Sentinel-1 Flexible Dynamic Block Adaptive Quantizer

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Abstract

The variable bit rate coding scheme designed for Sentinel-1 and named Flexible Dynamic Block Adaptive Quantizer (FDBAQ) is presented in this paper. FDBAQ technique adapts the number of quantization bits according to a local estimate of the signal-to-noise ratio (SNR) at the receiver. Its performance is shown to be superior to the currently used BAQ compressor [1] in terms of SNR related to the compression rate.
An overview of the design optimization, of the on-board and on-ground operations and of the system performances is provided. Results of simulations have been based on a 16-bit mosaic of reflectivity in C-band based on ENVISAT Global Monitoring data [2].

1 Introduction

Sentinel-1 is an imaging synthetic aperture radar (SAR) mission at C-band designed to supply all-weather day-and-night imagery to a number of operational Earth observation based services. The three priorities identified for the mission cover applications such as: mapping in support of humanitarian aid in crisis situations, monitoring sea, ice zones and the arctic environment, surveillance of marine environment, monitoring land surface motion risks, mapping land surfaces. Four different measurement modes have been included to fulfil the different mission requirements: a classical high resolution Stripmap mode, offering a choice of 6 different swaths of 80km width each; two Wideswath modes based on the progressive azimuth scanning principle [3] and the Wave mode designed for ocean applications. In table I the main features of these modes are given.

TABLE I. SENTINEL-1 INSTRUMENT MODE REQUIREMENTS

Mode	Access Angle	Single Look Resolution (rg x az)	Swath Width	Polarization
Strip Map (6 modes: S1…S6)	17°-41°	5m x 5m	80km	HH-HV, VV-VH
Interferometric Wide Swath(IW)	26°-40°	5m x 20m	250km	HH-HV, VV-VH
Extra Wide Swath (EW)	17°-41°	20m x 40m	400km	HH-HV, VV-VH
Wave Mode (WV1, WV2)	23°or 36°	5m x 5m	20x20 at 100km	HH or VV

			interval	

One of the key features of the CSAR payload is the flexible quantizer giving a better allocation of bits for bright scatterers and thus decreasing the average bit rate by using variable bit rate coding. Similarly to conventional BAQ techniques, the FDBAQ consists of a quantizer selection and a proper scaling of the input signal based on the estimated standard deviation of a small block of input data. Differently from the BAQ however, the FDBAQ offers the choice of a set of different quantizers to choose from. The quantizers have a different quantization levels per sample. The best quantizer is selected automatically on the basis of the input signal-to-noise ratio in an input data block. More quantization levels per sample are given to target areas with high signal-to-noise ratio (such as cities or ice), fewer quantization levels per sample are given to target areas with low signal-to-noise ratio (such as sea or desert area). The optimal choice of the finite set of quantizers to be used on-board for compression depends on the system characteristics and on the radar reflectivity statistics after appropriate optimization.

2 FDBAQ design and operations overview

The FDBAQ design for Sentinel-1 can be divided into two parts:

- The optimization procedure, which accounts for

ISBN 978-3-8007-3272-2

the radar reflectivity statistics to choose the best set of quantizers with the purpose of reaching the minimum downlink bit rate ensuring a minimum image quality defined by the NESZ requirement.

- The design of the on-board compression and on-ground decompression algorithms implementing the FDBAQ scheme for real-time acquisitions.

2.1 FDBAQ principle

To understand the above design the input to the quantizer is modelled as the sum of clutter signal and a thermal noise contribution σ_T^2, both assumed complex circular, zero-mean Gaussian processes. Signal power is proportional to the radar backscatter coefficient σ_0 by means of a range dependent factor, $\eta(r)$, which can be derived from the radar equation. The resulting SNR, taking the quantization noise σ_Q^2 into account, can be written as

$$SNR = \frac{\sigma_0 \cdot \eta(r)}{\sigma_T^2 + \sigma_Q^2} \qquad (1)$$

The signal power corresponding to the NESZ equals the noise power and therefore SNR=1. The NESZ then equals:

$$NESZ = \frac{\sigma_T^2 + \sigma_Q^2}{\eta(r)} \qquad (2)$$

Sentinel-1 image quality specifies a maximum value for NESZ, which is -22dB. In other words the actual NESZ shall be less than this bound: $NESZ \le \sigma_{0NE}$; even if this condition usually refers to image data it also applies to raw data. The SNR after quantization can be found to be then $SNR \ge \sigma_0 / \sigma_{0NE}$ for ideal (i.e. continuous) flexible quantization; really, combining Eqq. (1) and (2) with the bound on the NESZ we have:

$$SNR = \frac{\sigma_0}{\dfrac{\sigma_T^2}{\eta(r)} + \dfrac{\sigma_0 + \sigma_T^2/\eta(r)}{SQNR}} \ge \frac{\sigma_0}{\sigma_{0NE}} \qquad (3)$$

BAQ that applies a constant bit rate independent of radar signal power is not the optimum compression method. It produces a degradation of the SNR that varies with the power of the detected radar signal. In Figure 1 this principle is illustrated.

In the FDBAQ case a finite set of quantizers can be selected; the overall image quality is then improved since the ideal quantization line is more closely followed (see Figure 2). All the previous considerations assume that for a given quantizer the SQNR and the corresponding bit rate R are known values and joined by a linear relation (see [4] or table II).

The optimization procedure is the most critical task in the FDBAQ as this impacts the trade-off between image quality and the average output bit-rate. In principle this is an optimization problem with two conflicting objectives: the minimization of the average bit rate and the maximization of the total SNR. The problem however is complex as the clutter statistics changes with the range according to the scene, the incidence angle and the overall system gain.

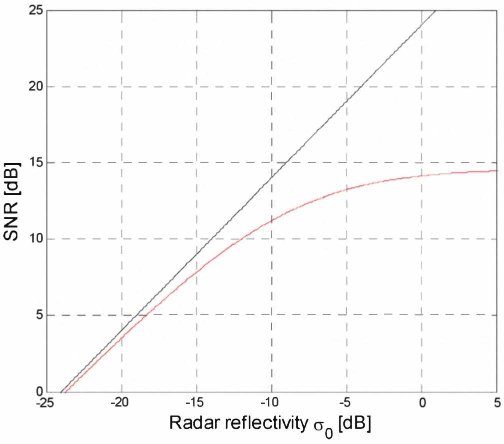


Figure 1: Ideal SNR (no quantization) as a function of σ_0 (black line); degradation of SNR when a BAQ with constant rate (3 bit/sample) is applied (red line).

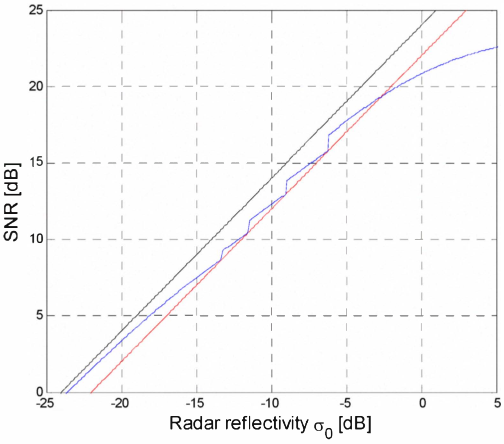


Figure 2: Ideal SNR (black line); tolerable SNR after continuous FDBAQ (red line); SNR after FBAQ with 5 discrete bit rates (blue curve).

2.2 Sentinel-1 FDBAQ optimization

With the constraint on the NESZ, the SQNR that is required is given by:

$$SQNR = \frac{\sigma_0 \eta(r) + \sigma_T^2}{\sigma_Q^2} \ge \frac{\sigma_0 + \sigma_T^2/\eta(r)}{\sigma_{0NE} - \sigma_T^2/\eta(r)} \qquad (4)$$

This equation relates the SQNR and the radar reflectivity; with the equality sign it relates each σ_0 and the best corresponding value of SQNR if we could select the quantizer from an infinite set. For each fixed quantizer (i.e. SQNR) there exists a threshold $\hat{\sigma}_0$ below which the selected quantizer satisfies the requirements ($\sigma_0 \le \hat{\sigma}_0$) but not for larger values of σ_0. For Sentinel-1 the FDBAQ on-board implementation has the restriction of a maximum of five quantizers. If the estimated standard deviation for a block

ISBN 978-3-8007-3272-2

of data is provided, the quantizer with a SQNR greater or equal to the required minimum is selected, as this is the choice that guarantees the required SNR at the minimum output bit-rate; this selection produces the staircase curve of SQNR vs. σ_0 illustrated in Figure 3. The identified four values of $\hat{\sigma}_0(k)$ mark the values of the radar reflectivity at which the different quantizers switch from one to the other (the rate selection thresholds).

For the selection of quantizers (and the rate selection thresholds) the average output bit rate was computed as a cost figure of the quantizer choice. To compute the average output bit-rate, the histogram (estimation of pdf) of σ_0 is a required input (an example is provided in Figure 3).

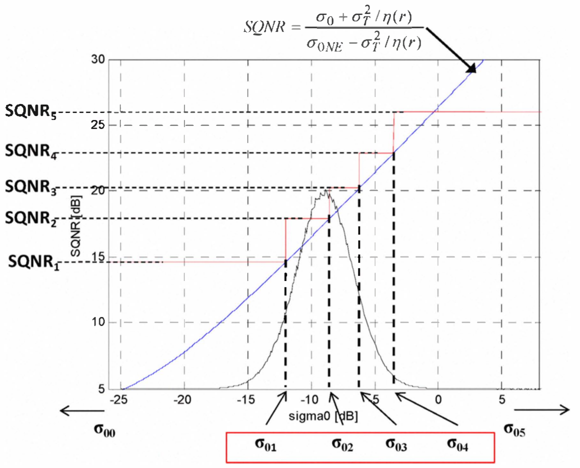


Figure 3: Quantized SQNR versus target σ_0 for a set of five quantizers (red staircase). An example of a σ_0 histogram is given by the black line.

A complication of this process is the variation of the radar reflectivity with the incidence angle [2,5]. To make a practical computation, the dependence of σ_0 on incidence angle was assumed constant for a given set of slant range intervals; the resulting *range zones* have constant average radar reflectivity with statistics defined by $P_{\sigma_0}(\sigma_0; n_{rz})$.

The optimal quantizers set can be chosen from a large population of possible quantizers (provided with some criterion) by an exhaustive search or restricting the exploration because of on-board hardware limitations. The best set $\{R_1, \ldots, R_5\}_{opt}$ is taken as the one achieving the lowest average bit rate,

$$\min_{R_k \in Q_{set}} \left[\sum_{sw} \sum_{rz} \sum_{k=1}^{5} R_k \cdot \int_{\hat{\sigma}_0(k-1)}^{\hat{\sigma}_0(k)} P_{\sigma_0}(\sigma_0; n_{rz}) d\sigma_0 \right] \quad (5)$$

where the previous weighted sum has been averaged over all the range zones of a swath and all swaths involved in the optimization process. The implementation used for Sentinel-1 is based on the minimum average bit rate for IW mode (three swaths), which is the default image mode.

Output of the optimization procedure is an optimal set of five quantizers, together with their rate selection threshold (in terms of radar reflectivity and consequently of the power at the antenna input) for all operational modes and for each range zone. The quantizers and the rate selection thresholds are used for on-board compression operations.

2.3 Sentinel-1 FDBAQ compression and decompression

The choice of the quantizer set and of the corresponding rate selection thresholds are the needed inputs for on-board operations. However the optimization process described above is a pre-launch procedure. As shown in Figure 4 the acquired C-band data could be used as a set of statistics for the update and refining of the thresholds Look Up Tables (LUTs) and quantizer set. However, to derive the pre-launch optimized values, an external source of radar reflectivity statistics is necessary.

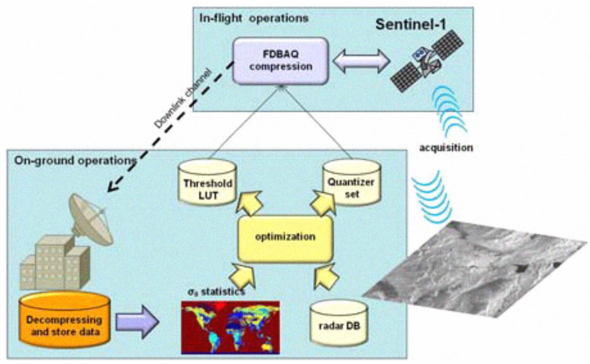


Figure 4: On-ground and in-flight operations rationale

In-flight operations include a first quantization using a finer ADC (a 10-bit ADC for Sentinel-1), next the Digital Down Conversion and filtering, finally followed by the FDBAQ, entropy encoding and packet formatting (see the scheme in Figure 5).

In-principle FDBAQ operations on-board and on-ground include:

- Segmentation of input data in blocks.
- Selection of the proper table with the rate selection thresholds for the current data block.
- Standard deviation of the power of the IQ baseband signal σ_{est} estimation and comparison with the set of four thresholds (five quantizers require four thresholds) selected from the loaded table for that range zone.
- Quantizer selection as the one satisfying the condition described in par. 2.2, i.e.

$$\mathit{find} \ \arg\min_{k=1,\ldots,4} \{\sigma_{est} \le \hat{\sigma}_0(k)\} \quad (6)$$

- Complex data scaling for their estimated standard deviation.

- ➢ Quantization of Normalized samples using the quantization table selected for that quantizer. Quantization consists in a look-up-table (LUT) operation, where the current (normalized) sample is compared with the quantized levels and an entropy codeword is then assigned as a result.

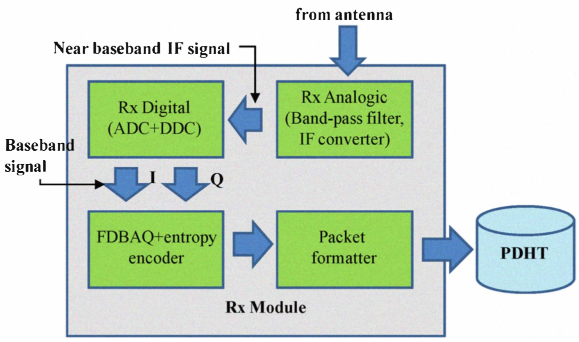


Figure 5: Schematic of the receiver elements. Rx analog has been exemplified as a single block.

Uniform quantizers followed by entropy encoding (e.g. a Huffman encoder) have been adopted for quantization, since literature states [4] that this choice is more efficient than Max-Lloyd for Gaussian statistics. In table II the set of possible quantizers used for Sentinel-1 is presented. The interval goes from 3 (2.5356) to 5 (4.2376) bits/sample (between brackets with entropy encoding applied) and has been chosen because of image quality constraints.

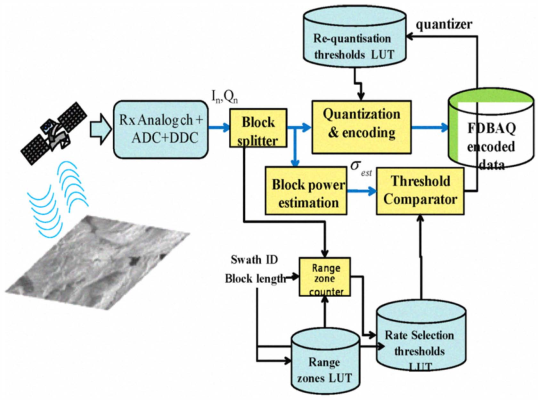
TABLE II. ADOPTED SQNR VS RATE TABLE. N IS THE NUMBER OF LEVELS OF THE UNIFORM QUANTIZER

K= N/2	SQNR [dB]	Entropy [bit/sample]	Huffman Rate [bit/sample]
4	13,3718	2,4871	2,5356
5	14,9823	2,7533	2,7910
6	16,3161	2,9739	3,0220
7	17,4552	3,1623	3,2234
8	18,4990	3,3267	3,3633
9	19,3291	3,4724	3,4926
10	20,1206	3,6035	3,6310
11	20,8398	3,7226	3,7512
12	21,4977	3,8315	3,8648
13	22,1045	3,9321	3,9717
14	22,6669	4,0252	4,0665
15	23,1920	4,1123	4,1584
16	23,6851	4,1940	4,2376

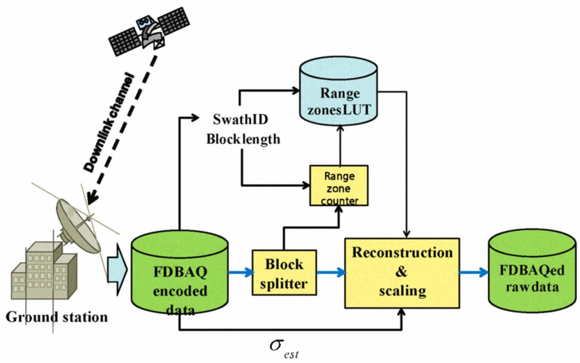
On-ground decompression takes advantage of the same set of tables (quantizers and entropy codebook), such that the reconstruction of the quantized samples basically consists in the following steps:

- ➢ Each range line is un-packed and range data blocks are selected.
- ➢ For each block the proper entropy codebook is selected on the basis of the on-board selected quantizer.
- ➢ Inverse assignment (codeword-to-quantized level) is then performed and levels are then multiplied by
the estimated standard deviation of the block to provide the final restituted values.

An overview of the operations is provided in Figure 6.



(a)



(b)

Figure 6: Schematic of: (a) the in-flight operations; (b) the on-ground decompression.

3 Implementation and Results

The optimization design of the FDBAQ requires an estimate of the radar reflectivity statistics and of the thermal noise power. The estimate of the radar reflectivity must have a minimum required resolution on ground of about 4km in azimuth (the antenna unfocused aperture) by 1km in range (i.e. about the extent of a BAQ range block).

The input power statistics come from the radar equation (space and ground system parameters knowledge) and from a model of the global radar reflectivity, based on the following assumption:

- ➢ the ocean backscatter model in [6] has been used for patches of sea/ocean, by assuming an average wind speed of 8 m/s;
- ➢ the mosaic of C-band reflectivity produced by the ESA-GRID team [2], has been exploited for the land.

ISBN 978-3-8007-3272-2

On the mosaic a correction of the incidence angle dependence of σ_0 (see in [2]) has been applied using the International Geosphere-Biosphere Programme (IGBP) model [8], which provides a classification of global land surfaces based on radiometric behavior.
For a selected areas of the world, chosen by mission opportunities (for example it could include only Europe and North America, or only icy regions, etc) it is possible to collect the reflectivity classes occurrences using the IGBP map. The estimated pdf of σ_0 at the reference incidence angle ϑ_{ref} is then the weighted pdf's of the various radiometric classes, the weights being the occurrence of each class for that area. The statistics retrieved this way refers to ϑ_{ref} while we need to restore the reflectivity trend at the incidence angles of the range zones $\vartheta(n_{rz})$ (that depend on system geometry and distribution of range zones in the slant range interval):

$$\sigma_0 = \sigma_0(\vartheta_{ref}) / \alpha(\vartheta(n_{rz}); n_c)$$
$$P_{\sigma_0}(\sigma_0; n_{rz}) = \sum_{n_c} \alpha(\vartheta(n_{rz}); n_c) \cdot P_{\sigma_0}(\sigma_0; n_c) \rho(n_c) \quad (7)$$

In Eq. (7) $\alpha(\vartheta; n_c)$ is the correction law used to compensate σ_0 variation with incidence angle for the envisaged IGBP classes; the weighted summation is applied to all the available radiometric classes, the weights being the relative frequencies of each class, $\rho(n_c)$, retrieved from the classification map of the selected area.
Processing has run using the nominal Sentinel-1 system parameters and orbit; the optimization procedure has been applied to the IW mode. Three different portions of the mosaic have been selected as areas of interest: all the *world*, *west* areas, i.e. the Nord America and Europe and *south* areas, i.e. the areas going from 60°S to 15°N latitude. The optimization procedure has been tested even at different orbit positions (minimum, maximum and average altitude). The results are presented in Table III. Optimization considerations have led finally to the following set of quantizers K=N/2={4,5,7,10,16}.
Robustness of the rate selection thresholds w.r.t. local discrepancies of reflectivity, system parameters and algorithm design approximations has been tested. To assure a fair validation, the quantization process has been tested using a set of images generated by a process totally different and independent of ESA-GRID mosaic. In this way the differences between the two databases can provide the degree of 'statistical fluctuations' required to validate the acquisition and quantization processes. The test site data come from the Wien University S-1 database [7], and have been simulated using ASAR WSM acquisitions collected over limited areas of the world and properly calibrated and corrected for backscattering variations.
Different land areas, chosen for different scene heterogeneity, have been selected to verify the constraint on the maximum bit rate (IW mode has been tested) and on mean SNR performance. In table IV the main results are summarized.

TABLE III. FDBAQ OPTIMIZATION PERFORMANCES. MARKED CELL IS THE DEFAULT CONDITION CHOSEN TO GENERATE THE THRESHOLDS USED FOR THE VALIDATION TESTS

Default quantizers (K=4,5,7,10,16)	Minimum H	Average H	Maximum H
West			
[Mbit/s]	209.667	210.709	211.651
[bit/sample]	2.727432	2.740985	2.753236
Mean SNR [dB]	12.497437	12.521011	12.583002
World			
[Mbit/s]	210.797	211.647	212.538
[bit/sample]	2.742133	2.753185	2.764778
Mean SNR [dB]	12.734243	12.757531	12.828703
South			
[Mbit/s]	212.217	213.279	214.277
[bit/sample]	2.760608	2.774426	2.787402
Mean SNR [dB]	12.666388	12.691824	12.755867

TABLE IV. VALIDATION TESTS RESULTS

Test Site name	Image center [lat x lon]. Area size is about 1100x240km (az X rg)	σ0 std/mu [dB]	Mean SNR [dB]	Average bit rate [Mbit/sec]
Amazon	[-12.1393 -59.6627]	0.1838	14.65	238.314
USA	[37.0104 -80.6428]	0.6879	13.39	225.707
Gobi	[36.1898 98.8893]	0.8481	11.05	206.587
Greenland	[66.2529 -45.8077]	0.8578	15.61	252.413
Sahara	[15.6430 6.7778]	1.0046	8.46	197.896
Korea	[39.9639 124.2864]	1.3315	12.48	219.502

In a perfectly homogenous scene, the FDBAQ degenerates to a fixed rate BAQ, and we do not expect relevant gain in performances. However, this is not the real world: the more heterogeneous is the scene (raw data), the better the FDBAQ performs. To appreciate this, we compared the SNR histogram obtained quantizing with FDBAQ and BAQ-3. BAQ-3 followed by Max-Lloyd has been chosen for the comparison (as the one adopted for ENVISAT, [1]), since the average bit rate of FDBAQ is still around 3bit/sample. In Figures 8 and 9 results are shown: the mean SNR was about 0.4 dB better than the BAQ-3.

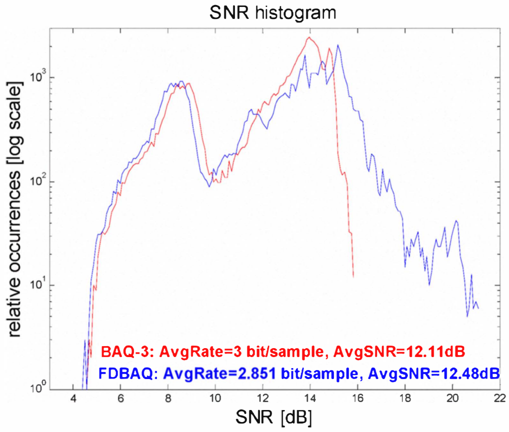


Figure 8: SNR histogram of the Korea test site in log scale (red curve: BAQ-3, blue curve: FDBAQ).

ISBN 978-3-8007-3272-2

However, for the strongest targets (for example the Seoul urban area), the FDBAQ provided an improvement in SNR up to 4 dB.
Finally, longer acquisition simulation has been also tested to verify the volume capability of the system in odd conditions of visibility of the ground stations. In Figure 10 one of most critical *timelines* suggested by Thales Alenia Space is reported, while in Table V the performances achieved by simulation on two of such timelines are provided.

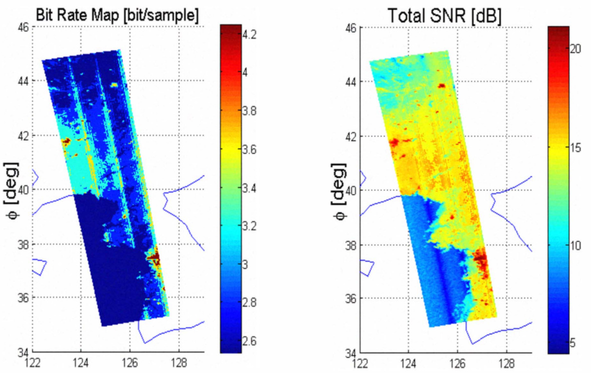


Figure 9: Bit Rate map (left) and SNR map (right) for Korea test site. Seoul can be seen at the low-right side of the image.

TABLE V. VALIDATION RESULTS ON BIT VOLUME

Timeline	Data Volume [Gbit]	Total acquisition time [sec]	Average bit rate [Mbit/sec]
TASI_001	**1043.31**	**5476.45**	**191.51**
TASI_002	**811.94**	**4260.23**	**191.59**

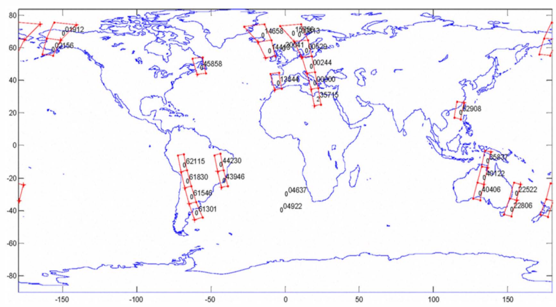


Figure 10: Thales Alenia Space Sentinel-1 acquisition timeline TASI_001 (acquisition is supposed always in TOPS-IW mode).

4 Conclusions

The FDBAQ compression technique for the Sentinel-1 mission has been presented in this paper. A pre-launch, on-ground optimization scheme has been provided as a method to find the optimal set of quantizers and rate selection thresholds for the FDBAQ implementation.
Generation of optimal values and validation on average bit rate have been based on different inputs (ESA-GRID mosaic and Wien University database); the system has shown to be sensitive to variations of reflectivity statistics but also sufficiently robust such that quantizers defined on a global average basis can also work very well for local acquisition even in cases of extreme reflectivity heterogeneity.

Acknoledgments

The work has been framed in the space segment activities for the next generation of Sentinel-1 SARs. Special thanks go to ESRIN (B. Rosich) who provided the C-band mosaic

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