

Performance-Optimized SAR Raw Data Quantization: On-Board Implementation and Trade-Off Analysis

Nicola Gollin[✉], Michele Martone[✉], Marc Jäger[✉], Rolf Scheiber[✉], Gerhard Krieger[✉], *Fellow, IEEE*,
and Paola Rizzoli[✉], *Member, IEEE*

Abstract—Synthetic aperture radar (SAR) represents nowadays a key technology in Earth observation (EO), evolving its original capabilities into both large-scale monitoring of geophysical parameters and very high-resolution imaging with short revisit times. The increase in system performance and the wide range of application scenarios require significant efforts in the design of current and future SAR missions: one of the most critical on-board operations is the digitization of the received echoes, directly impacting the final image quality and, at the same time, limited by the available downlink capacity. State-of-the-art quantization methods, such as block adaptive quantization (BAQ), offer a good tradeoff between signal quality and overall complexity but lack adaptivity to the imaged scenario. This leads to different impacts of the quantization error on the final SAR image. As an evolution of BAQ, performance-optimized BAQ (PO-BAQ) is a recently proposed quantization method, which addresses this issue by employing variable quantization rates across the scene, targeting specific performance requirements in the final SAR image. In this letter, we present a feasibility study of variable bitrate allocation in a realistic SAR mission scenario: to ensure flexibility, we consider the bitrate allocation map (BRM) to be uploaded at the commanding phase during each ground segment contact, individually tailoring the required performance quality for each acquisition. State-of-the-art uplink data rates are considered, and the complete performance evaluation after SAR processing is carried out using the experimental on-board processor developed within the SOPHOS Horizon 2020 Project.

Index Terms—Block adaptive quantization (BAQ), on-board feasibility, synthetic aperture radar (SAR) raw data quantization.

I. INTRODUCTION

SYNTHETIC aperture radar (SAR) enables high-resolution microwave imaging independently of daylight and weather conditions. Over the past few decades, novel space-borne radar techniques have been designed to overcome the limitations of conventional SAR systems, mainly represented by the tradeoff between swath width and high spatial resolution [1], [2]. Moreover, current and upcoming SAR missions

employ large bandwidths, multiple polarizations, short revisit time, and multistatic configurations [3], [4]. This increased complexity results in a significant volume of acquired data, posing relevant challenges in terms of on-board memory requirements and downlink capacity [1]. The efficient on-board storage of SAR raw data relies, at its core, on effective quantization methods, affecting on the one hand, the required memory and downlink capacity, and on the other hand, the quality of the generated SAR products. The most widely used SAR raw data quantization method is the block adaptive quantization (BAQ) algorithm, originally developed for the Magellan SAR mission to Venus [5]. In the past decade, novel algorithms have been proposed based on the principle of BAQ, offering improved performance optimization and resource allocation capabilities. These methods often rely on acquisition-dependent compression schemes, such as the flexible dynamic BAQ (FDBAQ) (employed on ESA's Sentinel-1 mission) [6], [7] and the performance-optimized BAQ (PO-BAQ) algorithm, which estimates a spatial-variant bitrate allocation map (BRM) in the raw data domain based on the final performance requirement of the higher level SAR and InSAR products [8]. PO-BAQ exploits prior knowledge on the SAR backscatter statistics to derive 2-D bitrate maps (BRMs), which must be available on board before quantization. This represents a minor limitation as the pregenerated BRM may not account for temporal and seasonal variations at the time of the SAR acquisition. This aspect is addressed in [9], where on-board BRM estimation is performed directly from the acquired raw data through deep learning, leading to more flexible settings. PO-BAQ has been validated on TerraSAR-X and TanDEM-X scenes to demonstrate its effectiveness [8] and, thanks to its promising capabilities, has been selected as the main data compression algorithm to be demonstrated in the frame of the Smart On-Board Processing for Earth Observation Systems (SOPHOS) Project, a three-year Horizon Europe initiative focused on efficient, high-performance SAR on-board processing for small and nanosatellites [10], [11].

In this letter, we investigate the feasibility of the PO-BAQ in a practical SAR mission scenario, where a BRM, previously derived on ground, is sent to the system, and for this relevant aspects, such as performance, complexity, uplink requirements, and formatting standard, are considered.

Received 22 June 2025; revised 11 August 2025; accepted 15 September 2025. Date of publication 8 October 2025; date of current version 3 November 2025. This work was supported in part by European Commission through the Horizon Europe Project "Smart On-Board Processing for Earth Observation Systems (SOPHOS)" under Grant HORIZON-CL4-2022-SPACE-01-13. (*Corresponding author: Nicola Gollin.*)

The authors are with the Microwaves and Radar Institute, German Aerospace Center (DLR), 82234 Weßling, Germany (e-mail: Nicola.Gollin@dlr.de; Michele.Martone@dlr.de; marc.jaeger@dlr.de; rolf.scheiber@dlr.de; gerhard.krieger@dlr.de; Paola.Rizzoli@dlr.de).

Digital Object Identifier 10.1109/LGRS.2025.3619107

This letter is structured as follows. In Section II, we report a background on SAR raw data quantization, variable bit allocation, and the SOPHOS processor used in this contribution. Section III collects all the experiments and results, and, finally, the conclusion and outlook are presented in Section IV.

II. SAR RAW DATA QUANTIZATION

SAR raw data quantization is performed using the block adaptive quantizer, in which the decision levels and clipping thresholds depend on the local statistics of raw data blocks (e.g., 128 samples in range are used for the implementation on board the DLR TerraSAR-X and TanDEM-X satellites). This is applied separately to the real and the imaginary part of the received SAR echo. This method represents a good tradeoff in terms of signal quality and resulting data volume. Practically, it is implemented using a block-based mantissa exponent quantizer with a constant rate for each acquisition scene, typically at 2, 3, 4, and 6 bits per sample (bps). For each BAQ block, the exponent is stored separately, while the mantissa length matches the selected quantization rate (e.g., 4 bps). Both must be recorded per block for efficient decoding on the ground.

In SAR acquisitions, the responses from illuminated scatterers overlap in the raw data domain within the integration window area A_{SAR} , with dimensions defined in [8] as

$$A_{\text{SAR}} = L_{\text{ch}} \times L_s \quad (1)$$

where L_{ch} is the chirp length and L_s is the azimuth synthetic aperture. Therefore, the quality of signal reconstruction for a given sample in the focused SAR domain is affected by the quantization quality in the corresponding A_{SAR} area. In addition to the quantization error (directly related to the selected number of bits N_b used for digitizing the data), the degree of heterogeneity in the SAR backscatter distribution significantly influences the performance of the quantization process on the final SAR and InSAR products. Taking this into account, quantization errors must be treated as a nonlinear and signal-dependent noise source that affects the quality of the SAR data. Therefore, a constant bit allocation results in a nonuniform quantization error throughout the scene [8], [12].

In this contribution, we consider the signal-to-quantization noise ratio (SQNR) as a performance evaluation metric, which is a representative figure of signal degradation caused by quantization and can be linked to higher order SAR and InSAR parameters [8]. It is calculated in the focused domain as

$$\text{SQNR} = \frac{|x|^2}{|x - x_q|^2} \quad (2)$$

where x represents the uncompressed signal in input to the quantizer, while x_q represents the distorted version of x , i.e., the output signal of the quantizer. Due to the overlap of the target response as expressed in (1), within the SAR scene we assess the quantization performance in windows of size A_{SAR} and to avoid potential estimation imbalances due to the presence of outliers (i.e., SQNR very low or extremely large), we consider the median value.

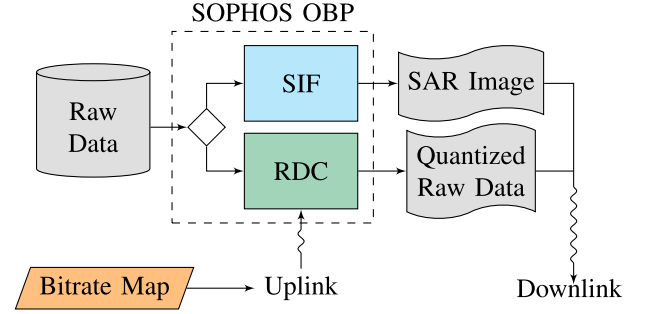


Fig. 1. Flowchart of the SOPHOS OBP: the input raw data from the instrument are processed through the SIF or the RDC algorithms. The SIF algorithm produces a focused SAR image, while the RDC implements a variable rate allocation depending on the uplinked BRM.

A. Variable Bit Allocation

The use of constant quantization rates for SAR raw data introduces a nonuniform quantization error related to the backscatter distribution [12]. Homogeneous scenes require lower quantization rates (e.g., 2 bps) to achieve a given performance, while inhomogeneous scenes need finer rates (e.g., 4 bps). Variable rate methods are therefore more efficient, potentially reducing the resulting data volume by locally adapting the quantization rate, as shown in [8].

Different from FDBAQ, which dynamically derives variable rates using lookup tables (LUTs), the PO-BAQ requires a predefined BRM, a 2-D representation of azimuth- and range-based bitrate values for the SAR survey. To implement a variable rate, an on-board BRM is necessary, which can be stored as an LUT or uploaded as part of a command routine for greater flexibility. The BRM can be optimized based on specific targets, such as uniform performance, SNR maximization, application-based, or landcover-based criteria, allowing multiple BRMs to be generated for a single scene. Being defined on ground with prior knowledge of the acquisition geometry and mode, PO-BAQ is scalable to future SAR systems, provided all relevant parameters are considered during the BRM generation process [8]. This approach makes the uplink of BRMs during commanding an attractive solution, allowing the selection of different bitrate allocation strategies and quality levels, such as uniform SQNR values of 10, 15, or 20 dB.

In this work, we focus on the PO-BAQ [8] as the primary optimization method for generating a BRM, which is then uplinked to the satellite and used to compress the acquired raw data. Specifically, we consider a BAQ that supports variable quantization rates in both azimuth and range, allowing for individual quantization rates per BAQ block, extending the fractional rate concept along azimuth presented in [13] to include range direction.

B. SOPHOS On-Board SAR Processor (OBP)

This work was developed within the EU Horizon 2020 SOPHOS Project, which aims to demonstrate next-generation SAR algorithms on space-grade hardware [14]. The on-board software processing module [on-board processor (OBP)] enables two workflows: raw data compression (RDC) using

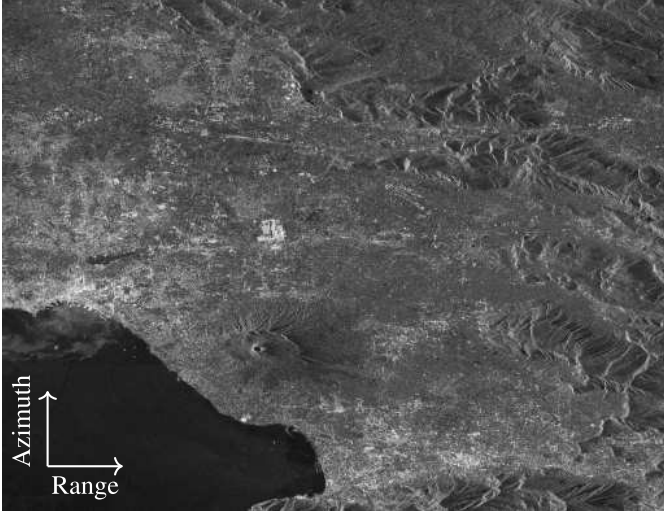


Fig. 2. Obtained SAR image over Naples (Italy) from the raw data of the high-end scenario. The area consists of 30×50 km and is one of the two scenes used to validate the method.

variable bit allocation based on an uplinked BRM and on-board SAR image formation (SIF) via an ωK algorithm. As shown in Fig. 1, the input data can follow either workflow, with SIF providing low-latency SAR products and RDC delivering high-quality raw data for ground processing.

The SAR data used in this letter and the SOPHOS Project is based on a Sentinel-1 backscatter image over the Naples area (Italy), a heterogeneous scene that provides a representative real-case scenario. Through reverse SAR focusing, it is possible to retrieve raw data with specific system parameters, such as bandwidth, pulse repetition frequency, and other acquisition settings, while also taking into account relevant factors like noise modeling, antenna patterns, and orbit and timing details. In this letter, two scenarios are investigated: a light and a high-end raw data scenario, which involve two possible bandwidths (B_w) that allow for 2 and 0.5 m ground range resolution, respectively. The resulting scene spans 50 km in length and has a swath width of 30–50 km, with varying resolutions for each scenario. This choice allows for the evaluation of the method on very high-resolution systems. The resulting SAR image obtained after forward SAR processing on the high-end raw data scenario is shown in Fig. 2. The detailed system parameters for the two scenarios are presented in Section III.

C. Raw Data Encoding

To efficiently encode and store raw data on board, a custom binary format has been defined, consisting of byte-aligned range line blocks within a single binary file, as detailed in Fig. 3. Each range line comprises a 32-bit header, which contains essential information for decoding, including the total number of samples (24 bits), filler bit size F (3 bits), and a BAQ control flag B (1 bit). The encoded data are divided into BAQ blocks, each consisting of N_b range samples (in this case, $N_b = 128$). Each BAQ block stores the BAQ rate R (3 bits) and BAQ exponent E (5 bits), followed by the quantized samples represented as binary interleaved-complex values, with

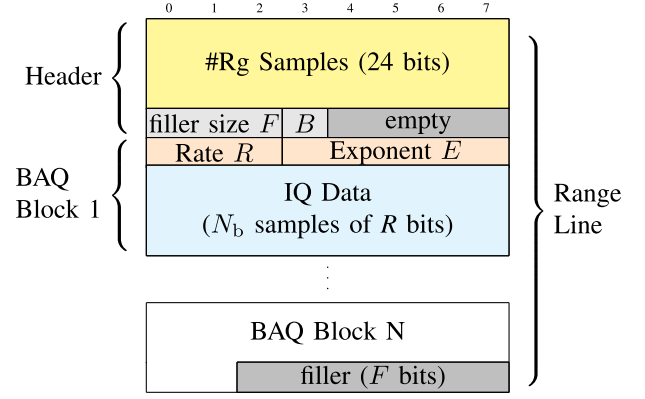


Fig. 3. Binary format of an encoded range line, illustrating the structure of the 32-bit header and the sequential BAQ blocks.

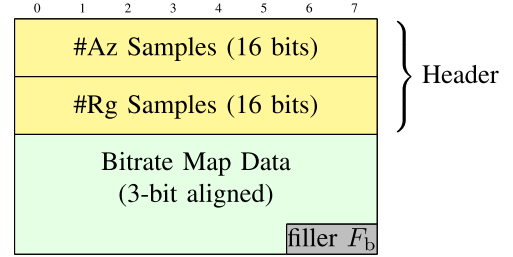


Fig. 4. Binary format of the encoded BRM: the number of range and azimuth samples is stored in a 32-bit header, while the bitrate values are represented in 3-bit integers and the data block is filled to the byte with zeros.

each sample encoded using the specified number of bits (R). To maintain byte alignment, the last BAQ block may be truncated or padded with filler bits, and the number of filled bits is stored in the range line header to facilitate efficient decoding.

The variable bit allocation is performed using a prederived BRM, which is uplinked to the system. To facilitate flexible BRM sizing, a custom binary formatting has been developed. The BRM size is adaptive, allowing each bitrate value to be applied to either a single BAQ block or multiple blocks, depending on the selected resolution (i.e., resampling factor) that matches the actual raw data dimensions. This flexibility enables tradeoffs between BRM size, uplink bandwidth, and SAR performance. The format definition for the encoded BRM is illustrated in Fig. 4.

III. EXPERIMENTS AND RESULTS

In the present investigation, we assume a realistic mission scenario: the considered system parameter values (reported in Table I) are representative of present missions, such as TanDEM-X, ICEYE, Capella, and Sentinel-1. A duty cycle of 10% is considered, resulting in a transmit time interval T_{acq} of approximately 9 min per orbit.

The total number of acquisitions for each orbit, denoted as N_{acq} , is defined as

$$N_{acq} = \frac{T_{acq}}{N_{cont} \cdot T_{dt}} = \frac{9 \cdot 60 \text{ s}}{2 \cdot 7.5 \text{ s}} = 36 \quad (3)$$

where the relevant mission and instrument parameters are listed in Table I. The upload of the BRM in an operational

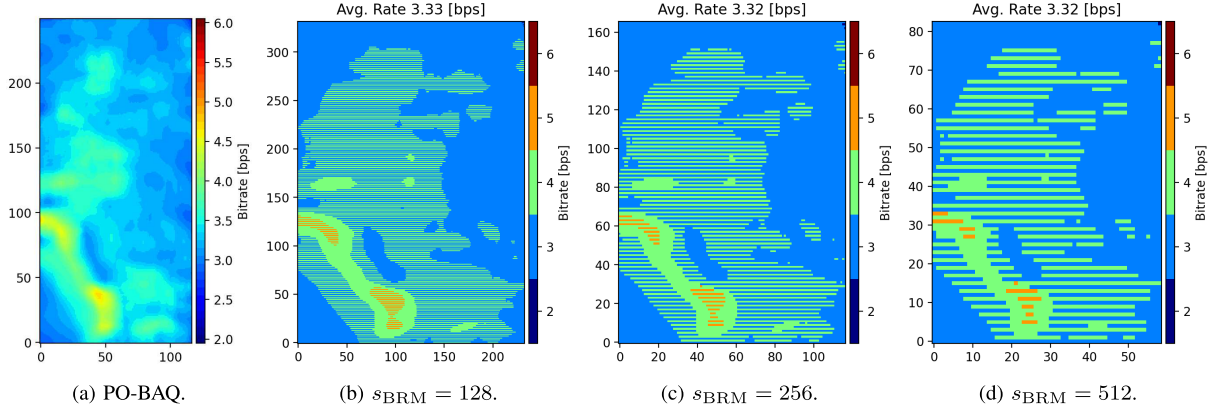


Fig. 5. Example of a BRM for SQNR = 15 dB derived from the focused domain in (a), and its resampled version for uplink considering a subsampling factor s_{BRM} equal to (b) 128, (c) 256, and (d) 512.

TABLE I

SYSTEM PARAMETERS CONSIDERED FOR THE SOPHOS SCENARIOS. THE TWO SCENARIOS NAMED LIGHT AND HIGH END DIFFER IN TERMS OF RESOLUTION AND SWATH WIDTH

Parameter	Symbol	Light	High-End
Center frequency	f_c	9.65 GHz	
Bandwidth	B_w	150 MHz	600 MHz
Range sampling freq.	f_s	165 MHz	660 MHz
Antenna length [az]	L_{az}		3.2 m
Antenna length [el]	L_{el}		0.4 m
Look angle	θ_{inc}		30°
Orbit height	h_s		560 km
Swath length	$S_{w,az}$		50 km
Swath width	$S_{w,rg}$	50	30 km
Ground resolution Az.	d_{az}	6	3 m
Ground resolution Rg.	d_{rg}	2	0.5 m
Raw data samples Az.	N_{az}	41984	41472
Raw data samples Rg.	N_{rg}	29784	94604
Orbit duty cycle	$d_c^{\%}, T_{acq}$	10%, 9 min/orbit	
Data take length	L_{dt}, T_{dt}	50 km, 7.5 s	
GS contacts (one orbit)	N_{cont}		2
GS contact time	T_{ul}		600 s
Uplink data rate	DR_{ul}		64 kbps

TABLE II

BRM SIZE IN KB FOR THE CONSIDERED SCENES AND DIFFERENT SUBSAMPLING FACTORS s_{BRM}

Case	$s_{\text{BRM}} = 128$	$s_{\text{BRM}} = 256$	$s_{\text{BRM}} = 512$
Light	27.8	7.0	1.7
High-End	87.3	21.8	5.5

scenario must comply with the available uplink datarate, which is a limiting factor in present SAR missions. The data rates available for ICEYE and Sentinel-1 are 32 and 64 kilobits per second (kbps), respectively [15], [16]. These limited bandwidths pose a constraint in our proposed approach. Assuming that two ground contacts per orbit are possible, the maximum BRM size ($\text{BRM}_{\text{size}}^{\text{max}}$) for the considered uplink datarate is defined as

$$\text{BRM}_{\text{size}}^{\text{max}} = \frac{DR_{ul} \cdot T_{ul}}{N_{acq}} = \frac{64 \text{ kbps} \cdot 9 \text{ min}}{36} \approx 130 \text{ kB}. \quad (4)$$

For the two considered SOPHOS scenarios, the size of the corresponding BRM (BRM_{size}) is calculated considering a specific BRM subsampling factor s_{BRM} and the number of bits for each BRM value. Assuming 3 bits per BRM value ($\text{BRM}_{\text{bits}} = 3$) BRM_{size} is calculated according to

$$\text{BRM}_{\text{size}} = \frac{N_{az} \cdot N_{rg} \cdot \text{BRM}_{\text{bits}}}{s_{\text{BRM}}^2} + 32 \quad (5)$$

where s_{BRM} is the assumed equivalent along range and azimuth and multiple of the BAQ block to reduce on-board

computational load (i.e., to avoid the extra logic and operations required to resample or interpolate the BRM values), while the term 32 stands for the 32 bits of the BRM header. We want to assess the potential impact of the subsampling factor on the achievable performance accuracy, as this has a direct implication on the required data rate for the BRM uplink. Large values of s_{BRM} lead to a reduction of the resulting BRM_{size} at the cost of coarsening its resolutions. This aspect potentially impacts the precision of the PO-BAQ in targeting a specific performance requirement in the SAR image. Three values of s_{BRM} have been considered, which lead to BRM_{size} described in Table II. An exemplary case of constant SQNR = 15 dB is depicted in Fig. 5, where different versions of the BRM are reported for the corresponding value of s_{BRM} .

To investigate the quantization effects in the focused SAR domain, the workflow of the SOPHOS OBP was integrated to analyze the impacts of different subsampling factors, as shown in Fig. 6: by including a decoding block, the SAR focusing algorithm (SIF) was applied to focus the BAQ-compressed data (output of the RDC), enabling performance evaluation in the SAR image domain. The application of the BRMs at various subsampling factors followed the same workflow, and the resulting performance impact of the BRM was evaluated with respect to the uncompressed (unquantized) SAR image in terms of SQNR.

The performance results in the focused SAR domain are summarized in Fig. 7 for all investigated cases, considering target SQNR values of 10, 12, 15, 20, and 22 dB with varying BRM subsampling factors. The $\text{BRM}_{\text{size}}^{\text{max}}$ constraints for 64- and 32-kbps uplink datarates are also included. Sub-sampling factors up to $s_{\text{BRM}} = 512$ caused no performance degradation, confirming the feasibility of variable bitrate allo-

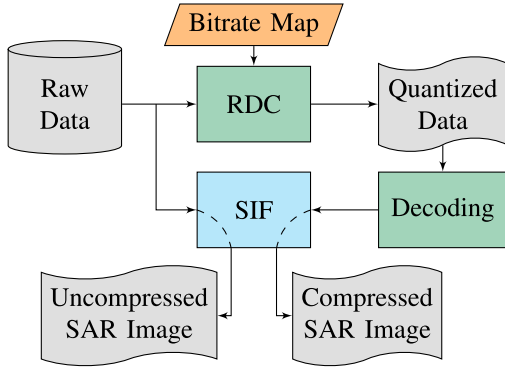


Fig. 6. Flowchart of the performance evaluation method: the raw data matrix is fed into the RDC module. The resulting quantized data are decoded and processed. Performance assessment is carried out in the final SAR image domain between the compressed SAR image and the reference uncompressed one.

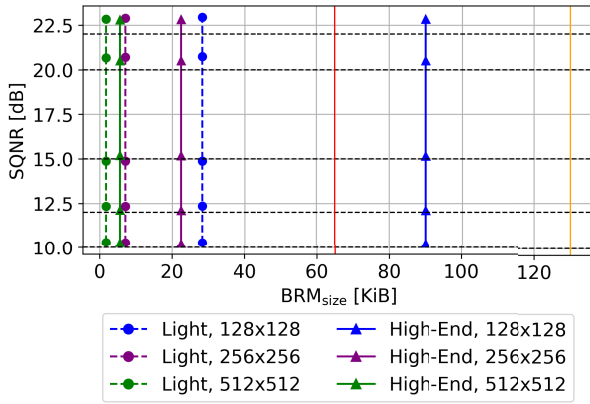


Fig. 7. SQNR results for light (dashed) and high-end (solid) scenarios with varying BRM subsampling factors ($s_{BRM} = 128, 256, 512$ in range and azimuth). The target SQNR levels (10, 12, 15, 20, and 22 dB) are plotted as horizontal dashed lines. BRM_{size}^{max} for the 32- and 64-kbps uplink constraints are represented by the red and yellow vertical lines, respectively.

cation in an operational context via uplinked BRMs and minimal bandwidth usage.

IV. CONCLUSION

In this letter, we investigated the use of variable bit allocation for satellite SAR systems in an operational mission context. The analysis focused on the SOPHOS Project scenario, detailing the implementation of a BRM and its specific formatting and application. The BRM quality (defined by its resolution) was assessed in terms of SAR-focused domain performance versus the required uplink datarate. Results showed that using a high-resolution BRM (e.g., 128×128) offered no performance advantage over coarser resolutions (e.g., 512×512), while all scenarios remained within current uplink constraints. These findings support the feasibility

of implementing variable bit allocation in real SAR missions, enabling new optimization opportunities for high-level product performance while complying with on-board memory and uplink limitations. The BRM concept is applicable beyond the tested PO-BAQ method and scene; it can be extended to any quantization technique employing BRMs at compatible resampling sizes and is suited for on-demand configurations and future SAR missions, provided that the relevant parameters are properly considered during BRM generation. Future work will include validating new bitrate allocation strategies and algorithm performance on space-grade hardware within the SOPHOS Project.

REFERENCES

- [1] A. Moreira et al., "Tandem-L: A highly innovative bistatic SAR mission for global observation of dynamic processes on the Earth's surface," *IEEE Geosci. Remote Sens. Mag.*, vol. 3, no. 2, pp. 8–23, Jun. 2015.
- [2] F. Queiroz de Almeida, M. Younis, G. Krieger, and A. Moreira, "Multichannel staggered SAR Azimuth processing," *IEEE Trans. Geosci. Remote Sens.*, vol. 56, no. 5, pp. 2772–2788, May 2018.
- [3] J. Mittermayer et al., "MirrorSAR: An HRWS add-on for single-pass multi-baseline SAR interferometry," *IEEE Trans. Geosci. Remote Sens.*, vol. 60, 2022, Art. no. 5224018.
- [4] S. Huber, M. Younis, and G. Krieger, "The TanDEM-X mission: Overview and interferometric performance," *Int. J. Microw. Wireless Technol.*, vol. 2, nos. 3–4, pp. 379–389, Aug. 2010.
- [5] R. Kwok and W. T. Johnson, "Block adaptive quantization of Magellan SAR data," *IEEE Trans. Geosci. Remote Sens.*, vol. 27, no. 4, pp. 375–383, Jul. 1989.
- [6] E. Attema et al., "Flexible dynamic block adaptive quantization for Sentinel-1 SAR missions," *IEEE Geosci. Remote Sens. Lett.*, vol. 7, no. 4, pp. 766–770, Oct. 2010.
- [7] P. Guccione, M. Belotti, D. Giudici, A. Monti Guarnieri, and I. Navas-Traver, "Sentinel-1A: Analysis of FDBAQ performance on real data," *IEEE Trans. Geosci. Remote Sens.*, vol. 53, no. 12, pp. 6804–6812, Dec. 2015.
- [8] M. Martone, N. Gollin, P. Rizzoli, and G. Krieger, "Performance-optimized quantization for SAR and InSAR applications," *IEEE Trans. Geosci. Remote Sens.*, vol. 60, 2022, Art. no. 5229922.
- [9] N. Gollin et al., "AI-BAQ: Deep learning for adaptive SAR raw data quantization," *IEEE Trans. Geosci. Remote Sens.*, vol. 63, 2025, Art. no. 5220620.
- [10] O. Flordal et al., "Smart on-board processing for next generation SAR payloads," in *Proc. 15th Eur. Conf. Synth. Aperture Radar (EUSAR)*, Apr. 2024, pp. 606–610.
- [11] M. Martone et al., "Smart on-board processing for Earth observation systems: The SOPHOS project," presented at the *On-Board Payload Data Compress. (OBPDC) Workshop*, las Palmas de Gran Canaria, Spain, 2024.
- [12] M. Martone, B. Bräutigam, and G. Krieger, "Quantization effects in TanDEM-X data," *IEEE Trans. Geosci. Remote Sens.*, vol. 53, no. 2, pp. 583–597, Feb. 2015.
- [13] M. Martone, B. Bräutigam, and G. Krieger, "Azimuth-switched quantization for SAR systems and performance analysis on TanDEM-X data," *IEEE Geosci. Remote Sens. Lett.*, vol. 11, no. 1, pp. 181–185, Jan. 2014.
- [14] (2025). *SOPHOS Website*. Accessed: May 19, 2025. [Online]. Available: <https://sophoshorizon.eu>
- [15] ESA. *ICEYE-X1 (SAR Microsatellite-X1)*. Accessed: Jun. 13, 2025. [Online]. Available: <https://www.eoportal.org/satellite-missions/iceye-x1#performance-specifications>
- [16] Copernicus: Sentinel-1. Accessed: Jun. 13, 2025. [Online]. Available: <https://www.eoportal.org/satellite-missions/copernicus-sentinel-1#spacecraft>