EFFICIENT RAW DATA COMPRESSION FOR FUTURE SAR SYSTEMS

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Outline

- Introduction and motivation
- Data volume reduction methods for multichannel SAR
- Smart on-board processing for Earth observation systems: the SOPHOS project
- Conclusions & outlook

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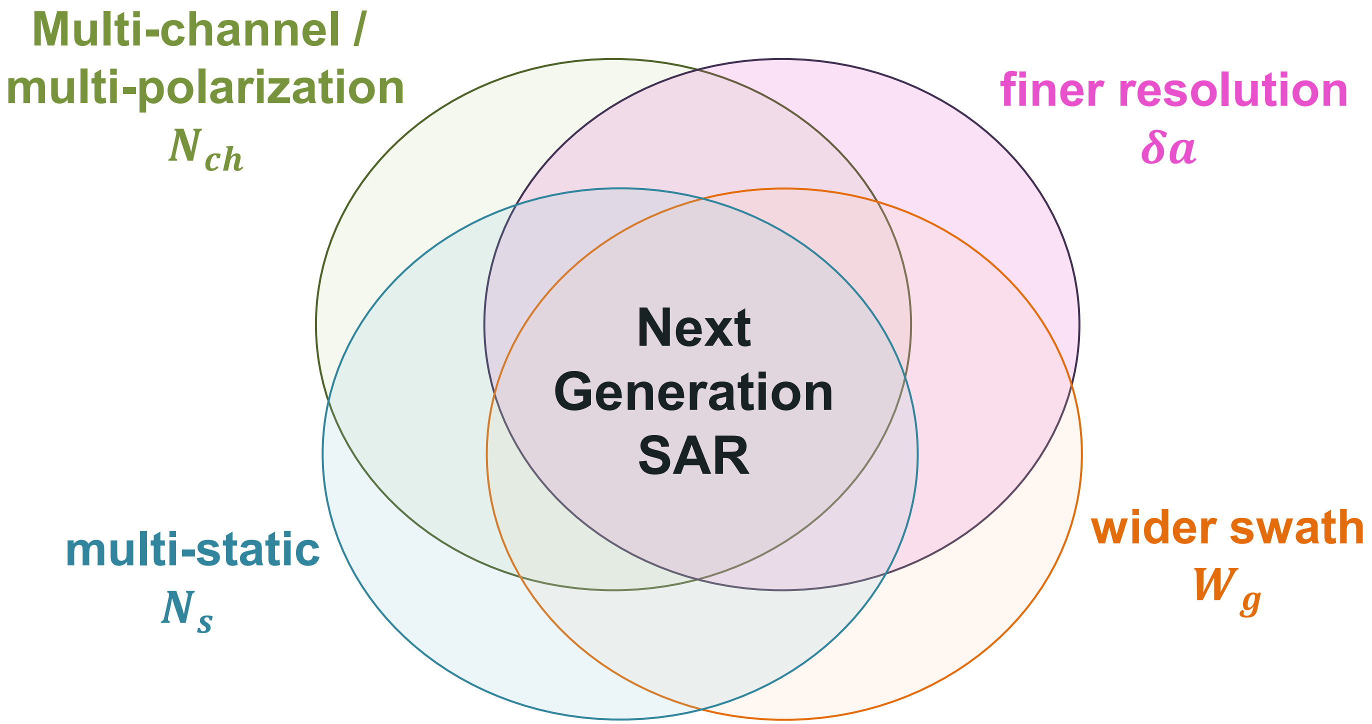
Spaceborne SAR Missions and Data Volume Challenges



Data rate $\propto N_s \cdot N_{ch} \cdot \frac{W_g}{\delta a}$

	Current Systems	Next Generation
Swath width W_g	30 km	100 km
Resolution δa	3 m	1 m

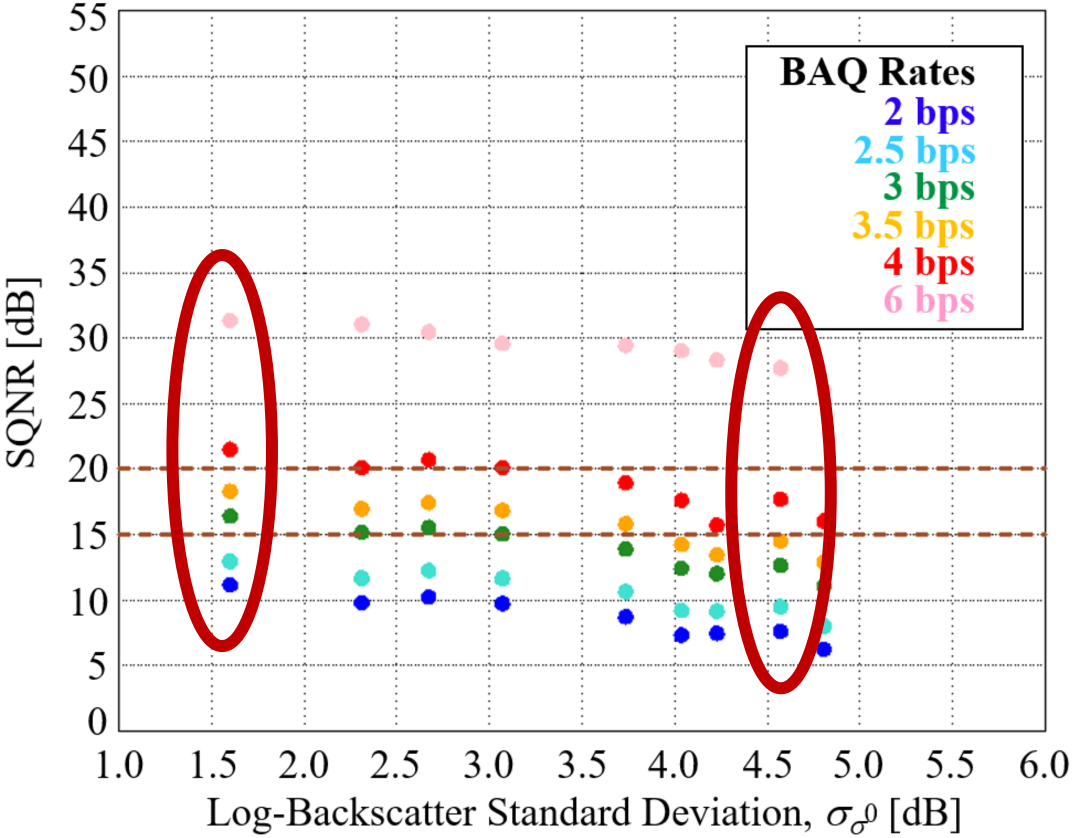
- Next-generation spaceborne SAR missions
  - **Large data rates required**
  - Harder requirements for: **Onboard memory**
    Downlink capacity

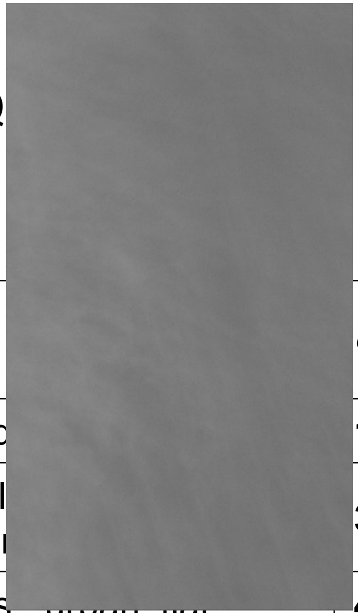
- **Quantization** of SAR raw data affects
  - **Amount of data** to be handled
  - **Quality** of the SAR products

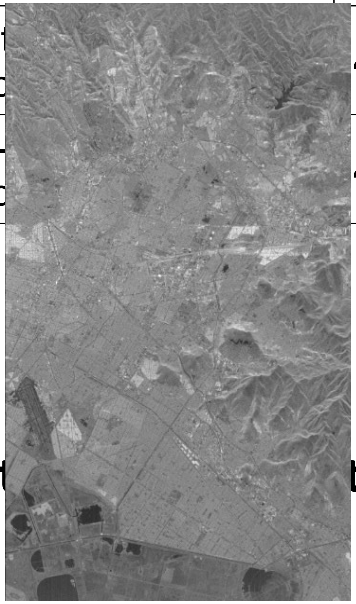
Impact of Raw Data Quantization on InSAR Performance

$$\mathrm{SQNR} = \frac{|x|^2}{|x - x_q|^2}$$

x: uncompressed SAR image
x_q: Block-Adaptive Quantization (BAQ







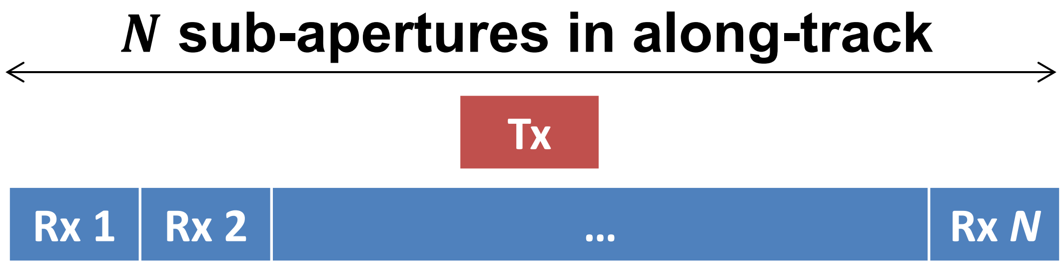
Test Site		σ_σ^0	bps for SQNR = 15 dB	bps for SQNR = 20 dB
Greenland		1.6		
Death Vall rock, mour		3.1 dB	3.0 bps	4.0 bps
Las Vegas	– urban, flat	4.0 dB	3.6 bps	4.3 bps
Mexico Cit mountaino		4.6 dB	3.6 bps	4.3 bps
Malaysia - mountaino		4.8		

Homogeneous

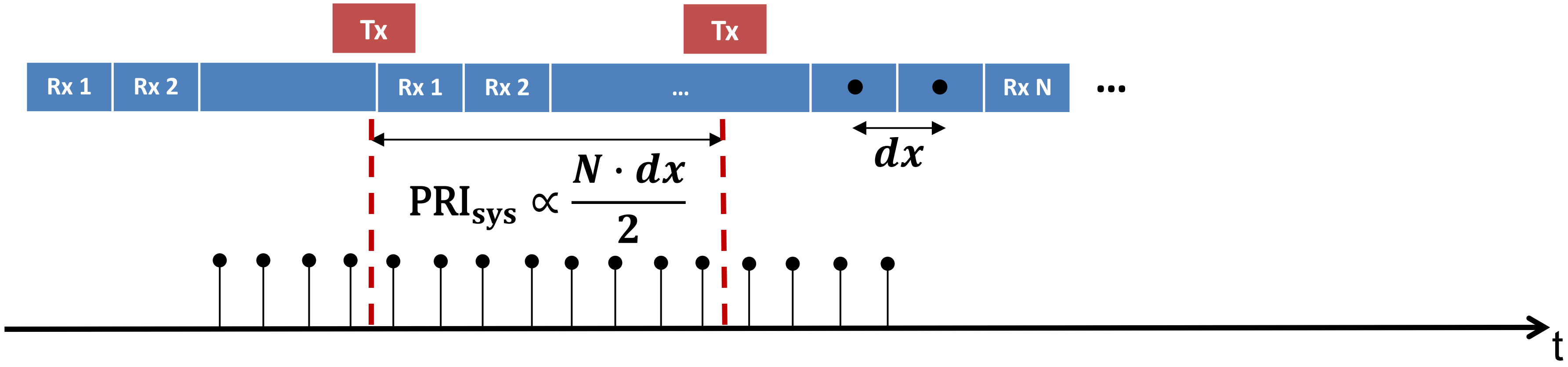
Heterogeneous

Strong impact of local backscatter characterist … tion performance

High-Resolution Wide-Swath with Multiple Azimuth Channels



$$\mathrm{PRF}_{\mathrm{sys}} = \frac{2 \cdot v_{sat}}{N \cdot dx}$$ condition for uniform sampling



Limitations of conventional SAR can be overcome

Wide swath width ⇐ **PRF** ⇒ **Fine azimuth resolution**

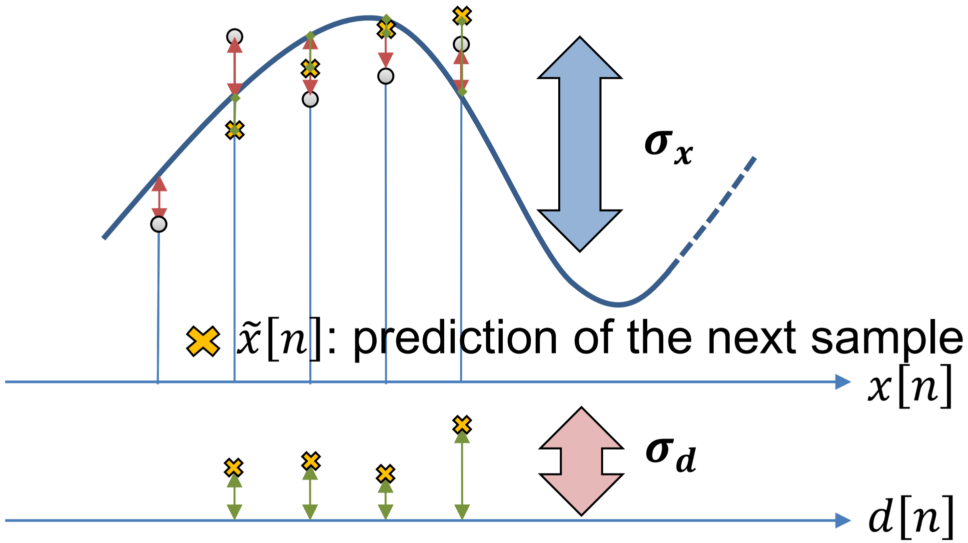
Data volume reduction methods for multichannel SAR

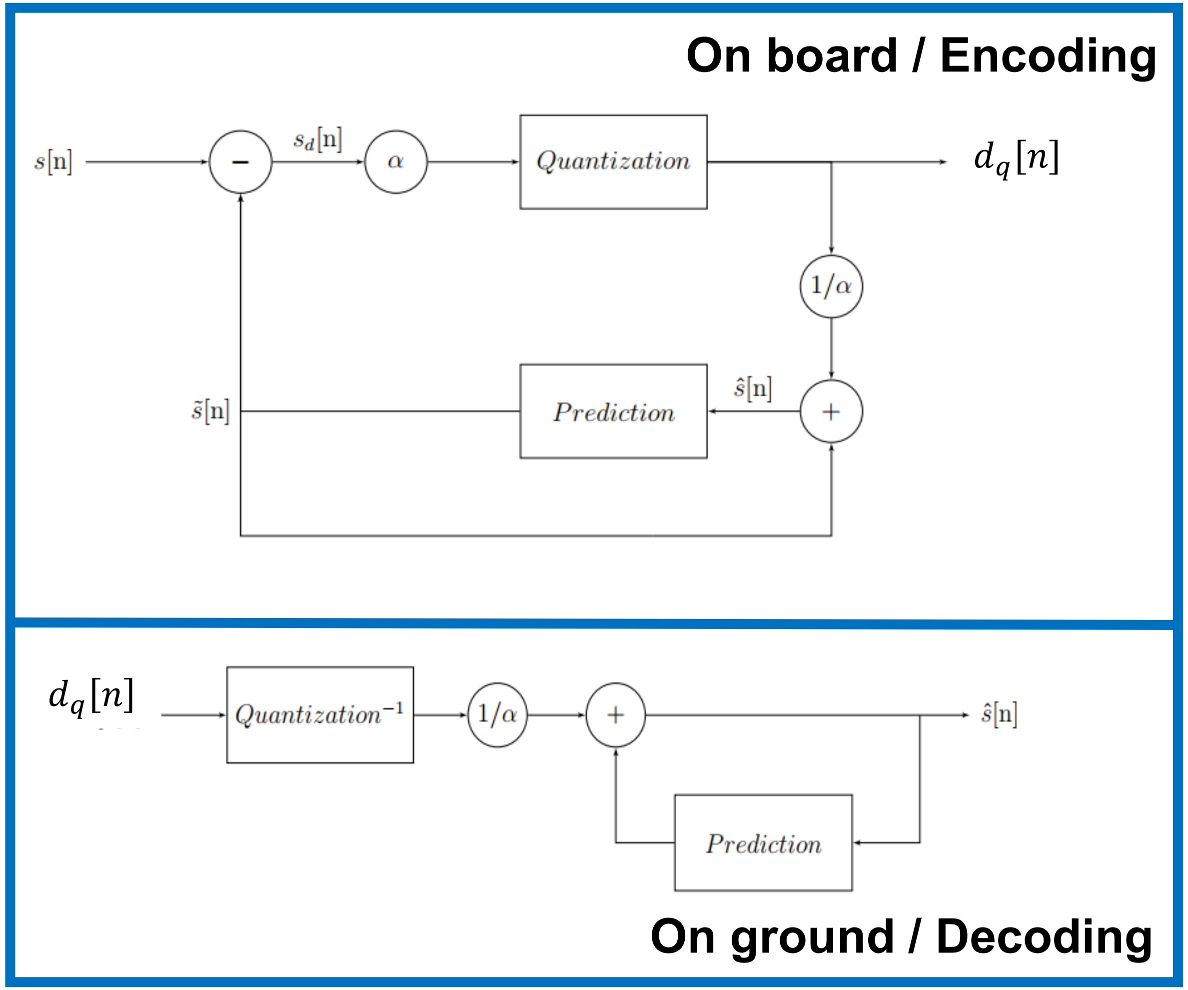
Linear Predictive Coding (LPC)

Doppler-Based Transform Coding (TC)

Method 1 – Linear Predictive Coding (LPC) Encoding / Decoding Scheme

Exploit azimuth autocorrelation to reduce the signal dynamic range and, in turn, the quantization errors





Prediction order

$$\tilde{x}[n] = \sum_{i=1}^{N_P} \beta_i x[n-i]$$

Prediction gain

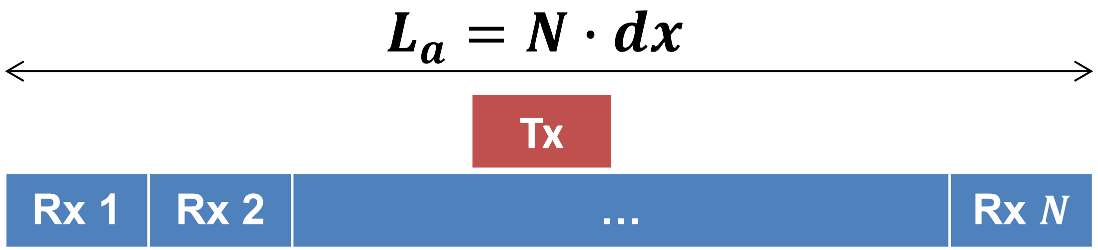
$$G_{N_P} = \frac{\sigma_x^2}{\sigma_d^2} \text{ with } \sigma_d < \sigma_x$$

- **BAQ-quantized prediction error $d_q[n]$**

$$d_q[n] = \mathbb{Q}[x[n] - \tilde{x}[n]]$$

- **Modest computational burden** (N_P-coefficient filter)
- Promising approach for **staggered SAR systems** (large azimuth oversampling)

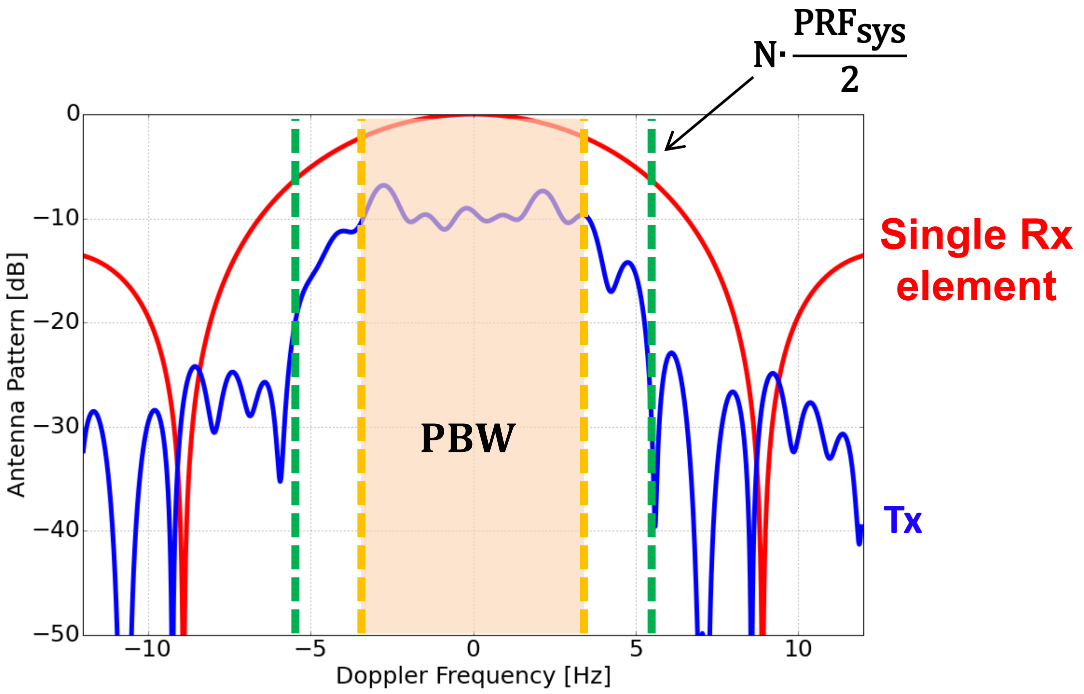
Method 2: Doppler-Based Transform Coding (TC)



$\mathrm{PRF}_{\mathrm{eff}} > \mathrm{PBW}$

Correlation/redundancy among azimuth samples

Efficient data compression: joint DFT and variable bit allocation



- **Achievable data volume reduction** mainly determined by the antenna pattern and oversampling factor $ovf = \frac{N \cdot \mathrm{PRF}_{Tx}}{\mathrm{PBW}}$
- **Modest computational burden** (N-point DFT)

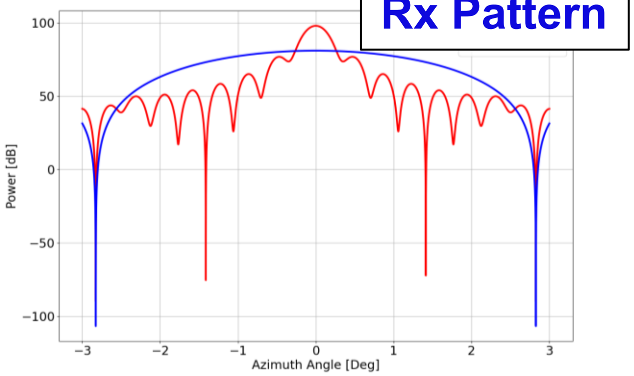
Multichannel SAR Systems Parameters

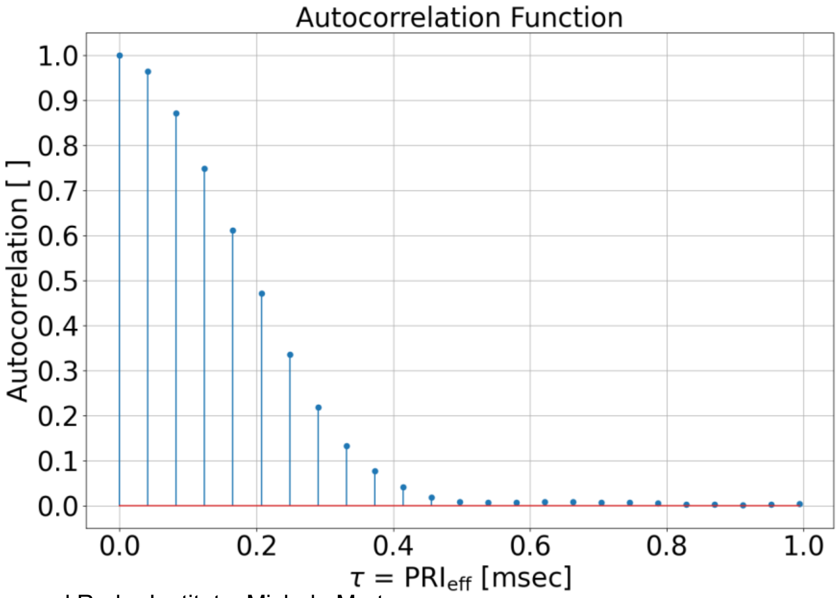
Parameter	ROSE-L-like	HRWS C-band	HRWS X-band
Carrier frequency, f_c	1.25 GHz	5.04 GHz	9.65 GHz
Satellite height, h_s	697 km	697 km	514 km
Antenna type	Planar array		
Acquisition mode	Stripmap		
Azimuth antenna length, L_a	11 m	12.8 m	5.04 m
Number of azimuth channels, N	5	8	[4, 8]
Pulse repetition frequency,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

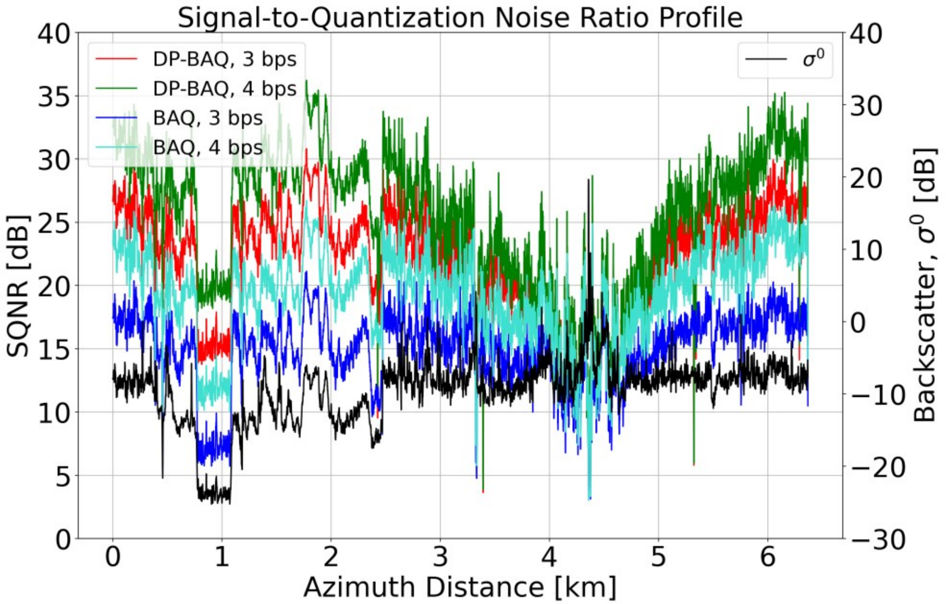
Dynamic Predictive DP-BAQ and Data Reduction HRWS X-Band

- ***HRWS system, X band, N = 8 channels***

Prediction Order	Data Reduction Homogeneous	Data Reduction „Jump“	Data Reduction Iowa	Data Reduction Mexico City
1	30.5 %	29.2 %	41.4 %	42,2 %
2	41.8 %	36.4 %	46.6 %	52.7 %
3	42.0 %	36.0 %	47.2 %	54.2 %
4	42.1 %	35.5 %	47.1 %	54.8 %







Mexico City, 1st order prediction

Transform Coding TC-BAQ and Data Reduction HRWS C-Band

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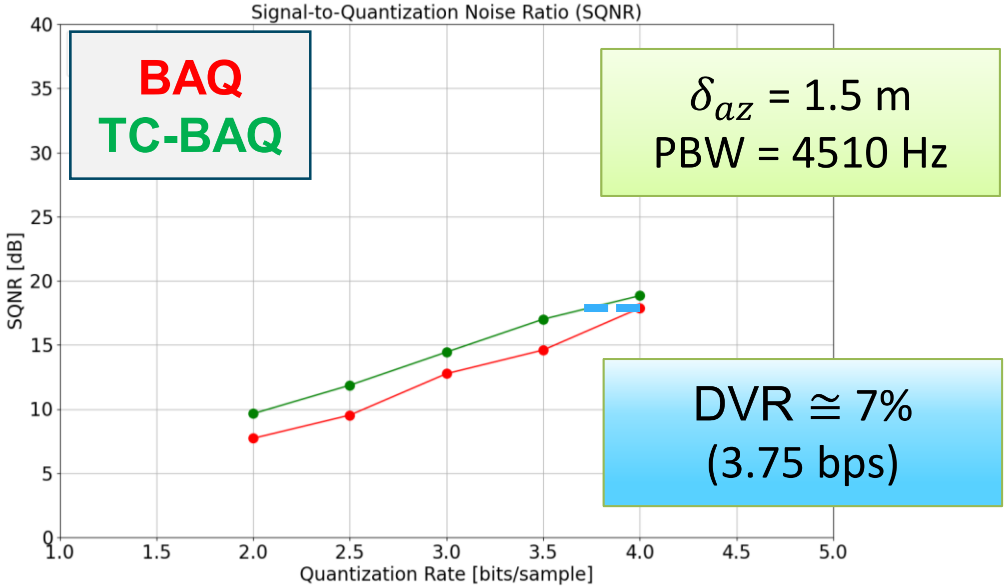
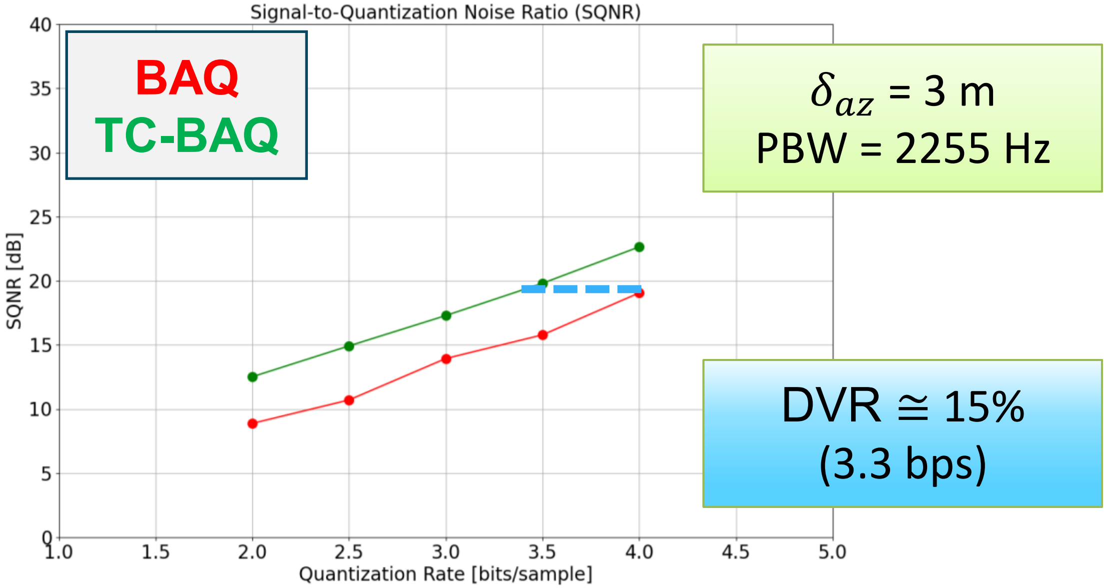
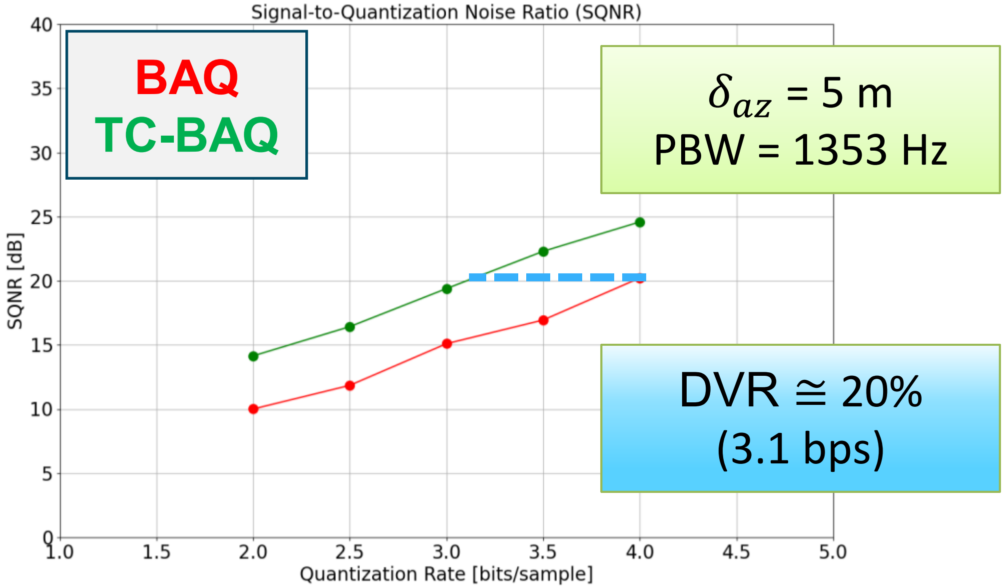
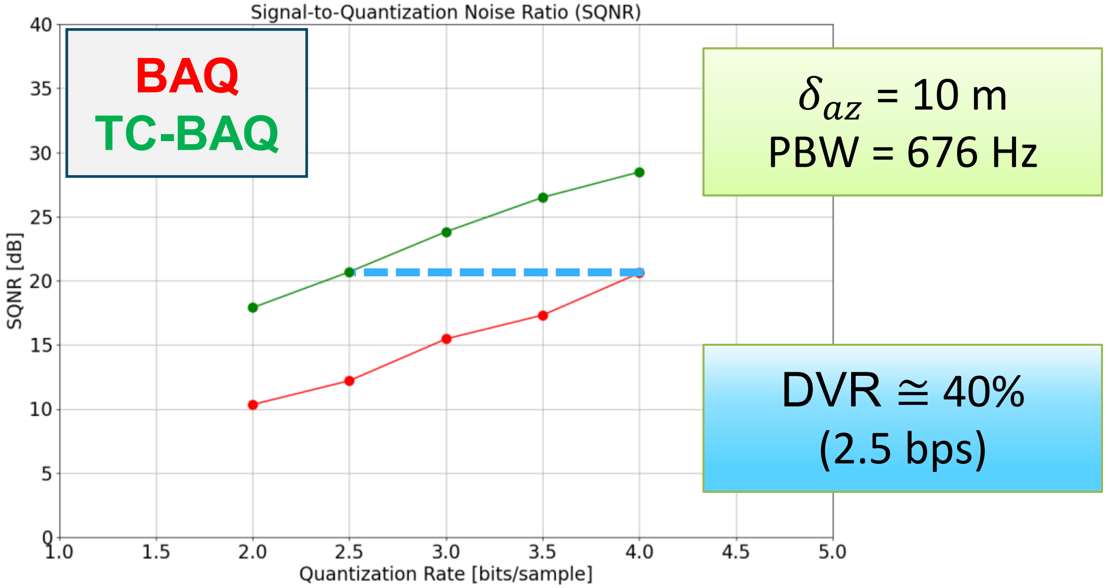
Data volume reduction (DVR) w.r.t. 4-bit BAQ – homogeneous scene









[1] M. Martone, M. Villano, M. Younis and G. Krieger
"Efficient Onboard Quantization for Multichannel SAR Systems"
IEEE Geoscience and Remote Sensing Letters, vol. 16, 2019.

[2] M. Martone, N. Gollin, G. Krieger, E. Imbembo and P. Rizzoli
"Coding-Based Data Compression for Multichannel SAR"
IEEE Geoscience and Remote Sensing Letters, vol. 22, 2025.

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Smart On-board Processing for Earth Observation Systems

- *3-year Horizon Europe project (Grant Agreement ID 101082745) – KO end of 2022*
- *Main goal of SOPHOS: design and implementation of enabling technology for high-end data products generated on board spacecraft via the implementation of power-efficient high-performance space processing chains for various Low-Earth Orbit (LEO) missions, with focus on Synthetic Aperture Radar (SAR).*

SOPHOS

Smart on-board processing for earth observation systems

DSI Aerospace Technology

Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

UNIBAP

teletel

UNIVERSITÄT ZU LÜBECK

https://sophoshorizon.eu/

Funded by the European Union

SOPHOS Objectives and Concept

- O1: Enhance data access to on-board mass storage
- O2: Miniaturisation of HW modules within the processing chain
- **O3: Improvement in on-board SAR raw data compression**
- O4: Improvement in / Feasibility of on-board SAR image formation (Stripmap ω-K algorithm, multi-looking and detection, block processing)
- **O5: Optimization of portable processing SW routines to enable enhanced on-board SAR processing**

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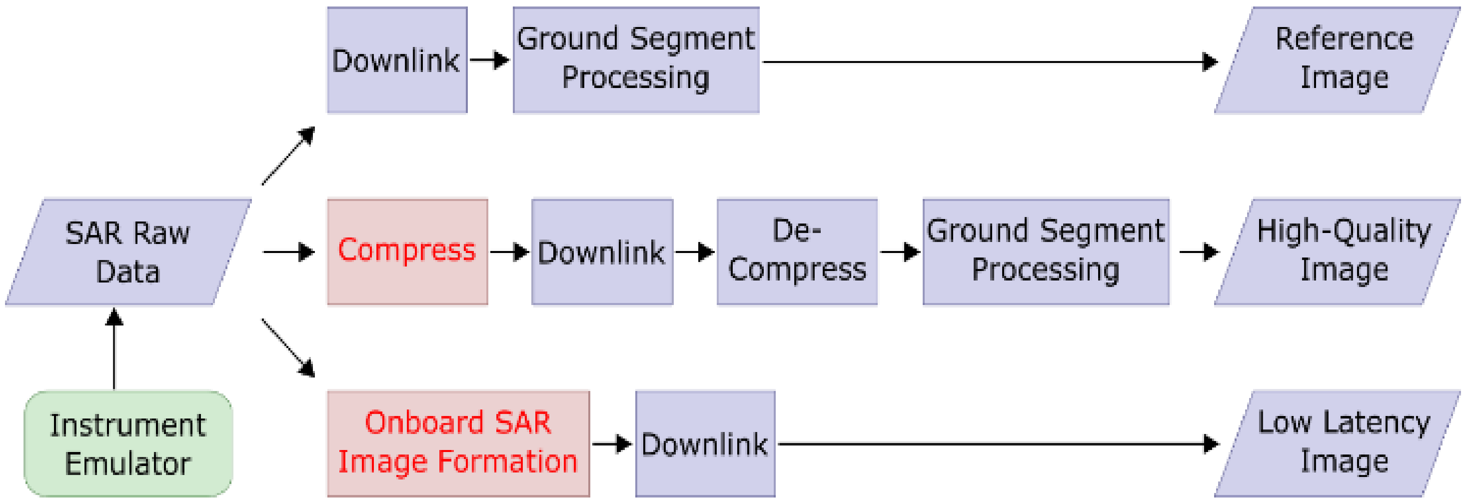
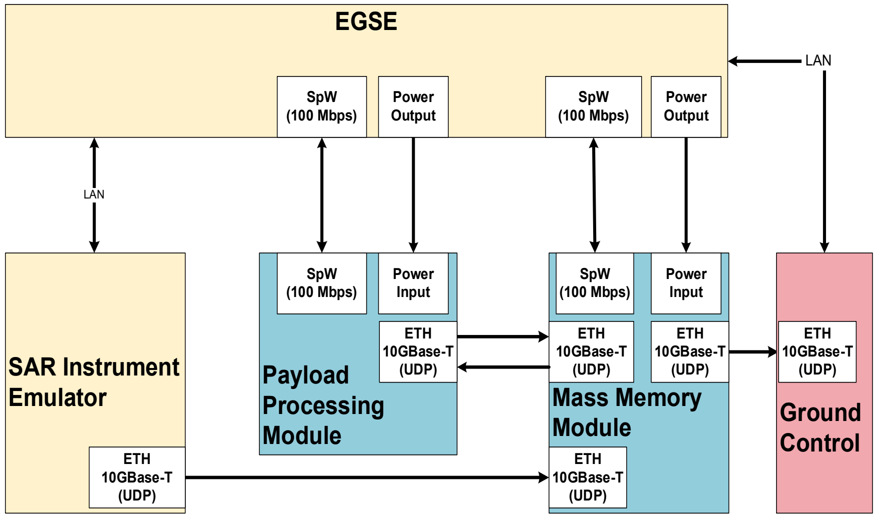
Proposed onboard processing algorithms

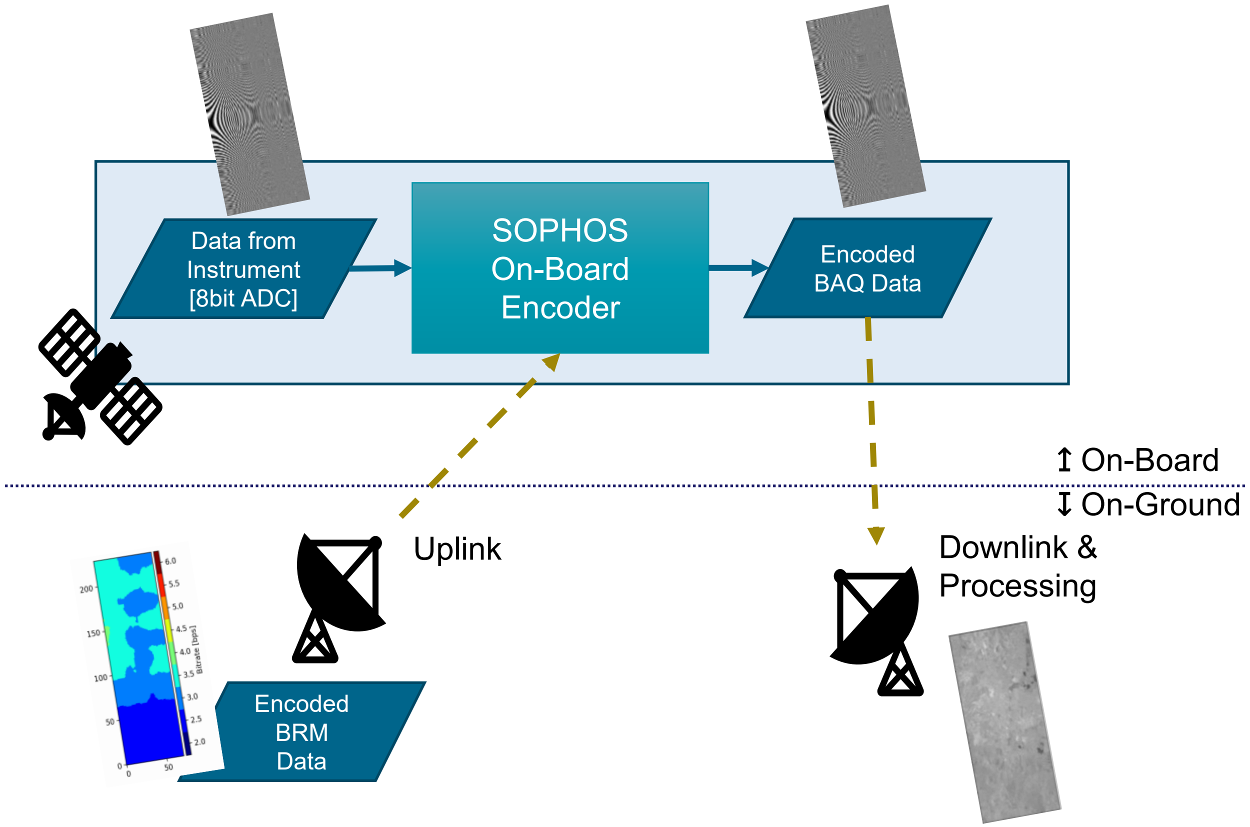


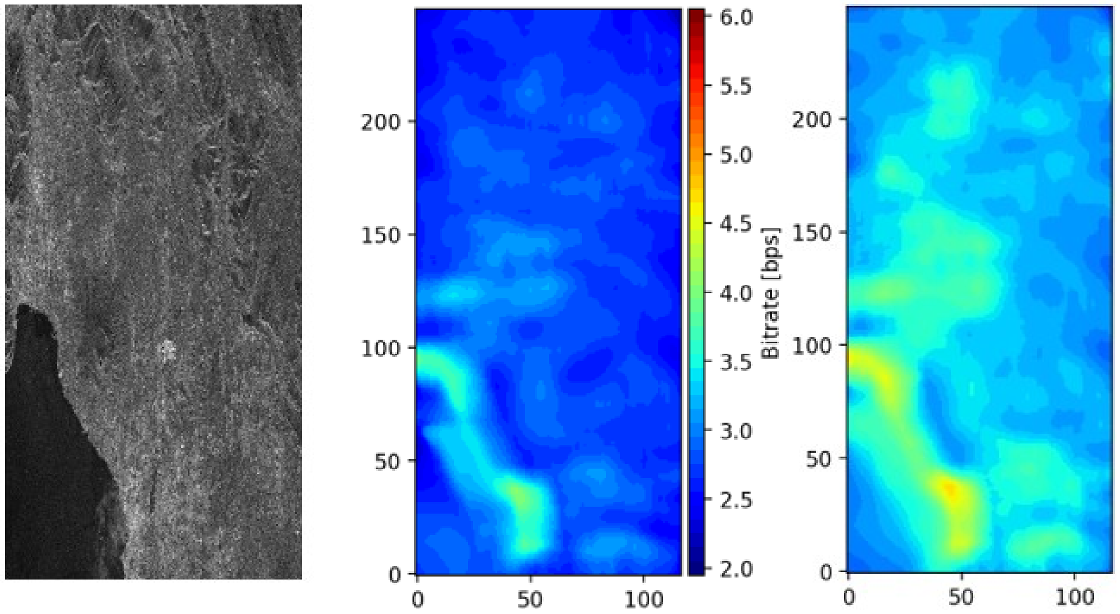
Demonstrator concept



PO-BAQ for SAR Raw Data Compression

- Performance-Optimized PO-BAQ: a bit-rate map (BRM) is generated to jointly optimize target SAR performance and resulting data rate
- A-priori information on the backscatter characteristics exploited
- BRM uploaded to the sensor before commanding





Test SAR image (Naples, Italy)

BRM SQNR = 10 dB

BRM SQNR = 15 dB

M. Martone, N. Gollin, P. Rizzoli and G. Krieger, "Performance-Optimized Quantization for SAR and InSAR Applications„ in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 60, 2022.

System Parameters and BRM Uplink Considerations

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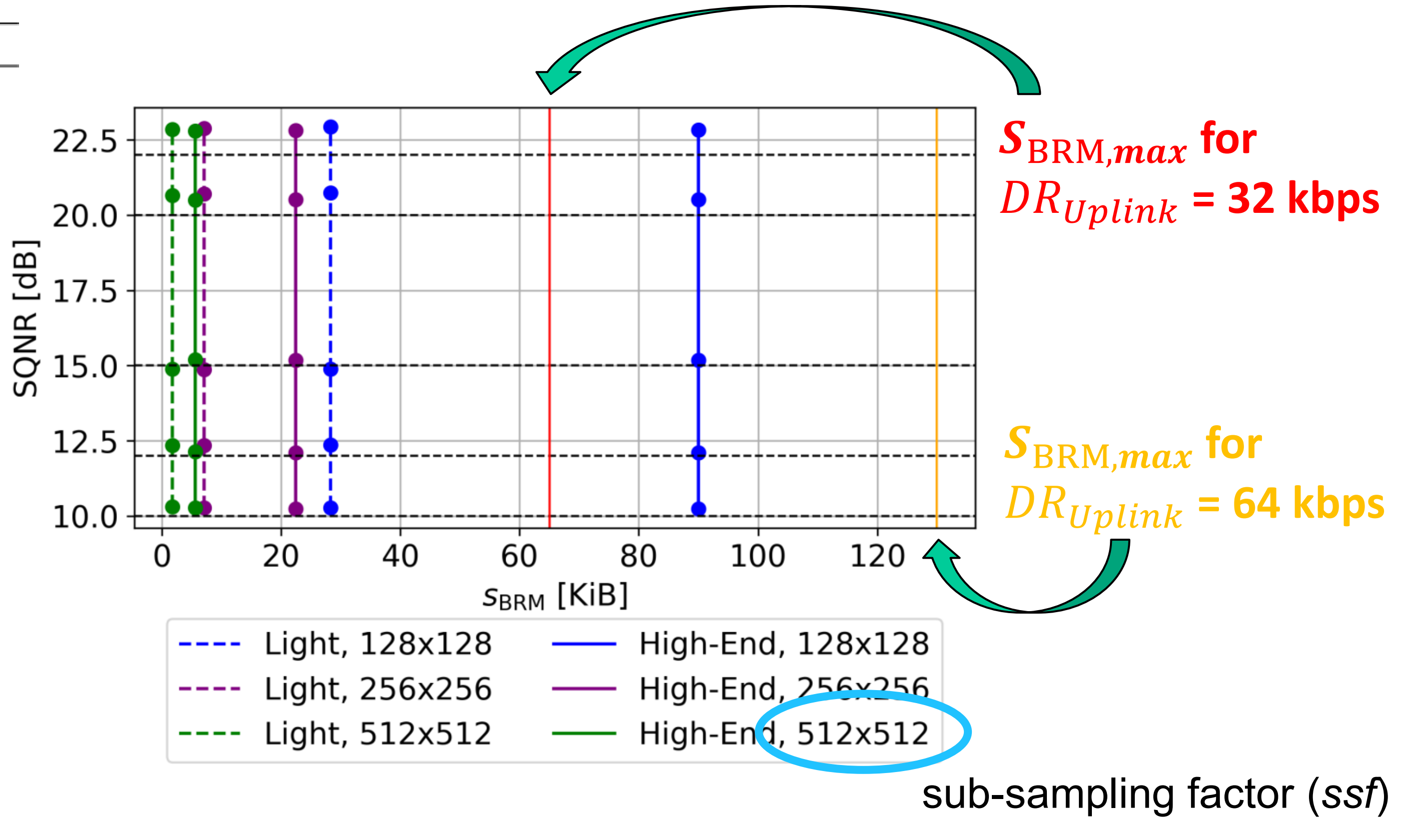
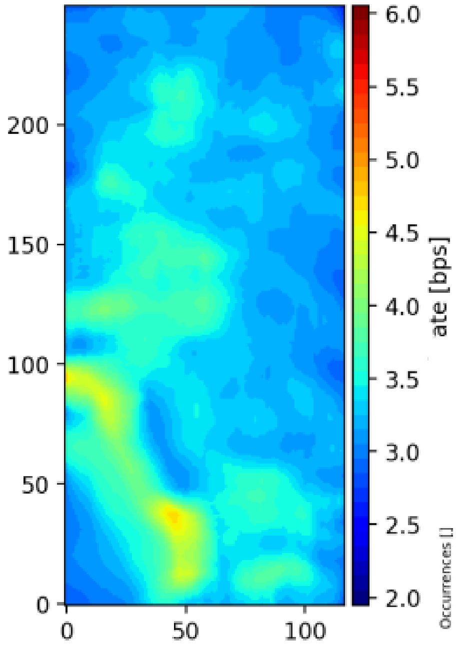
System parameters based on present SAR missions:
TerraSAR-X, **ICEYE**, **Capella Space**, **StriX**

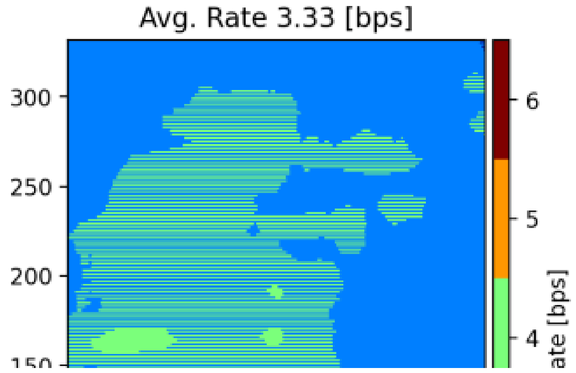
Parameter		Light	High-End
Center frequency	f_c	9.65 GHz	
Bandwidth	B_w	150 MHz	600 MHz
Range sampling freq.	f_s	165 MHz	660 MHz
Antenna length [az]	L_{az}	3.2 m	
Antenna length [el]	L_{el}	0.4 m	
Look angle	θ_{inc}	30°	
Orbit height	h_s	560 km	
Swath length	$S_{w,az}$	50 km	
Swath width	$S_{w,rg}$	50	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 kpbs	

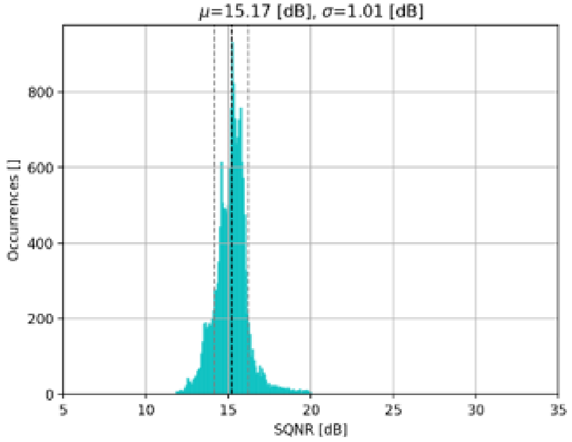


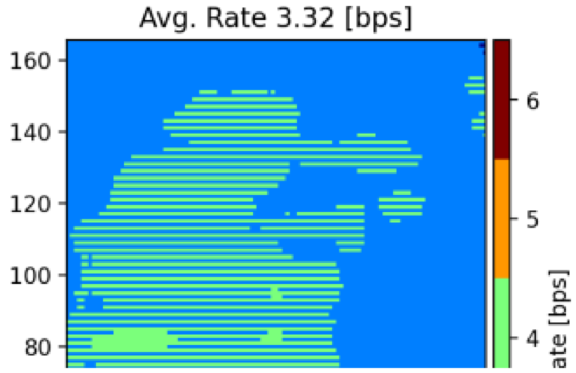
SAR Data Compression: BRM & Performance

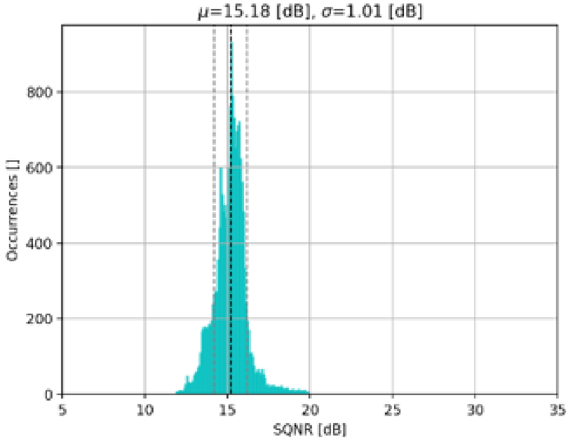
Original BRM	*ssf* = 128 x 128 BRM size = 88 kB	*ssf* = 256 x 256 BRM size = 22 kB	*ssf* = 512 x 512 BRM size = 6 kB

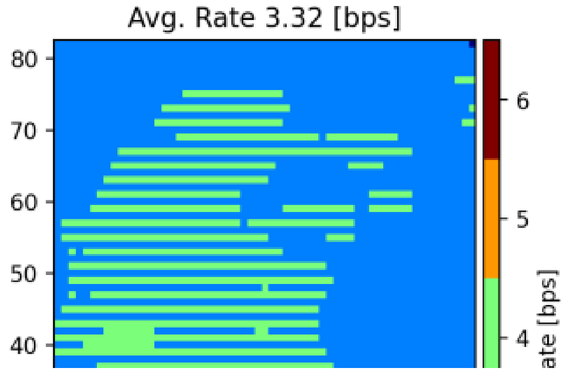


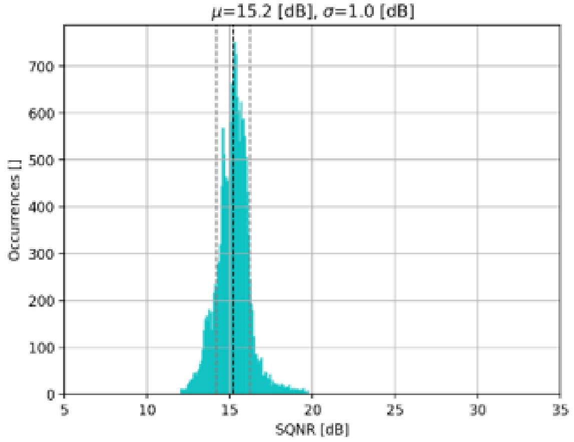












- **Feasible BRM design** for the SOPHOS acquisition scenarios and requirements
- **Software optimization**: preliminary results of C-code implementation compatible with the processing time requirements (100s); final numbers after integration on the hardware (ongoing)

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Summary & Conclusions

- Efficient **on-board raw data compression** of utmost importance for present and future SAR missions
- Efficient multichannel SAR raw data compression using **Linear Predictive Coding** and **Transform Coding**
- **Performance-optimized quantization** developed in the SOPHOS project
- Both approaches can be applied **jointly** to reduce & optimize the data rate and performance

Outlook

- Alternative approach: **AI-based bitrate allocation** method for **application-optimized** SAR raw data compression (presentation by N. Gollin in this session)
- Data volume reduction for **multi-static SAR**: opportunities and challenges

Thank you for your attention!

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