be exploited as a helpful tool for performance budget definition and data rate optimization of present and future SAR missions.

MULTI-CHANNEL BLOCK-ADAPTIVE QUANTIZATION FOR MAC SAR

For conventional single-channel SAR systems, it is well known that the pulse repetition frequency (PRF) poses opposite constraints for the imaging of wide swaths and, at the same time, of fine azimuth resolutions. Indeed, the former dictates a low PRF to allow for a sufficient temporal separation between subsequent SAR pulses, while the latter requires a large Doppler bandwidth and, therefore, high PRFs. Such inherent limitations can be overcome by exploiting multiple receiving apertures which are mutually displaced in along-track, together with digital beamforming (DBF) in elevation. The coherent combination of the individual received signals allows for an adequate suppression of the ambiguous parts of the Doppler spectra so that high-resolution wide-swath imaging can be achieved [1], [2].

Let us consider a multi-channel SAR with N receiving azimuth apertures. We define v_{sat} as the satellite velocity, PRF_{sys} as the transmit PRF and l as the azimuth separation between the sub-apertures, i.e. the total azimuth antenna length $\text{L}_{\text{az}} = N \cdot l$. If the following constraint on the PRF is fulfilled

$$\text{PRF}_{\text{sys}} = \frac{2v_{\text{sat}}}{L_{\text{az}}} \tag{1}$$

then the azimuth raw data stream is uniformly sampled, hence the resulting system is equivalent to a single-channel SAR with $\mathrm{PRF}_{\mathrm{eff}} = N \cdot \mathrm{PRF}_{\mathrm{sys}}$ and a conventional SAR processing can be applied. More in general, due to timing constraints and requirements on the ambiguity-to-signal ratio, the PRF is often selected so that (1) is not fulfilled, and an appropriate signal reconstruction of the unambiguous Doppler spectrum of the non-uniform azimuth data needs to be carried out on ground by properly combining the N subsampled channels as in [1], [3]. In multi-channel SAR systems, a swath width of hundred kilometres and more can be imaged with an azimuth resolution in the order of one meter [2], [4].

The present analysis was carried out on the example of a single platform C-band system ($f_c = 5.5$ GHz) with planar array antenna with length L_{az} =12.8 m and $N = 8$ azimuth receive channels. For such a system, the raw data samples received by its N azimuth channels exhibit a certain degree of correlation, introduced by the antenna pattern (or Doppler spectrum) together with a certain signal oversampling (defined by $\mathrm{PRF}_{\mathrm{sys}}$) of the azimuth data stream [5]. Typically, for multi-channel SAR, a processed bandwidth PBW significantly smaller than the "effective" pulse repetition frequency $\mathrm{PRF}_{\mathrm{eff}}$ (given, in turn, by the product of the number of apertures times the transmit PRF) is required in order to get a sufficient azimuth ambiguity-to-signal ratio (AASR), i.e. $\mathrm{PBW} < N \cdot \mathrm{PRF}_{\mathrm{sys}}$ [1], [2]. However, a direct downlink of the acquired multichannel data is associated with an unnecessarily high data rate, as the effective PRF is significantly higher than the processed Doppler bandwidth. A way to exploit the existing spectral selectivity is to perform a (lossless) discrete Fourier transform (DFT) on the multi-channel azimuth block. Then, an efficient quantization strategy is implemented, which allocates more (or less) resources for those sub-bands lying in the more (or less) "useful" portion of the Doppler spectrum (respectively, carrying a smaller amount of information, i.e. that are located outside the processed bandwidth).

The workflow for the proposed onboard data reduction strategy is sketched in Fig. 1 and discussed in detail in [6]: for each instant of time m, the signal received by the i-th azimuth channel, s_i is first digitized by a high-resolution analog-to-digital converter (e.g. 10-bit ADC). The multi-channel raw data block is then decomposed by using the orthogonal transformation $\boldsymbol{F}$ into a set of K azimuth beams $y = \boldsymbol{F}s$ ($\boldsymbol{F}$ represents to the discrete Fourier transformation matrix), each one corresponding to a different portion of the Doppler spectrum. The output transformed coefficients are then further compressed by means of a set of block-adaptive quantizers (BAQ), and for this a proper selection of each compression rate n_k associated to the k-th coefficient y_k needs to be applied. BAQ is one of the most widely used lossy data reduction techniques for SAR raw data compression which employs a space-varying estimation of the raw data statistics in order to set the quantization decision levels. BAQ offers a good trade-off between scheme complexity (a simple scalar quantizer), achievable compression ratio, and resulting image quality, hence representing an attractive solution for data volume reduction in spaceborne SAR systems. The set of quantized coefficients $\hat{\boldsymbol{y}}$ is then downlinked to the ground, where the inverse transform, multichannel reconstruction and SAR focusing are finally carried out.

The optimum bit rate to be selected for the k-th output channel is derived from rate-distortion theory [7] as

$$R_k \cong \bar{R} + \tfrac{1}{2}\log_2 \frac{\sigma^2{}_k}{\left[\prod_{l=1}^{N} \sigma^2{}_l\right]^{1/N}} = \bar{R} + \Delta R_k, \tag{2}$$

where $\bar{R}$ is the mean allowed bit rate, $\sigma^2{}_k$ is the power associated to the k-th sub-band, and ΔR_k is the resulting bit rate contribution to be added ($\Delta R_k > 0$) or subtracted ($\Delta R_k < 0$) for the k-th channel. The power contribution $\sigma^2{}_k$ is estimated as the fraction of the power spectrum integrated over the Doppler bandwidth and its expression is provided in [6].

Regarding the required onboard complexity, the proposed technique can be performed in real time by using a state-of-the-art FPGA, since a limited amount (in the order of a few tens) of additional operations is required for each received range line and multi-channel azimuth block for the implementation of an N points Fast Fourier Transform (FFT).

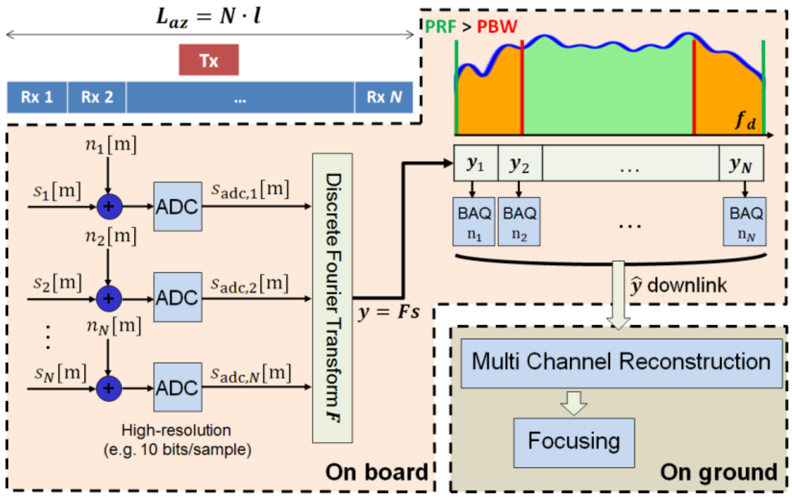


Fig. 1. MC-BAQ for onboard data reduction for a SAR system with multiple azimuth channels: s_i is digitized by a high-precision ADC. The multi-channel azimuth block of length N is then decomposed by means of a discrete Fourier transform. As a next step, a proper bit allocation is applied to the transformed coefficients (the BAQ n_i blocks on the right-hand side) to optimize the resulting data volume and performance. The quantized coefficients $\hat{\boldsymbol{y}}$ are finally downloaded to the ground, where inverse transform, multi-channel reconstruction, and SAR focusing are performed.

Fig. 2(a) shows the patterns for the transmit antenna (in blue) and a single receiver element (in red) for the considered system. Phase spoiling is applied in transmission and a transmit $\mathrm{PRF_{sys}}$ of 1265 Hz is selected. The actual processed bandwidth PBW is represented by the shaded orange area and is of about 5.6 kHz, which corresponds to about 55% of the effective PRF (delimited by the dashed green lines, the sampling rate in reception is $\mathrm{PRF_{eff}} = 8{\cdot}1.26 \sim 10$ kHz). By this, a swath width of about 100 km can be achieved with an azimuth resolution of 1 m.
For the assessment of the proposed method, we have considered the signal-to-quantization noise ratio (SQNR) as performance measure, evaluated on simulated focused SAR images. The SQNR is defined as the power ratio of the non-compressed signal s to the quantization error $\varepsilon_q = s - s_q$ affecting the reconstructed signal s_q

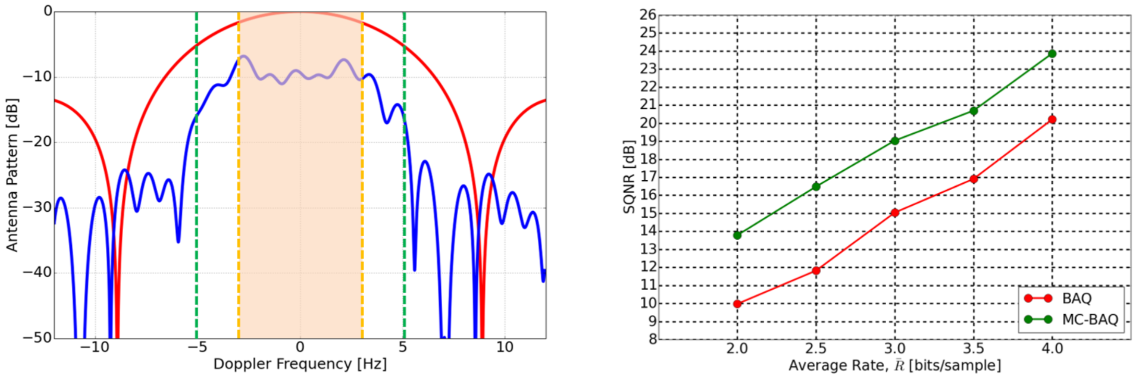
$$\mathrm{SQNR} = |s|^2/\left|\varepsilon_q\right|^2. \tag{3}$$

Fig. 2(b) shows the SQNR (in dB) obtained for a simulated homogeneous SAR scene, as a function of the average rate $\bar{R}$. The performance of a standard BAQ is taken as reference and is depicted in red, while the SQNR for the proposed MC-BAQ is shown in green. As an example, a 4-bit BAQ has the same SQNR as a 3.25-bit MC-BAQ (both around 20 dB), hence achieving a data reduction of about 18-20%. On the other hand, if a 3-bit BAQ is used as reference, the resulting data reduction is around 25%. For the given system parameters (PRF, PBW, antenna patterns), the optimum bit rate sequence to be employed for the quantization of the transformed coefficients is derived according to (2), leading to $\Delta\boldsymbol{R}$ =[-2.0, -1.3, +0.9, +0.8, +0.9, +0.8, +1.0, -1.1] bits/sample.
The performance of the proposed MC-BAQ strongly depends on the ratio $r = \mathrm{PBW}/\mathrm{PRF_{eff}}$. This implies that the more r gets closer to one, the lower is the achievable data reduction will be. The number of receive channels N also plays a key role in determining the achievable performance, since the larger N is, the finer the power spectrum is sampled, and hence reconstructed by the transformed coefficients, allowing for a more effective data reduction.

LINEAR PREDICTIVE QUANTIZATION FOR STAGGERED SAR SYSTEMS

Staggered synthetic aperture radar (SAR) is an innovative SAR acquisition concept which exploits digital beamforming (DBF) in elevation to form multiple receive beams and continuous variation of the pulse repetition interval (PRI) to achieve high-resolution imaging of a wide continuous swath. Staggered SAR is currently considered as the baseline acquisition mode for Tandem-L, a DLR proposal for a highly innovative L-band single-pass interferometric and fully polarimetric radar spaceborne mission, developed to monitor the dynamic processes of the Earth [8]. The requirement of swath width (350 km in ground range) and azimuth resolution (less than 10 m), together with the use of large bandwidths and multiple acquisition channels, is clearly associated to the generation of a large data volume. A method consisting in an interpolation combined with low-pass Doppler filtering and decimation of the acquired raw data has been proposed in [9], which allows for a data reduction of up to 50% at the cost of a large onboard computational burden. Conventional SAR raw data usually exhibit very little correlation, which can be only partially used for compression algorithms. On the other hand, in staggered SAR, a certain azimuth oversampling is mandatory to properly reconstruct the information lost in the blind ranges. The system parameters of Tandem-L are listed in Table 1: it employs a mean PRF on transmit around 2.7 kHz, while the processed Doppler bandwidth PBW is of 1130 Hz, which corresponds to an increase of the data volume by almost 140%. In this scenario, we propose a compression algorithm based on linear predictive coding (LPC) and differential pulse code modulation (DPCM). The use of predictive quantization in the context of conventional SAR has been previously investigated in [10], [11]. The present method aims at exploiting the correlation exhibited by adjacent azimuth samples, by encoding the difference between one sample and its prediction. This is obtained as a linear combination of N_P preceding samples (N_P being the prediction order), such that be the raw azimuth sample taken at the discrete time instant n, $s[\mathrm{n}]$, is expressed by a linear combination of its N_pr preceding samples as

$$\tilde{s}[\mathrm{n}] = \sum_{\mathrm{i}=1}^{N_\mathrm{P}} \beta_\mathrm{i} s[\mathrm{n}-\mathrm{i}], \tag{4}$$



(a) (b)

Fig. 2. (a) Transmit (blue) and single element receive patterns (red) versus Doppler frequency (in transmission a phase spoiled pattern is employed). The shaded orange area indicates the processed bandwidth, while the effective sampling bandwidth ($\mathrm{PRF_{eff}} = N \cdot \mathrm{PRF_{sys}}$) is delimited by the dashed green lines. (b) Signal-to-quantization noise ratio (SQNR) for a homogeneous scene for a standard BAQ (red) and for the proposed MC-BAQ (green), as a function of $\bar{R}$.

where β_i is the weight associated to the i-th previous sample. The prediction error $d[\mathrm{n}]$ is defined as

$$d[\mathrm{n}] = s[\mathrm{n}] - \tilde{s}[\mathrm{n}]. \tag{5}$$

The set of weights $\boldsymbol{\beta}$ is selected in order to minimize the mean square error (MSE) of the resulting prediction error and is derived by exploiting the covariance matrix of the random process $s[\mathrm{n}]$ [7]

$$\boldsymbol{\beta} = \boldsymbol{C}^{-1}\boldsymbol{\rho}, \tag{6}$$

being $\boldsymbol{C}$ the covariance matrix of the random process $s[\mathrm{n}]$, and $\boldsymbol{\rho}$ is the vector of the correlation values between the N_P previous samples and the sample to be estimated at the time instant n.

A quantized version (using BAQ) of the prediction error $d_q[\mathrm{n}]$ is stored on board and then transmitted to the ground, but it is also further employed in a feedback loop on board. After the acquired data are downlinked to the ground, the decoding process is carried out by implementing the same prediction loop, which is utilized to finally retrieve a quantized version of the original SAR raw data sample.

The performance gain G_{N_P} obtained with a N_P-order predictor is expressed as the ratio between the variance of the prediction error $\sigma^2_{\mathrm{d},N_\mathrm{P}}$ and the one of the input signal σ^2_s [7]

$$G_{N_P} = \sigma_s^2 / \sigma^2_{\mathrm{d},N_\mathrm{P}}. \tag{8}$$

The proposed approach, including simulations and a theoretical performance assessment, is discussed in detail in [12].

Gap Considerations and Dynamic-Predictive Quantization

The location of blind ranges (so-called gaps) along the azimuth dimension of a staggered SAR acquisition and their corresponding range extension is associated to the specific sensor orbit position and to the particular sequence of PRI employed. This information is known at data take commanding level and can be exploited to dynamically optimize the bit rate allocation together with the prediction process for the samples located in the vicinity of the gap [12]. To obtain focused images, staggered SAR raw data are first interpolated on a uniform grid and, for this purpose, a Best Linear Unbiased (BLU) interpolation is applied [9], which exploits the correlation between neighboring azimuth samples to optimally estimate the values on the output grid and to reconstruct a missing sample. The proposed method jointly exploits a dynamic bit rate allocation and a variable prediction order in the gap vicinity and is therefore named Dynamic Predictive Block-Adaptive Quantization (DP-BAQ) [12], since it allows for a consistent mitigation of the errors introduced by the combined effect of quantization and interpolation.

Fig. 3 shows the SQNR, defined as in (3), for a homogeneous SAR scene as a function of the average rate $\bar{R}$ and for different quantization schemes. The performance of a BAQ with constant bit rate is taken as reference and is depicted in black, together with the SQNR for the proposed DP-BAQ for different prediction orders (no significant additional gain is observed for prediction orders $N_\mathrm{P} > 4$). A 4th-order DP-BAQ (depicted in red in Fig. 4) at 3 bits/sample provides the same SQNR of a 4-bit BAQ (both around 22 dB) approximately, hence allowing for a data reduction of about 25%.

If compared with the method proposed in [9], DP-BAQ results in general in a higher data rate, but on the other hand, it allows for a simpler and cheaper onboard implementation. Indeed, the prediction process basically consists of a linear combination of $N_\mathrm{P} \leq 4$ range lines, while the data reduction technique in [9] typically requires the storage and processing of more than 15 range lines. Hence, the suggested algorithm can be performed in real time by using a single state-of-the-art FPGA, which has strong storage limitations making the onboard real-time implementation a cost-driving challenge. Moreover, the proposed method preserves the non-uniformly sampled SAR raw data that may be used for a more advanced on-ground processing as in [13]. In addition to [12], which discusses in detail the theory and simulations, an assessment of the proposed DP-BAQ with real data will be presented at the Workshop [14].

Table 1: Tandem-L system parameters.

Parameter	Value
Orbit height	745 km (@ equator)
Carrier frequency, *fc*	1.25 GHz (L band)
Horizontal baselines	800 m . . . 20 km
Revisit time	16 days
Range bandwidth	up to 84 MHz
Mean (staggered) PRF	2700 Hz
Doppler bandwidth, PBW	1130 Hz
Azimuth resolution	7 m
Swath width	175 km (quad), 350 km (single/dual)
Raw data quantization	BAQ @ 4 bits/sample
Reflector diameter	15 m
Mission lifetime	10 years
Polarization	single/dual/quad

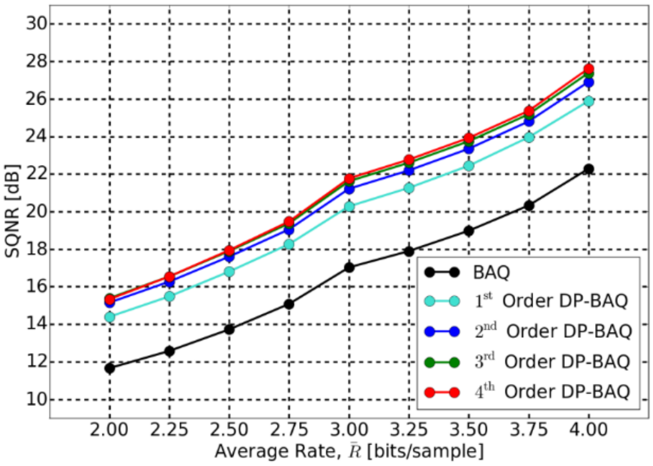
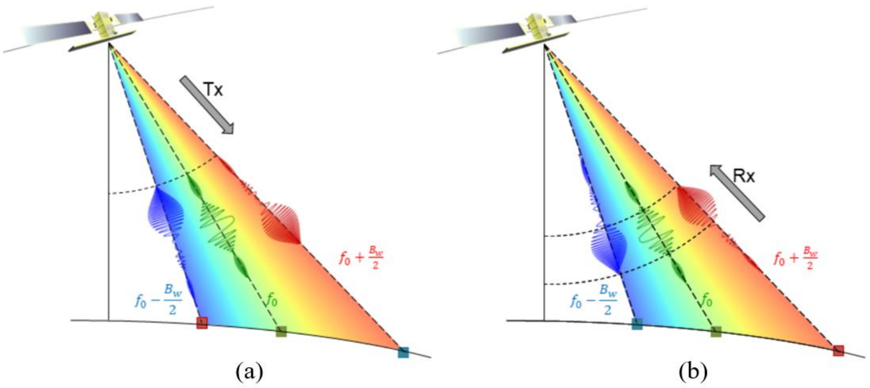


Fig. 3. Signal-to-quantization noise ratio (SQNR) obtained from a homogeneous SAR scene as a function of the average rate $\bar{R}$, for a standard BAQ with constant bitrate (black), and for the proposed DP-BAQ (with different colours, $N_{\mathrm{P}} \leq 4$), with variable bit rate allocation and dynamic selection of the prediction order in the gap vicinity.

BLOCK-FREQUENCY QUANTIZATION FOR DATA VOLUME REDUCTION IN FSCAN SAR SYSTEMS

Frequency Scanning (FScan) is a novel acquisition mode for SAR systems, first introduced in [15]. The method is based on the frequency-dependent beam pointing capabilities of phased array antennas, artificially increased via the combined use of true time delays and phase shifters within the array antenna. A graphical representation of the FScan acquisition principle is presented in Fig. 4 in transmission (a) and reception (b). According to it, the radar echoes from the target area are not only separated in range time but also in range frequency: this means that the echoes from different targets on ground are mutually displaced in both the time domain, because of different pulse travelling times, and the frequency domain, as the impinging wave has a different centre frequency (Fig. 4(b)), depending on the range position. By comparing this approach with a conventional SAR (e.g. Stripmap) system, a considerably long chirp pulse is used with a high bandwidth B_{Tx} and variable centre frequency, and a wider swath can be captured by means of a shorter echo window length (EWL) by illuminating first far-, then mid- and finally near-range. By this, typical limitations of conventional SAR systems can be mitigated, and so a wide swath up to 80 km can be imaged maintaining a fine azimuthal resolution in the order of one meter. In particular, the target information is non-uniformly distributed within its time and frequency, as it is shown in Fig. 5(a): here, the range frequency support is depicted as function of the range time. The grey area represents the time-frequency support for one range line, which includes all received echoes (generally, a trade-off exists between the chirp length and the echo window T_{ewl}). The diagonal coloured lines represent the echoes of three reference targets in near (blue), mid (green) and far (red) range, respectively. Starting from these considerations, it is clear how a direct digitization and onboard storage of the entire signal support is highly inefficient, since the actual informative content occupies only a certain portion of it, resulting in coverage limitations due to overhead in the system memory or downlink capacity. A simple subsampling of the signal would not help, as the target information is spread along the entire signal bandwidth B_{Tx} and would lead to aliased signal components from sidelobes of the antenna elevation beams. On the other hand, starting from the signal support in Fig. 5(a), we propose a convenient data reduction method in which a (lossless) DFT is performed on the SAR raw data. By this, those samples which do not carry useful information (green area in Fig. 5(a)) are discarded [16]. For the assessment of the proposed method, an X-band system (f_c =9.8 GHz) flying in a Terra-



(a) (b)

Fig. 4. The FScan imaging principle: (a) the linearly frequency-modulated transmit pulse is weighted by the dispersive frequency dependent antenna pattern to illuminate different areas across the swath with different frequencies; (b) on receive, the main signal components arrive quasi simultaneously at the antenna.

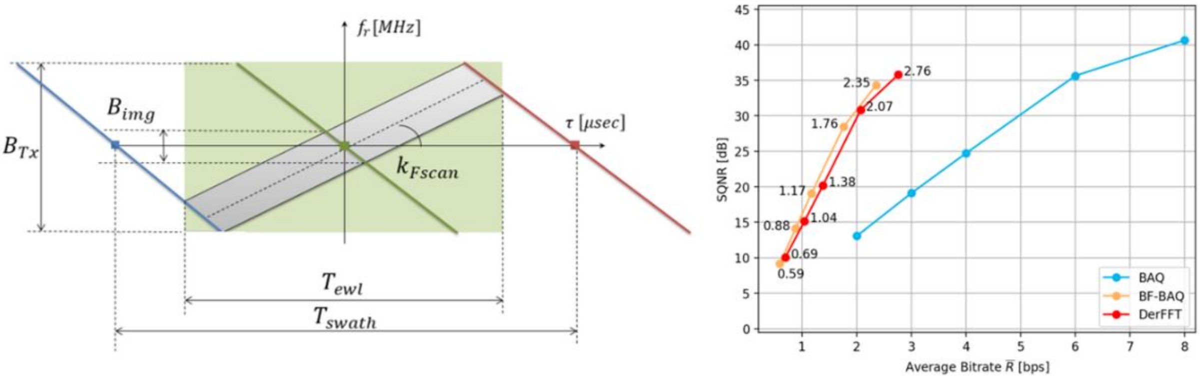
SAR-X-like orbit, equipped with $N = 4$ azimuth channels, transmit $B_{Tx} = 1.2$ GHz and target $B_{img} = 300$ MHz is considered. The simulation results are shown in Fig. 5(b), which depicts the SQNR for a homogeneous target, in the case that a data transformation is directly applied in blocks, which is referred to as Block-Frequency (BF)-BAQ (for this $N_{\mathrm{bl}} = 50$ blocks are considered), and assuming that data are first "deramped" before transformation and compression (DerFFT). The two proposed approaches show similar performance and a significant reduction in data volume up to 60% with respect to BAQ, as it is indicated by the resulting data rate values in Fig. 5(b).

PERFORMANCE-OPTIMIZED QUANTIZATION FOR SAR AND INSAR APPLICATIONS

The methods described in the previous sections aim at reducing the data volume acquired by the SAR systems by exploiting a certain redundancy in the SAR raw data, which is introduced by the specific system architectures and acquisition modes (multi-channel, staggered SAR, frequency scan). The proposed approaches can be combined with a performance-optimized quantization (PO-BAQ), presented in [17], which extends the concept of the state-of-the-art BAQ and allows for an optimization of the resource allocation by controlling the resulting SAR image degradation.

In addition to usual the granular and the overload noise contributions, inhomogeneities in the SAR backscatter distribution cause a further signal-dependent performance degradation due to quantization. This is the case, for example, of urban areas, where a high dynamic range in backscatter is typically observed. Such an effect is also referred to as low-scatterer suppression [18] and has to be considered as an additional, non-linear and signal-dependent quantization error source, and it significantly impairs the resulting SAR image performance. In addition to the compression rate R used for data digitization, the degree of inhomogeneities in the backscatter distribution can therefore be exploited to quantify and predict the impact of quantization on SAR performance. A possibly good estimator of this is represented by the standard deviation of the local SAR backscatter σ_{σ^0}, calculated within a sufficiently large area, comparable with the chirp extension L_{ch} in range and the synthetic aperture L_{sa} in azimuth. According to this, a lower performance degradation is expected for homogeneous scenes (corresponding to low values of σ_{σ^0}) and vice-versa. In [18] the impact of quantization on TanDEM-X SAR bistatic data over selected test areas showing different land cover types and topography characteristics is evaluated. For this, experimental TanDEM-X data takes, acquired with full 8-bit analog-to-digital converter (ADC) resolution, are re-compressed on ground using BAQ at the available rates and corresponding SAR images and interferograms are generated. Fig. 6 shows a zoom-in of the radar backscatter σ^0 for the test site over (a) the agricultural area in Iowa (USA) and (b) the urban area of Mexico City. The former (Fig. 6(a)) extends by about 3 km×8 km in azimuth and range, respectively, it is characterized by flat terrain and a rather homogeneous backscatter area ($\sigma_{\sigma^0} \approx 2$ dB), resulting in a mean SQNR of about 15 dB for the 3-bit BAQ case (Fig. 6(c) and Fig. 6(e)); the latter (Fig. 6(b)) extends by about 4 km×8 km in azimuth and range, and it shows heterogeneous backscatter due to the presence of urban settlements as well as of rugged terrain (and $\sigma_{\sigma^0} \approx 4.5$ dB), for which smaller SQNR values are observed in Fig. 6(d) and Fig.6(f). In particular, higher SQNR values are observed in correspondence of high backscatter areas, and vice versa.

We have repeated this analysis for several test areas with the goal of characterizing the quantization errors for different SAR scene characteristics. These findings are exploited to implement the proposed performance-optimized block-adaptive quantization (PO-BAQ), which allows one to control the compression rate and, at the same time, the resulting performance degradation. According to that, the required bitrate R_{req} to be used for SAR raw data quantization is determined as a function of several parameters, such as, e.g., the local backscatter information, the number of looks N_{l}, the number of available acquisitions N_{acq}, and the specific performance requirement, which can be defined in terms of, e.g., SQNR or InSAR phase errors. As an example, Fig. 7 shows the global bitrate maps resulting from a requirement on the InSAR phase errors of $\sigma_{\Delta\varphi_q} = 5°$, obtained by combining the X-band backscatter standard deviation map from TerraSAR-X data. More detailed performance analyses and examples for the proposed method are presented in [17].



(a) (b)

Fig. 5. (a) Time-frequency diagrams in FScan mode for three exemplary targets placed in near (blue), mid (green) and far (red) range. (b) SQNR as function of the average bitrate $\bar{R}$ for a simulated SAR data for the BAQ (light blue curve), BF-BAQ assuming $N_{\mathrm{bl}} = 50$ blocks (orange) and assuming deramping operation prior to quantization in frequency domain (red curve). The resulting data rate is reported close to the corresponding SQNR value in the graph.

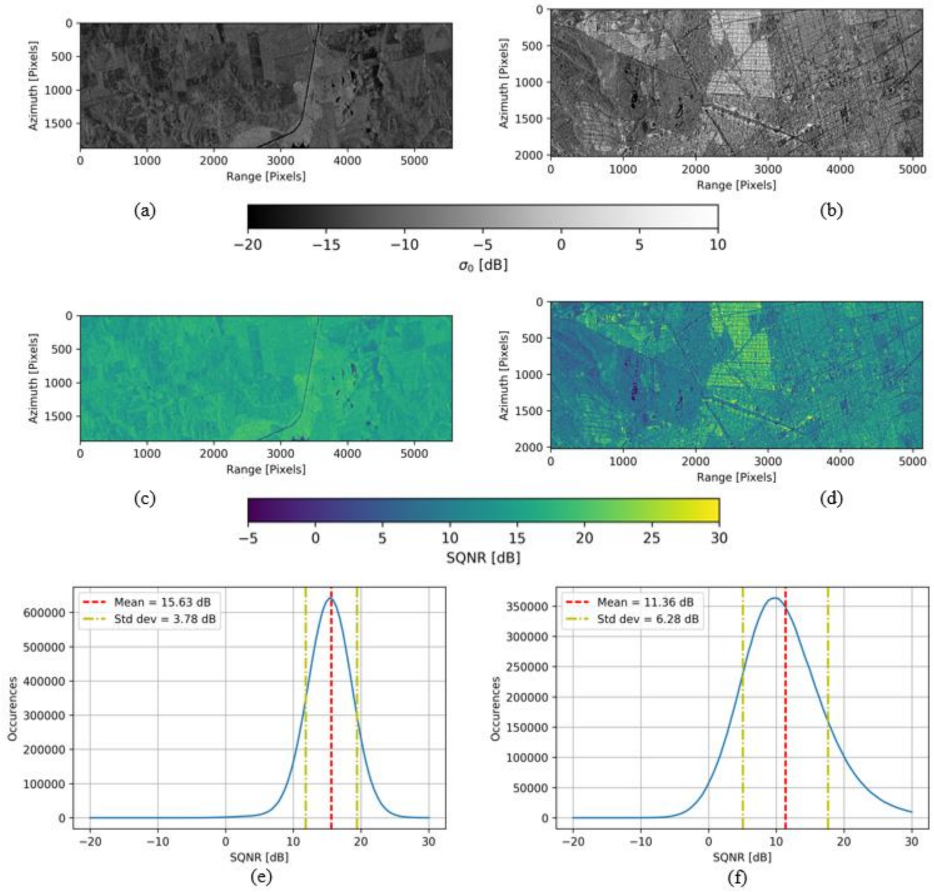


Fig. 6. Zoom-in of the radar backscatter map σ^0 for (a) the homogeneous test area located in Iowa (USA) (σ_{σ^0} of about 2 dB) and (b) of the urban area of Mexico City (σ_{σ^0} of 4.5 dB); (c), (d) SQNR maps resulting from 3-bit BAQ; (e), (f) corresponding SQNR distributions.

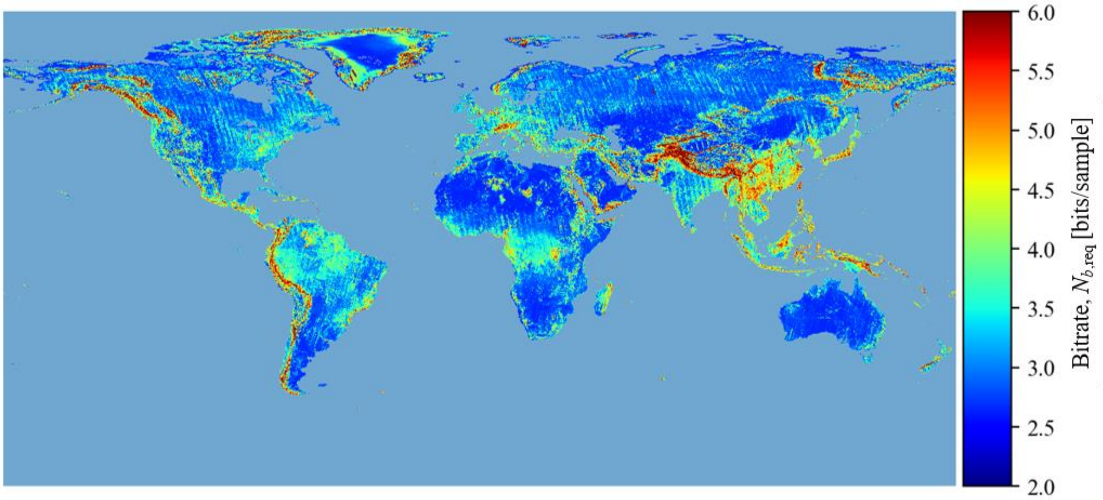


Fig. 7. Global bitrate map resulting from a phase error requirement $\sigma_{\Delta\varphi_q} = 5°$.

CONCLUSIONS AND OUTLOOK

On-board raw data compression represents an aspect of utmost importance for the design of present and future SAR systems, which will be capable to acquire wider swaths at finer resolution. This poses challenging requirements in terms of data volume to be handled by the SAR system. In this paper, different approaches to tackle the problem are presented. In the context of MAC SAR, a multi-channel quantization (MC-BAQ) has been proposed, which exploits the intrinsic correlation between adjacent multi-channel azimuth data samples by applying a discrete Fourier transform combined with an optimized selection of the quantization rates. Staggered SAR systems are characterized by a significant system oversampling as well. In this case, linear predictive quantization has been considered, which aims at removing the data redundancy by means of an efficient encoding of the azimuth SAR raw samples, and for this purpose a novel dynamic-predictive quantization (DP-BAQ) is proposed. Furthermore, opportunities for data volume reduction for Frequency Scanning (FScan), an innovative SAR acquisition mode which allows for high-resolution wide-swath imaging by implementing a frequency dependent (i.e. dispersive) beam pointing, have been discussed as well. Different solutions for on-board data volume reduction have been investigated, which are based on the use of transform coding (DFT), including deramping and data block-wise quantization.

Simulations for different SAR backscatter distributions and compression schemes have been carried out, showing that the proposed approaches allow for a significant reduction of the data volume by requiring, at the same time, a modest processing effort for their onboard implementation, which can be performed in real time by using presently available hardware technology (FPGA). Future studies will address the investigation of alternative data transformation and compression techniques, such as non-linear and non-causal prediction, to further improve the resulting data reduction capacity. The proposed approaches can also be exploited in the context of polarimetric SAR data, by applying it on each polarization channel independently, or extended to multiple transmit pulses by combining transform coding in the Doppler domain with alternative compression schemes such as, e.g., vector quantization, to achieve a more effective data reduction.

Finally, a novel performance-optimized BAQ (PO-BAQ) has been introduced, which grounds on state-of-the-art quantization algorithms for SAR systems and aims at optimizing the performance of the processed SAR and InSAR products. This allows for achieving a targeted bitrate allocation which can be adapted to the target higher-level SAR products and to the corresponding performance requirements. PO-BAQ can be opportunely combined with the other data volume reduction methods described in this paper, and represents a promising technique for improving the design of present and future SAR missions, since it specifically aims at a joint adaptation not only of the resource allocation but also of the product quality of the specific higher-level SAR application. In this context, the potentials of Artificial Intelligence (AI) and Deep Learning (DL)-based approaches for SAR data compression will be investigated, possibly in combination with efficient on-board processing solutions.

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